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MONITORING IN GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

OBJECTIVES, STRATEGIES, TECHNOLOGIES AND PUBLIC INVOLVEMENT

Proceedings of an International Conference and Workshop,

Luxembourg, 19 – 21 March 2013

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EURATOM

Foreword

Support from the European Commission (EC) to research on the management and disposal of radioactive waste stems from the European Atomic Energy Community (EURATOM) Treaty, which was signed in 1957. Since 1975, the EC has continuously supported research in the field.

One of the requirements of the research programmes is to promote dissemination and use of the results in the European Union (EU) Member States and to promote international cooperation in research activities. With this in mind, in the present Framework Programme 2007-2013, the EC has requested from all the large and key projects it is funding in geological disposal, that they organise a final conference in order to present and discuss the results obtained. The Monitoring Developments for Safe Repository Operation and Staged Closure (MoDeRn) project is one of these key projects and because of its specific importance and international dimension the EC decided to host an international conference and workshop on monitoring in geological disposal of radioactive waste. The conference and workshop received support from the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA), Integration Group for the Safety Case (IGSC).

On the topic of monitoring, one could say that activities on this specific issue at European and international level started only fairly recently compared to other research and development activities. At an EC level, it started in 2001 with the Thematic Network on Monitoring, which is available for download from the EU bookshop http://bookshop.europa.eu . In the meantime, the International Atomic Energy Agency (IAEA) produced, in 2001, Technical Document guidance on monitoring and later in 2006 it issued safety requirements for the geological disposal of radioactive waste including the need for a monitoring strategy. The 2006 requirements were updated in 2011. The NEA for its part launched the reversibility and retrievability project in 2007. Reversibility and retrievability issues are closely linked with monitoring.

Many national programmes have also worked on the issue in parallel, starting from the launch of a performance confirmation programme for the Waste Isolation Pilot Plant in the United States back in 1983, to the international workshop on repository monitoring strategies hosted by the Radioactive Waste Management and Funding Centre (RWMC) of Japan and United Kingdom Nirex in Geneva, in 2007, and others. The Geneva workshop laid the foundation for future activities, based on which the MoDeRn project was prepared for submission to EC funding.

Many aspects of monitoring have been addressed until now but it seems that many of us still do not feel at ease with the issue. The question is: what do we really want monitoring for and is it technically feasible? Would we implement monitoring for performance confirmation, for compliance with regulatory requirements, for decision making, for confidence building or because of public concern and societal demand?

In calling for this project in 2008, the EC was asking somehow to address these questions: what, why, how, when and for how long? Recognising the importance of public involvement on the topic, the EC had also asked the project to involve and seek input from local stakeholders and the public concerned by repository projects.

I hope that the MoDeRn project and this international conference will have contributed to clarifying the issues and making progress on the different aspects of monitoring.

Christophe Davies

European Commission, Directorate General for Research and Innovation, Energy, Unit Nuclear Fission.

EC project officer for the MoDeRn project and other projects in the field of radioactive waste management – geological disposal.

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The active contribution of the OECD/NEA IGSC in the organisation of this conference, thereby further raising the profile and added value of the event, is also gratefully acknowledged, as is the OECD/NEA's financial support through the sponsorship of an independent general rapporteur.

Gratitude is expressed to the following experts for their participation and contributions:

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Finally, thanks are due to Stefan Mayer and his assistant, Ms. Samira Ouchhi, both formerly of Andra, for their instrument role in launching, coordinating and managing the project and the conference until recently.

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1. Introduction

Elizabeth Harvey and Matthew White (Galson Sciences Ltd)

1.1 Background to the MoDeRn Project

Long-lived radioactive waste must be safely isolated and contained for long periods. Current radioactive waste management programmes are focused on disposal in geological repositories as the most appropriate strategy for ensuring the long-term safety of people and the environment.

A successful strategy for radioactive waste disposal should address both technical and societal needs, and monitoring has the potential to contribute to both of these aspects. It can underpin a repository safety strategy and the quality of the engineering design, it can contribute to public and stakeholder understanding of processes occurring in the repository, and hence, it can be used to build confidence in geological disposal. Monitoring therefore plays an important role in enabling waste management organisations to work towards the safe and accepted implementation of geological disposal.

The role of monitoring through the staged implementation of geological disposal has been considered on an international basis through production of an International Atomic Energy Agency (IAEA) Technical Document (TECDOC) on monitoring of geological repositories (the IAEA Monitoring TECDOC) [1] and by the European Commission (EC) within a Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste (the Monitoring ETN) [2]. These two documents have described how monitoring can support the implementation of geological disposal in a broad sense.

Building on these activities, the European Commission (EC) is co-financing the MoDeRn (**Mo**nitoring **De**velopments for Safety **R**epository Operatio**n** and Staged Closure) Project, within its 7th Euratom Framework Programme (FP7). The project, which started in May 2009, and which runs until later in 2013, involves 18 partner organisations drawn from across Europe, Japan and the United States (US), including:

- National radioactive waste management organisations.
- Organisations with specialist technical monitoring expertise.
- A specialist radioactive waste management consultancy.
- Organisations with social science expertise, including understanding of the interfaces between technical and societal needs, and understanding of stakeholder engagement in the context of radioactive waste disposal.

The MoDeRn Project aims to further develop 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. Key objectives of the project are to provide a reference framework for the development and implementation of a monitoring programme, including associated stakeholder engagement, and to consider the role and technical feasibility of using a range of monitoring technologies within the reference framework, particularly during the period following emplacement of waste packages in a repository (the “post-emplacement period”).

Activities within the MoDeRn Project consider a range of strategic, technical and social issues associated with monitoring, and are structured into six inter-related work packages (WPs):

- WP1: Monitoring objectives and strategies.
- WP2: State-of-the-art, and research and technological development (RTD) of relevant monitoring technologies.
- WP3: *In situ* demonstration of innovative monitoring techniques.
- WP4: Case study of monitoring during all stages of the disposal process.
- WP5: Synthesis and dissemination of MoDeRn Project results.
- WP6: Reference framework for repository monitoring.

1.2 Objectives of the Conference and Workshop

A key activity under WP5 of the MoDeRn Project is to hold an international conference on repository monitoring under the auspices of the EC. This conference, entitled "Monitoring in Geological Disposal of Radioactive Waste: Objectives, Strategies, Technologies and Public Involvement", and hereafter referred to as the "International Conference and Workshop on Repository Monitoring", was held on 19-21 March 2013 at the EC's offices in Luxembourg. The objectives of the conference and workshop were as follows:

- To present and discuss the results of the MoDeRn Project, as part of ensuring wide dissemination of this EC-funded work.
- To invite further input to the issues being considered in the MoDeRn Project.
- To discuss how monitoring can be used to inform the disposal process, respond to regulatory requirements, and contribute to enhancing confidence in, and acceptance of, geological disposal of radioactive waste.

The conference took place on the afternoon of 19 March and the morning of 20 March and included oral presentations and plenary discussion under three themes, as well as a poster session covering all three themes. This was followed by a series of six workshops, which were held on the afternoon of 20 March and the morning of 21 March, with the objective of providing an opportunity for further discussions on the conference topics and to investigate whether a shared understanding of repository monitoring can be developed. The key conclusions from each workshop were presented and discussed during a final plenary session later on the morning of 21 March 2013. The conference and workshop were attended by 133 participants from 20 countries.

1.3 Scope of the International Conference on Repository Monitoring

The conference was organised around the following three themes:

- Theme 1: Monitoring – Implementers' perspectives: Programmes and case studies on repository monitoring.

- Theme 2: Monitoring – The wider perspective: Regulatory and stakeholder viewpoints.
- Theme 3: Monitoring technologies: Feasibility and limitations.

Twenty five oral presentations and seventeen poster presentations were spread across seven plenary conference sessions under these three themes, as illustrated in the conference timetable provided in (Fig. 1.1). A detailed conference programme is provided in Appendix A.

1.4 Scope of the Associated Workshops

Six workshop sessions were held, in three parallel tracks. These focused on:

- How to monitor, including discussion of technical feasibility and the limitations of existing monitoring technologies (Workshop 1, Track 1).
- Why to monitor, including discussion of the driving forces for monitoring and why monitoring is required (Workshop 1, Track 2).
- When and how long to monitor for, including discussion of the role of post-closure monitoring and associate stakeholder views (Workshop 1, Track 3).
- How to use monitoring results, including discussion of the role of monitoring within decision making and governance (Workshop 2, Track 1).
- Who should be involved in monitoring, including discussion of the different roles and responsibilities that the different actors involved in monitoring could adopt (Workshop 2, Track 2).
- What and where to monitor, including discussion of the parameters that could be included within a monitoring programme, the spatial distribution of monitoring locations and underlying justifications for approaches suggested (Workshop 2, Track 3).

MoDeRn Project partners acted as the chair person and rapporteur for each of these workshops.

MoDeRn *Monitoring in Geological Disposal of Radioactive Waste*

Objectives, Strategies, Technologies and Public Involvement

General timetable

Tuesday March 19th

Time	Session	Programme
11:00 13:00		Registration
13:00 14:00	S1	Opening: keynote presentation and MoDeRn overview presentation
14:00 16:00	S2	Theme 1 - *"Implementers' Perspective : Programmes and case studies on repository monitoring"*
16:00 16:30		Coffee break
16:30 18:30	S3	Theme 2 - *Monitoring : The wider perspective, the regulatory and stakeholders view point*
18:30	S4	Poster Session & Buffet Reception

Wednesday March 20th

Time	Session	Programme
08:30 09:25	S5	Theme 2 - Monitoring : *The wider perspective, the regulatory and stakeholders view point*
09:25 10:45	S6 S6d	Theme 3 - *"Monitoring technologies : Feasibility and limitations" - Technology*
10:45 11:10		Coffee break
11:10 13:00	S6t	Theme 3 - *"Monitoring technologies : Feasibility and limitations" - Technology*
13:00 13:10	S7	Closure of plenary sessions and introduction to workshops
13:10 15:00		Lunch*
15:00 17:00		**Workshops (3 parallel tracks)**
	ws1-1	"How to monitor ? Feasibility & limitations"
	ws1-2	Why Monitor ? Driving force ?
	ws1-3	When & How long to monitor ?

*: *EC cafeteria will be open for conference delegates*

Thursday march 21st

Time	Session	Programme
09:00 11:00		**Workshops (3 parallel tracks)**
	ws2-1	How to use results Monitoring & governance
	ws2-2	Who is involved ? Roles & responsabilities
	ws2-3	What & where to monitor ? Parameters, spatial distribution & justification
11:00 11:30		Coffee break
11:30 12:50	ws3	Workshop sessions reporting
12:50 13:10	S8	General conference conclusion (General Rapporteur) Closure & adjourn

Figure 1.1: Summary timetable for the International Conference and Workshop on Repository Monitoring.

1.5 Structure of these Proceedings

These proceedings of the International Conference on Repository Monitoring incorporate the following components:

- An independent analysis and synthesis of the conclusions arising from discussion at the conference and workshop (Section 2), based on the observations of an independent expert in the geological disposal of radioactive waste (Alan Hooper) who had not been previously involved in the MoDeRn Project, and who acted as the "general rapporteur" for the conference.

- A record of the key points raised and discussed during plenary conference sessions (Section 3) and associated workshops (Section 4).

- A list of references associated with Sections 1 to 4 (Section 5).

- A detailed conference programme (Appendix A).

- A list of registered participants in the International Conference on Repository Monitoring (Appendix B).

- Full papers for each of the oral and poster presentations submitted to the conference (Appendix C).

Section 2 of these proceedings was prepared by the conference general rapporteur. The discussion in this section reflects the general rapporteur's independent analysis of the event, and does not necessarily reflect the opinions of the MoDeRn Project. Papers provided in Appendix C were prepared by the listed authors. The rest of these proceedings were prepared by Galson Sciences Ltd, on behalf of the MoDeRn Project partnership, as a factual record of discussion.

2. An Overview of the Important Outcomes from the MoDeRn International Conference

Alan Hooper, Visiting Professor of Repository Science and Engineering, Imperial College, London (Independent General Rapporteur)

2.1 Introduction

Monitoring in geological disposal was, until relatively recently, a topic that was treated with apprehension in many radioactive waste management programmes. This was in large part because of a possibility that it implied a need to monitor a repository in the period after closure to somehow prove that it was performing satisfactorily. This in turn could be linked with the hypothetical proposition that long-term safety would rely upon continued human actions and possible intervention, in contradiction of various international and national statements on safety requirements for geological disposal.

Whereas the relationship of monitoring to long-term safety remains an area of lively debate, as evidenced at the conference, successive international initiatives culminating in the Euratom MoDeRn Project have promoted a systematic analysis of the role that monitoring can play in implementing safe geological disposal of long-lived, high-activity radioactive wastes. This progress has been made not least because of the involvement of other players alongside the organisations responsible for implementing disposal. The conference provided a showcase for some of the outputs from the MoDeRn Project but additionally received valuable inputs from other contributors. Formal presentations and contributions to discussions were made with great honesty, exposing the problematic nature of the topic of monitoring rather than ignoring it.

As a matter of practicality, the formal presentations at the conference were structured around the three themes of, respectively: the implementers' perspective; the wider (regulatory and stakeholder) perspective; and monitoring technologies. This disaggregation of the overall topic made it difficult to place some of the information in an appropriate context, although material provided to delegates illustrated a workflow for the Project that could be seen as an approach to integration of the various inputs. A philosophical point established in the introduction to the conference and reaffirmed by various speakers was that monitoring can be characterised as a socio-technical activity in that it can provide a visualisation of what is meant by safety to non-technical members of society and potentially build confidence as a practical commitment to maintain vigilance. However, it was difficult to determine the societal context of some of the technical inputs to the conference. Conversely, from the information presented at the conference, the MoDeRn Project has generated some valuable inputs from stakeholders, for example that monitoring has the potential to build confidence, but subject to constraints such as monitoring being clearly related to showing compliance (with regulatory and other standards or requirements) and to system optimisation. Therefore, it is to be hoped that a successful integration of the outcomes from the technical and societal work packages will take place in finalising the reporting of the Project.

2.2 Definition and Purpose of Monitoring

A range of views was evident on the meaning of monitoring and therefore of its purpose. However, delegates at the conference generally accepted that it was not fruitful to argue whether a specific activity should be defined as a monitoring activity or otherwise. It was very helpful to have a view of the draft *IAEA Safety Guide DS357: Monitoring and Surveillance of Radioactive waste Disposal Facilities*. Noting that the safety guide applies to all types of radioactive waste disposal system, this defines monitoring as "Continuous or periodic observations and measurements to help evaluate the behaviour of the components of a waste disposal system and the impact of the waste disposal system on the public and environment". Surveillance is additionally defined as "Physical inspection of a waste disposal facility in order to verify its integrity to protect and preserve the safety barriers". The two IAEA definitions appeared to be combined in the minds of most participants as a broader definition of monitoring. The draft of the International Commission on Radiological Protection's publication *ICRP-122: Radiological Protection in Geological Disposal* introduces the idea of "oversight" as a form of control even after the repository is closed and which involves monitoring of more than technical parameters. It is envisaged by the ICRP that, with the passage of time after closure of a repository, society would play an increasingly important role in such oversight.

In the keynote address to the conference *Monitoring and Long-term Safety (P. Zuidema, Nagra, Switzerland)* it was proposed that monitoring can:

- Provide specific technical information to implement geological disposal.

- Provide important inputs to the scientific and technological basis for geological disposal.

- Provide information for society that helps the interaction between technical experts and society.

This set of purposes of monitoring is very much in line with the thrust of the draft IAEA Safety Guide and its statement that monitoring should be driven by and inform the safety case. It implies a focus on the monitoring of technical aspects of a geological disposal system, whereas the ICRP draft publication appears to imply monitoring of non-technical aspects also. These are not mutually exclusive positions; the monitoring of non-technical aspects after closure of a disposal facility is generally accepted as an important element of an institutional control period that is expected in most national programmes.

2.3 A Systematic Framework

The value of establishing a framework in which to discuss the role and objectives of monitoring became clear in the initial stages of the conference. Based on the stepwise implementation of geological disposal, it helps to overcome differences in terminology and of focus in different national programmes to consider that monitoring is necessary in each of the following stages that support decision-making:

- Site selection (e.g. monitoring seismicity, geodesy).

- Site investigation (e.g. monitoring ecology, hydrology, hydrogeology).

- Design of engineered barrier system (e.g. monitoring prototypes in an underground research laboratory (URL) or mock-up facility).

- Construction (e.g. monitoring response of host rock to excavation of tunnels etc.).

- Operation (e.g. monitoring emplaced wastes and engineered barriers).

- Closure (e.g. monitoring of engineered sealing systems).

- Post-closure institutional control (e.g. monitoring conditions at the surface according to any regulatory or societal requirements).

Both the approach to monitoring according to this stylised schedule and the objectives of the monitoring are clearly dependent upon respective national policies, implementation plans and repository concepts. For example, the Swiss national programme envisages a pilot facility where real wastes will be emplaced specifically for the purpose of monitoring. The French national programme has to meet a requirement for reversibility until repository closure, necessitating long-term monitoring of the engineered disposal system after waste emplacement.

Also in the early stages of the conference, there was a clear consensus from presentations and discussions that a systematic approach to defining the link between monitoring activities and long-term safety is helpful to implementers, regulators and stakeholders. Well-chosen examples showed that it is practicable to start with the safety functions of the various barriers in the multiple barrier system and then to identify the processes that are involved in the delivery of each safety function, for example by using a features, events and processes (FEPs) database appropriate to the system under consideration. The ability to measure the parameters that characterise these processes as part of a monitoring programme can then be considered in turn.

2.4 Confidence Building

Confidence building is an important theme of the MoDeRn Project and this was emphasised at the conference. Presentations of work carried out as part of the project showed that, by commissioning relevant social scientific research, it has gone beyond simply asserting that monitoring per se will build or assure confidence in the minds of stakeholders. Additionally, valuable insights were afforded by presentations on the views of stakeholders in specific disposal projects (Mol / Dessel Partnerships in the framework of short-lived LLW/ ILW disposal in Belgium, and the local community for the Waste Isolation Pilot Plant at Carlsbad, New Mexico, USA).

An important aspect to note from all the relevant information presented, including an analysis of the socio-technical nature of monitoring, is that monitoring cannot be considered in isolation from the governance of waste disposal. The roles, responsibilities and behaviour of the relevant organisations will strongly determine whether monitoring can play a role in confidence building. There was general agreement that monitoring has the potential to build confidence, but that realising this potential is subject to a number of conditions. Conditions might include establishing a relationship with compliance and optimisation and establishing appropriate governance arrangements within which the time and dimensional space to be covered by monitoring can be discussed and agreed. Such conditions may vary for individual groups of stakeholders. The merit in engaging with a locally-based partnership at the earliest opportunity was clear both from the more theoretical analyses and from the experience of real projects.

Many significant points emerged during the conference concerning the expectations of stakeholders in relation to monitoring, three of which are highlighted for the purposes of this section of the summary.

i. Stakeholders expect monitoring to test compliance with relevant regulations and standards, thereby providing some level of assurance that the facility is safe at the time of monitoring and will continue to be safe in the future. This supports a general agreement on the necessity for society to be satisfied with a programme of environmental monitoring along the lines of those programmes routinely carried out currently at nuclear sites (for example measuring radioactivity in environmental samples, including foodstuffs, soils, water and air), which would continue after operations had been completed and the disposal facility had been closed.

ii. Additionally stakeholders expect that monitoring will be used to inform optimisation of the facility; this is particularly strongly manifested when a local partnership such as the Mol/ Dessel partnerships are engaged with the implementer in discussions of facility design.

iii. Finally, there is the expectation that a monitoring programme will be comprehensive, not least in the sense of being able to identify unexpected behaviour. It follows from this finding that stakeholders expect the implementer to be willing and able to respond to the results of monitoring, for example by retrieving waste if appropriate.

It seems that the respective views of the different actors in relation to uncertainties, and how they are to be treated, underpinned many of the findings from stakeholder groups. Very possibly fuelled by the use of jargon such as "performance confirmation" or "demonstration experiments", the impression has been given that technical experts have a closed mind to the possibility that systems or sub-systems will behave differently from the manner intended or modelled. Therefore an important contribution can be made to confidence-building in relation to a monitoring programme if the programme is presented in the context of the classical scientific method of testing.

Independent regulation is an important aspect of confidence-building and the role of the regulator in monitoring the implementing organisation's monitoring activities was emphasised. A possible tension is recognised between stakeholders' expectations of monitoring after repository closure and the current expectations of regulators. As discussed in the following section, in general regulators have an expectation for monitoring to support the safety case and for this to be achieved principally in the period up to the time when an application is made to close the repository. Thereafter monitoring requirements would be to support post-closure institutional control of the repository site until it would be decided that such control is no longer necessary. Currently there appear to be no known regulatory requirements for specific monitoring activities after repository closure, although some regulatory bodies have clearly stated a requirement for such monitoring and associated systems and in some cases are giving the topic further consideration, which may lead to specific requirements on the objectives and duration.

2.5 Post-closure Monitoring

One generally accepted principle, as stated clearly in *Monitoring Requirements in the Swiss Regulatory Framework (A.-K. Leuz et al., ENSI, Switzerland)*, that monitoring activities should not adversely affect the passive safety barriers of a repository and therefore potentially impair safety, applies equally to the post-closure period. However, beyond this, whereas there is a reasonable level of agreement both between the various actors and between different groups of technical experts as to what types of monitoring activities can and should be conducted in the stages leading up to the time of closure of a disposal facility, there is not such unanimity of view for the time after closure. The role and objectives of post-closure monitoring are recognised as requiring further consideration in some national programmes. As expressed clearly at the conference, poorly conceived undertakings to carry out post-closure monitoring as some means of confirming the long-term safety case presents difficulties for the regulator. Once the designated disposal activities have been completed and the relevant actors have determined that the isolation and containment multi-barrier system should be fully established, it is for the regulator to judge whether the arguments presented in a long-term safety case are sufficiently substantiated to allow the closure of the facility.

Therefore the necessary level of substantiation of the safety arguments, including modelling of the long-term evolution of the facility, must rely on information already available and cannot rely upon the promise of future results from a monitoring programme.

The draft IAEA safety guide presents the position (for geological disposal) that monitoring after closure is rather for the purpose of public reassurance than for ensuring the performance of the disposal system. Although perhaps a little stark in its presentation, this hints at the questions concerning post-closure monitoring posed by a regulator at the conference, namely “Why, for who and how long?” The stakeholder views expressed at the conference already go some way to answering these questions in principle at least. However, the important conclusion that can be drawn from the conference workshops is that currently it is neither practicable nor necessary to have detailed, definitive answers to the questions. Furthermore, it may be that we can never a priori formulate definitive answers and that these questions frame an ongoing dialogue between the various actors. The MoDeRn Project is successfully laying out the technological and societal possibilities such that these can then be discussed between the relevant actors in national programmes, as is envisaged by the Finnish regulator STUK.

In the absence of the specification of a detailed post-closure monitoring programme there does appear to be an issue in the event that the design, construction and operation of a disposal facility might preclude monitoring activities that are subsequently identified as required. However, there is a generally agreed requirement to be able to show, through test monitoring, that the “initial state” of the disposal facility, as described at the time of closure in the long-term safety case, has been achieved. Substantial provisions for monitoring are likely to be established in meeting that requirement.

2.6 Monitoring Technologies

Under the MoDeRn Project, impressive progress has been made in developing and analysing the capabilities of monitoring technologies in each of the fields of measurement probes and methods, data transmission, and energy supply. The physical limitations on the various technologies are much better understood as a result, for example the distances over which various types of signals can be reliably transmitted, the influence of the host rock-water system, and the energy demand of various technologies. Some problems remain to be investigated, for example the reliability of technologies operating in the radiation field presented by emplaced radioactive wastes.

A key challenge that the technologies have to meet is that monitoring should not impair the safety of a disposal facility. This is seen as precluding the use of cables to carry signals from the wastes and engineered barrier system back to the surface and has led to a focus on wireless transmission of data; the technologies explored to date have relied on radio frequencies while the non-radio alternatives do not look promising. The long timescales of interest in geological disposal, even in relation to monitoring relatively short-term transients in the disposal system, are greater than those covered by our experience of any of the technologies of interest. Furthermore some technologies require access to measurement points obtained by open boreholes to depth, which is potentially problematic if such monitoring is envisaged in the post-closure period or if borehole sealing is considered to be an issue.

Nevertheless, valuable information has been, and continues to be, obtained from monitoring large scale tests of excavations and engineered barrier systems in underground research laboratories, using some of the most recently developed monitoring technologies. Coupled with the more fundamental studies on the physical science of monitoring technologies, this experience can be used to point to the most promising areas for further research and development, thereby presenting a picture of the possibilities that can be pursued.

Despite the considerable progress that has been made, it appeared unlikely that current monitoring technologies will be developed such that they can be relied upon to function for the nominal period of 100 years considered in the case studies of repository evolution in the MoDeRn Project.

2.7 Important Considerations in a Monitoring Programme

Transferability of information

In order that monitoring activities carried out in successive stages of implementation of a disposal facility can fulfil the role of supporting the eventual long-term safety case, the transferability of the information obtained needs to be understood. The Swiss national programme exemplified how monitoring information on the behaviour of the engineered barrier system (EBS) in a generic URL might be transferred to the design for a site-specific disposal facility. The legislation for the development of the disposal facility itself at the selected site envisages monitoring in a test area whereby the safety-relevant properties of the EBS and host rock must be tested in support of the safety case. In the subsequently developed pilot facility, the behaviour of representative waste, backfill and host rock is required to be monitored over a long period such that it is readily transferable to the processes occurring in the main disposal area and ultimately supports the decision to close the facility.

The requirement for transferability of monitoring information was raised consistently by implementers, regulators and stakeholders but its implications were not much discussed at the conference. The observation, in connection with the monitoring strategy for the French “Cigeo Repository”, that the homogeneity of the properties of the host-rock formation is important for developing a practicable monitoring programme merits attention. It is likely to be problematic to transfer monitoring information obtained from one location in the engineered system to infer the evolutionary behaviour of un-monitored parts of the system elsewhere when a repository is located in a heterogeneous host rock. As is already recognised in site characterisation programmes, the implementer would need to exercise caution in considering transferability of monitoring information for host rocks with spatially heterogeneous processes and properties, where possible taking account of the influence such heterogeneity could have on the variability of any parameter to be monitored.

Transient conditions

A favourable host rock for a disposal facility is typified by the property of low hydraulic conductivity. This desirable property will cause processes such as the saturation of the components of engineered barrier systems (EBS) by inflowing groundwater to occur very slowly. Furthermore, heterogeneity in the rock local to the EBS and/ or in the interfaces between the EBS and host rock will cause such saturation to occur at different rates at different locations. It is noticeable that the saturation process is frequently cited as one that should be monitored, purportedly to demonstrate that the system is showing its expected evolution. However, the conference received a striking example of the risks of making such assertions.

The example concerned the monitoring of the evolution of stresses and pore pressures in and around a sealing dam installed in the German ERAM Repository. It has to be recognised that this does not represent an idealised situation, such as might be achieved in a future disposal system designed and operated in accordance with current knowledge and experience. Nonetheless, the conclusions from the monitoring carried out to date include that there are inhomogeneous distributions of permeabilities, stresses and pore pressures in the contact zone between the engineered dam and salt host rock so that the monitored pore pressures and normal stresses are influenced by local conditions. Furthermore, "many challenges arise in the analysis and interpretation of the captured values even with the careful planning of the measurement programme and installation of the devices". It was reasonably concluded that homogenisation of properties might occur eventually but that this cannot be predicted with confidence from the information obtained.

This valuable example fits very well with the messages in the keynote address concerning the societal aspects of monitoring, namely that interpretation of monitoring data in the context of overall system behaviour is the other half of building confidence, and that to inspire confidence through monitoring the inherent limitations must be recognised and explained. These statements in the keynote address were made in the context that even the attainment of steady-state conditions in the near field of a disposal system is unlikely to be realised over timescales that are short enough to allow it to be monitored; therefore monitoring is restricted to the measurement and observation of transients which need to be strong enough to provide clear indicators of the system evolution. The monitoring of transient conditions themselves can be of great value during the period prior to closure of a repository, for example providing information on temperature rises as a result of the radiogenic heat-loading in emplaced high-level waste and its effects on the disposal system and geological environment.

2.8 In Conclusion

In line with the position of the participants in the MoDeRn Project, there will be no single, international prescription that national programmes can take as the basis for the design of a monitoring programme. The national waste inventory, disposal concept, governance arrangements, regulations, and societal values and norms will establish the necessary context and input. Nonetheless, in line with the objectives of the MoDeRn Project, this conference provided much of the information required to establish the framework for designing a national monitoring programme.

There appears to be a reasonable degree of consensus between all the interested parties concerning the role and objectives of monitoring in supporting step-wise decision making up to the point of closure of a disposal facility, and there is also a shared understanding of the issues that should be further discussed in relation to the post-closure period. The expectations of stakeholders are expressed in different terms to those often used by implementers but in fact there appear not to be fundamental differences. The same important aspects that apply to implementation of geological disposal overall, such as governance arrangements and the ability of stakeholders to have access to information and to influence decisions, apply equally strongly in the area of monitoring.

The inputs made by regulators proved invaluable and it is encouraging that national regulatory bodies in some of the more advanced programmes are planning to give monitoring, particularly in the post-closure period, more detailed consideration. It is recommended that these regulatory bodies should, if possible, be involved in any ensuing international initiative in this area.

A matter not specifically considered under the auspices of the MoDeRn Project concerns the practical reality of funding monitoring activities, particularly in the long term after repository closure. It might be worthwhile to analyse how this matter is dealt with in national plans, particularly as reflected in the planning information provided to international organisations, to determine whether it requires further consideration.

3. Record of Conference Plenary Discussion

Elizabeth Harvey (Galson Sciences Ltd)

This section provides a factual record of discussion during the International Conference on Repository Monitoring, for each of the three themes of the conference. For each theme, the papers presented under the theme are listed, and a reference is given to the paper numbers. In these numbers, "S" refers to the conference session in which the paper was presented. "O" refers to an oral presentation (associated full papers can be found in Appendix C.1, C.2, C.3, C.5, C.6D and C.6T) and "P" refers to a poster presentation (associated full papers can be found in Appendix C.4). This is followed by a summary of the key points discussed during plenary sessions associated with each theme.

3.1 Theme 1: Monitoring – Implementers' Perspectives: Programmes and Case Studies on Repository Monitoring

The following oral presentations were delivered during Session S2 of the International Conference and Workshop on Repository Monitoring:

- S2O1: Michael Jobmann (DBE-TEC, Germany) presented a summary of monitoring case studies carried out under the MoDeRn Project.

- S2O2: Steve Wagner (Sandia National Laboratories, USA), described the development and use of conformation monitoring programmes in association with radioactive waste repositories in the US.

- S2O3: Stephane Buschaert (Andra, France), set out the monitoring strategy for a French reversible waste disposal facility.

- S2O4: Assen Simeonov (SKB, Sweden), described the proposed approach to monitor the repository for spent nuclear fuel in Sweden.

- S2O5: Brendan Breen (NDA, UK), summarised the approach taken to develop the monitoring programme for a UK geological disposal facility.

The following poster presentations were delivered during Session S4 of the International Conference and Workshop on Repository Monitoring:

- S4P1: Jorge Villagran (NWMO, Canada), presented work conducted to develop a repository monitoring programme within the framework of Adaptive Phased Management in Canada.

- S4P2: Richard Guppy (NDA, UK), on behalf of James McKinney, presented integrated guidance on controlling storage conditions and monitoring higher-activity waste packages during interim storage.

- S4P3: Mansueto Morosini (SKB, Sweden) provided an overview of the hydrogeological monitoring programme carried out at the Äspö Hard Rock Laboratory in Sweden.

- S4P4: Susanna Andrén (SKB, Sweden) presented the groundwater monitoring programme at the Forsmark site in Sweden, performed to establish the baseline (undisturbed) conditions of the site.

- S4P5: Susanna Aro (Posiva Oy, Finland) presented results from the Finnish programme to monitor the hydrogeological effects of construction of the ONKALO URL in Finland.

- S4P13: Jiro Eto (RWMC, Japan) described the requirements on a wireless monitoring system for application during the stepwise backfilling and sealing of a geological repository.

- S4P14: Hiromi Tanabe (RWMD, Japan) discussed the basic requirements on monitoring activities in geological disposal, and the role of wireless data transmission in supporting the delivery of these requirements.

- S4P21: Matthew White (Galson Sciences Ltd, UK) described the monitoring plan for the new low-level waste facilities at Dounreay in the UK, and implementation of the associated groundwater monitoring programme.

The points below record the key areas of discussion following oral presentations under this theme.

Impact of National Context on Development of a Monitoring Programme

The scope of a monitoring programme developed for a particular repository will be affected by a range of factors that are specific to the disposal programme in question. For example, the disposal concept design and safety functions associated with different parts of the disposal system could have a significant impact on monitoring objectives and decisions on where and how to monitor. There may also be national policies, such as a requirement for retrievability, and/or regulatory requirements to monitor a particular process, or to carry out monitoring in a particular part of the repository, that influence the choice of monitoring parameters. In addition, the feasibility of successfully employing certain monitoring and wireless data transmission techniques is strongly dependent on the thickness and composition of engineered barriers such as the backfill, and plugs and seals, and on the characteristics of the local host rock. For example, clay rocks typically impede magneto-induced wireless data transmission to a greater extent than evaporites and crystalline rocks, and this effect is particularly significant when signals are transmitted over long ranges using low frequencies. The water-filled porosity of rocks also has a significant effect on the potential transmission distance. For similar reasons, micro-seismic monitoring tends to yield better results in crystalline rocks, compared to clay rocks.

Collectively, the considerations that are relevant for a particular repository development programme can be referred to as the national context for monitoring. This term has been widely used in the MoDeRn Project (which included a task to collate national contexts for partner countries) and also in previous collaborative studies on repository monitoring.

The implication of variations in the national contexts for monitoring is that there will be significant differences from country to country in the specific objectives for monitoring, the desired timescales for monitoring, and how monitoring is targeted at different components of the disposal system and the surrounding environment (and hence, in the characteristics of the associated monitoring programmes). Clear communication of the reasons for these differences to stakeholders might be important to allow stakeholders to understand why there are differences between monitoring programmes in different national programmes.

Monitoring Objectives from the Implementers' Perspective

A key objective for monitoring in many national programmes is to confirm[1] acceptable performance of components of the disposal system, particularly those providing key safety functions. At least theoretically, performance of such components could either be monitored directly, for example through the use of sensors attached to dummy waste packages, or indirectly, for example through the measurement of any radionuclide contamination in the groundwater around a repository. However, there is some evidence that public stakeholders would be typically more interested in monitoring conditions in their local environment, to ensure that there is no direct impact on them.

Direct monitoring of barrier performance may require the use of instrumented example (demonstrator) units or sacrificial components of the disposal system, possibly located within a pilot facility. This could be facilitated by a plan for retrieval and re-packaging/re-emplacement of a small quantity of waste at some point, once sufficient monitoring has been carried out. Information on the performance of disposal system components is also derived from the wider science programme, including experiments conducted within URLs and surface laboratories, and through modelling.

Drivers for Post-closure Monitoring

International guidance on repository monitoring recognises that monitoring and surveillance could be maintained for as long as society considers it beneficial [1]. However, it is a principle of geological disposal that assurance of safety does not require post-closure monitoring. Any post-closure monitoring undertaken by future generations should be designed in such way that no negative impacts on the performance of the containment barriers and therefore on the long-term safety of the repository would occur. Implicit in this principle is that the safety case has to provide sufficient confidence that a repository is safe and performing as expected before permission is granted to close the facility.

However, in some countries, notably Germany and France, national legislation and/or regulations either explicitly or implicitly require some form of post-closure monitoring or surveillance to be carried out. For example, in Germany[2], safety requirements governing the final disposal of heat-generating radioactive waste require the establishment of a monitoring system "during emplacement operations, decommissioning, and for a limited period following decommissioning, in order to verify that the input data, assumptions and statements of the safety analyses and safety cases performed for this phase have been observed" [3]. This contrasts with the situation in some other countries (for example in Sweden and Switzerland), where the responsibility of the implementer ends when the repository is closed, such that the implementer would not be responsible for any post-closure monitoring carried out.

It is recognised that even in countries where there is no requirement for post-closure monitoring associated with confirming the continued acceptable performance of the repository, there may still be other reasons for undertaking some form of post-closure monitoring. Key among these is the use of post-closure monitoring to provide confidence to local communities that a repository is safe.

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[1] Note that the perception and interpretation of terminology such as 'confirmation', when used in the context of describing monitoring objectives, was the subject of repeated discussion during the International Conference and Workshop on Repository Monitoring, as reflected in Sections 2.4 and 3.2.

[2] In Germany, the implementer is required to provide a comprehensive monitoring concept. However, German regulations state that the authorities are free to decide who will be responsible for conducting monitoring. This means that monitoring could be performed by an independent institution, rather than the implementer. This point has relevance for discussion of the independence of repository monitoring captured within Sections 2.4, 3.2 and 4.4.

The way in which post-closure monitoring is implemented will be strongly dependent on why it is being carried out. It is therefore crucial to understand the drivers for post-closure monitoring, in order to evaluate the potential benefits it offers, and to plan an appropriate programme of monitoring activities.

It was noted during the conference discussions that the public has a relatively high degree of confidence in the implementers in Finland and Sweden – countries that do not expect to carry out post-closure monitoring. A participant suggested that there may be a connection between these two points, based on the observation that post-closure monitoring is often driven by lay stakeholders not trusting an implementing body, and wanting reassurance that a repository continues to perform safely.

Balancing Technical Feasibility against Timescales for Post-emplacement / Post-closure Monitoring
If desired, monitoring could be employed during all phases of repository implementation, from monitoring the baseline (undisturbed) conditions of a repository site, through repository construction, operation, closure and post-closure. Applicable techniques and timescales for monitoring vary depending on the phase in question.

During the operational period, there is an opportunity to monitor the engineered barrier system following emplacement of the waste, buffer, backfill and initial plugs and seals. There are several challenges associated with monitoring repository evolution after waste emplacement, and, in particular, with extending such monitoring into the post-closure period. Barrier functions will typically be provided over many hundreds or thousands of years (or longer), and many processes in a repository are expected to occur very slowly. In many cases, it will not be feasible to monitor such processes over relevant timescales using either currently available technology, or even taking account of anticipated future advances. It is therefore important to define realistic objectives for post-emplacement and/or post-closure monitoring, and to link these objectives to sensible monitoring timescales.

In addition to timescale issues, there are specific technical issues associated with monitoring following emplacement. For sensors emplaced in the engineered barrier system, these include the capabilities for wireless data transfer and *in situ* power supplies, and the possible impact of the sensors on the performance of the barriers. For non-intrusive monitoring, technical issues are associated with the resolution of monitoring data, translating measured parameters to information on repository evolution, and recovery and backfilling of measurement equipment (e.g. geophones placed in boreholes). It is important to communicate the technical limitations of monitoring to stakeholders, and to avoid "promising too much", which could undermine confidence in future. One possible objective for post-closure monitoring could be to carry out post-closure monitoring to support a potential decision to remove institutional controls from a closed repository. This would then focus such monitoring on surface activities such as human actions rather than on detailed monitoring of the engineered barrier system.

Successful implementation of a pre-defined post-emplacement monitoring programme over a realistic timescale could be used to demonstrate, to a variety of stakeholders, an implementer's capability to emplace the engineered barrier system as specified in the design. This could help to build trust in the implementer's subsequent activities and in the long-term safety of the disposal system.

Once realistic timescales for monitoring have been identified, these can be used as the basis for targeting future RTD on monitoring technologies to meet specific needs.

Future generations will be responsible for taking decisions on whether to continue to monitor a repository after closure. However, it was recognised that there is a need to plan ahead so that post-closure monitoring *could* be undertaken, if it appears that this may be a requirement in the future.

Dealing with Unexpected Results and Building Stakeholder Confidence

There is a clear requirement to demonstrate that a repository will be safe before implementation, which is achieved through development of the safety case. Once construction and operation have begun, integrating the results of an ongoing monitoring programme into the long-term safety case could increase confidence in it.

However, results from a monitoring programme may not be consistent with the assumptions or arguments within a safety case. These would be classified as unexpected results. A monitoring programme should specify trigger values, based on the characteristics of a particular disposal system, which, when exceeded, call for an action in response to the monitoring results. Different scales of response can be implemented, depending on the extent of implications for safety. The significance of unexpected results to the safety case could be considered by re-running performance assessment calculations and by carrying out a range of sensitivity studies. Other possible responses to unexpected results include engineering intervention and retrieval of waste.

The potential for obtaining unexpected results with implications for performance of the disposal system (particularly to the point where retrieval of waste packages might be considered to be necessary) will be mitigated through implementation of a comprehensive safety strategy in development of the safety case and through the design and planning of repository implementation. Nevertheless, putting plans in place to respond to unexpected monitoring results is considered to be important in giving stakeholders confidence that appropriate contingency measures exist if a repository does not perform as expected.

Development of European Standard on Geotechnical Monitoring

The European Standards Organisation is in the process of drafting a standard for geotechnical monitoring. The monitoring requirements associated with this new standard, once published, should be considered within all national disposal programmes.

3.2 Theme 2: Monitoring – The Wider Perspective: Regulatory and Stakeholder Viewpoints

The following oral presentations were delivered under this theme during Sessions S3 and S5 of the International Conference and Workshop on Repository Monitoring:

- S3O1: Anne Bergmans (University of Antwerp, Belgium) presented different views on monitoring and governance of repository development and staged closure based on engagement with expert and lay stakeholders.

- S3O2: Herman Sannen, (STORA, Belgium) presented a stakeholder viewpoint of monitoring for geological disposal.

- S3O3: Punam Thakur (Carlsbad Environmental Monitoring and Research Center, USA) described the environmental monitoring programme of the Waste Isolation Pilot Plant (WIPP) in the US, including presentation of recent results.

- S3O4: Morgan Meyer (CNRS, France) presented a theoretical and sociological analysis of monitoring and demonstration.

- S3O5: Claudio Pescatore (NEA) discussed preliminary findings from the Records, Knowledge and Memory Across Generations (RK&M) Project, currently being undertaken under the auspices of the NEA. The project is considering the role of "oversight" and the role of monitoring in the development of geological repositories.

- S5O1: Kai Moeller (IAEA) presented the status, structure and content of the IAEA draft safety guide on monitoring and surveillance of disposal facilities.

- S5O2: Jussi Heinonen (STUK, Finland) described the regulatory view on monitoring of spent fuel geological disposal in Finland.

- S5O3: Ann-Kathrin Leuz (ENSI, Switzerland) set out monitoring requirements in the context of the Swiss regulatory framework.

The points below record the key areas of discussion following the presentations under this theme.

Lay Stakeholder Perspectives on Monitoring Objectives

Lay stakeholders are typically of the view that the details of how a repository monitoring programme should be undertaken should be specified by the responsible implementing organisation, with input from the relevant regulators and government.

At the conference, it was suggested that where stakeholders do suggest specific monitoring activities, there is typically a greater degree of interest in environmental monitoring (as discussed under Theme 1), with the objective of ensuring that there are no detrimental impacts of a repository on the area stakeholders are living in, than on monitoring parameters more directly linked to performance of the disposal system, such as package corrosion and seal integrity. This is reflected in the creation of organisations such as the Carlsbad Environmental Monitoring and Research Center (CEMRC), which was set up primarily to undertake environmental monitoring of the WIPP site and the surrounding area.

For monitoring that *is* associated with an objective to confirm barrier performance, it was noted that from a lay stakeholder perspective, it is considered difficult to demonstrate the safety of a repository purely using laboratory experiments. This implies that some form of monitoring of the underground environment is called for by some lay stakeholders (e.g. monitoring of disposed waste packages and/or the surrounding engineered barriers or monitoring within a pilot facility).

A related point is the perception by some lay stakeholders that the typical implementer focus on confirmation, rather than on checking, of expected behaviour comes across as arrogant. The implementers' perspective arises because of the requirement to develop a robust safety case before any disposal activities take place. However, the basis for this perspective needs to be successfully communicated, to avoid a perception of over-confidence and dismissal by implementers of the important role that monitoring can play in checking successful implementation of geological disposal.

Use of Monitoring to Build Public Confidence

For confidence building, there needs to be a clear demonstration that the choice of parameters to monitor is developed, at least in part, through dialogue, engagement and participation with stakeholders. Some monitoring may be undertaken largely (or even purely) to address stakeholder concerns. An example proposed at the conference was monitoring of seismic activity in the area around a proposed repository, even when expert analysis suggests that this will not be a significant factor affecting repository performance.

A key requirement for building local stakeholder confidence appears to be the continual collection of data on the properties of the repository system, so that any changes in behaviour can be identified. This includes a significant period collecting information on the properties of the system before any waste is emplaced. This desire is already recognised within international guidance on repository monitoring as the requirement for the collection of monitoring data on baseline conditions at proposed repository sites [1,2]. Baseline environmental monitoring was undertaken by the CEMRC in the vicinity of the WIPP, including air quality sampling before the facility began to receive waste, and is also being undertaken at proposed repository sites by other national waste management organisations, for example in Sweden and in Finland.

An associated point is a preference expressed by some stakeholders that all monitoring data should be made publicly available, to avoid any perception that only selected results are being communicated to the public. Whilst such an approach increases the openness and transparency of a monitoring programme, it is recognised that raw data may not always provide meaningful information to local communities. To address this point, the CEMRC publishes the results of specific monitoring activities in newsletters and in local newspapers, and includes guidance on the interpretation of data and its perceived significance within these publications. This is done in conjunction with making all monitoring data available on the internet, once it has be checked internally for quality assurance purposes.

At the conference, participants noted that stakeholders expect implementers to develop expectations for what will be observed through monitoring, and how monitoring results may change over time. Bearing in mind the duration of a repository implementation programme (likely to be in excess of a hundred years), as well as the long timescales over which some processes in the repository will occur, there is an expectation that implementers will periodically re-evaluate their understanding of system performance as the implementation programme progresses, taking account of new data as they become available, and considering any associated changes in requirements for monitoring. Developments in the implementer's understanding also need to be discussed with stakeholders in a transparent and accessible way.

The level of public interest in repository activities in general, and monitoring in particular, is expected to be relatively low in situations where a significant level of stakeholder confidence in disposal system performance has been established, i.e. if no releases to the accessible environment have been measured from the onset of monitoring. During such periods, the very existence of an on-going monitoring programme can contribute to public confidence. Interest in, and scrutiny of, monitoring programmes may increase if concerns arise over system performance. This might result from factors that are specific to the repository in question, such as small increases in the measured radioactivity in the environment. However, it might also arise as a result of external factors, for example if there were any increased concerns over nuclear safety on a global basis in the future. An increased interest in the CEMRC's monitoring activities was observed following the Fukushima Daiichi disaster.

Lay stakeholders often express a preference for repository monitoring to be carried out by an independent organisation not associated with the implementer, regulators or government. This is particularly the case in countries where, due to the national context of the repository development programme, there is limited confidence in the actions of the implementing organisation, and/or limited confidence in the ability of the nuclear regulators to provide independent scrutiny of a repository development programme on behalf of the public. As an example, it was noted that environmental monitoring around the WIPP facility is carried out by both the CEMRC and the Department of Energy (DOE). However, there is generally a greater degree of public trust in the results of monitoring carried out by the CEMRC, due to the perceived independence of this organisation. Some participants commented that in cases where the funding for independent monitoring organisations originates from the implementing organisation (as is the case for the CEMRC), this could undermine confidence in the independence of the monitoring organisation. This point was discussed further in Workshop 2, Track 1 (see Section 4.4).

Role of Informed Lay Stakeholders and Approach to Stakeholder Engagement

Public stakeholder groups, particularly in the vicinity of an existing nuclear site, often include individuals with expert knowledge in highly relevant fields. Examples noted at the conference included structural engineers with expertise on the performance of concrete in civil construction, and former/current site workers with knowledge of nuclear safety and plant operation. Such groups are also likely to include individuals without relevant expertise and with only limited understanding of key issues for radioactive waste management and disposal. Depending on the extent of previous engagement and outreach activities, and the involvement of individuals within a group in such activities, there is also likely to be a varying degree of understanding of key issues such as:

- An appreciation of the technical limitations of monitoring.
- The requirement that monitoring does not adversely affect the passive safety provided by the repository.
- Recognition that it may be difficult to monitor safety relevant parameters directly, or over meaningful timescales.

This raises the question of what constitutes a “lay” and an “expert” stakeholder, and indicates that the distinction between the two types of stakeholder may not be straightforward. It also has important implications for approaches used to engage with public stakeholders in the development and implementation of monitoring programmes.

Lay stakeholders with specialist expertise may play an important role during engagement activities with an implementing organisation, acting on behalf of a wider public group. For example, they may be comfortable challenging detailed aspects of information presented by implementers. They may also be able to assist in explaining the significance of technical information and technically complex ideas (e.g. probabilistic safety assessment) to less informed members of a public group, although conversely, they may deliberately choose not to do so, if they regard this to be an important responsibility of the implementers themselves.

Sociological analysis of monitoring and demonstration has identified key considerations to be taken into account when planning and conducting the involvement of lay stakeholders in the development and implementation of monitoring programmes. In particular, there is a need for implementers to appreciate that the public are already involved in monitoring, through taking an interest in, and commenting on, repository programmes, and that lay stakeholder perspectives need to be considered, and where feasible, integrated into development of a monitoring programme, even if the implementing organisation does not agree with these perspectives. It was suggested that the philosophy of an implementing organisation in engaging with local stakeholders will have profound implications for the success of a repository development programme, particularly where local communities have a role in decision-making associated with repository siting. In order to be successful, the implementing organisation needs to wish to engage, and to hope to gain something through doing so. There is an associated need to appreciate that engagement activities are not just about communicating technical information; the act of stakeholder engagement and involvement is one of reassurance, particularly where this is done in a continuous, repeated or ongoing manner.

Monitoring versus "Oversight"

The concept of oversight of a repository was discussed. Oversight is a general term for "watchful care" and refers to society "keeping an eye" on a technical system and the actual implementation of associated plans and decisions. In the context of radioactive waste disposal, oversight and safety assurance are considered in terms of the active institutional control of a repository, including factors such as a dedicated monitoring programme, knowledge management and long-term records management, as well as passive control of the facility, for example through built-in design features and safety functions provided by components of the disposal system. Passive controls could also include indirect monitoring of factors affected by repository performance. A gradual transition from active controls requiring human intervention, to passive controls that do not require intervention is expected to occur as a repository implementation programme progresses. Requirements for active controls, such as long-term records management may be strongly linked to the timescales for monitoring, particularly post-closure monitoring.

The International Commission on Radiological Protection (ICRP) is currently developing guidance on the concept of oversight and associated recommendations for international and national policy and guidance. A draft of this guidance has been released for consultation, and has been reviewed by the NEA and various radioactive waste management organisations [4]. The guidance is expected to be published shortly.

Oversight can also be used as a term to indicate that something has been overlooked and missed. Careful communication of the context for using this term is therefore important.

Monitoring Hazardous Waste Disposal

Transferable experience may be available from approaches to monitor the disposal of stable hazardous (non-radioactive) wastes such as wastes contaminated with heavy metals, although the regulatory basis for disposal of such wastes is quite different from that for radioactive waste disposal. Radioactive waste management organisations have been involved in reviewing the outputs from EC projects considering this topic, and there may also be valuable experience to feed back into development of monitoring programmes for geological disposal of radioactive waste.

Regulators' Perspectives on Monitoring

Regulatory requirements relating to monitoring tend to focus on demonstration of the assumptions and arguments in the safety case provided as a basis for licensing, and typically place a lower emphasis on aspects of trust and confidence in the implementer than perspectives expressed by lay stakeholders.

Where monitoring is used in order to demonstrate repository performance, there is a requirement that this monitoring is representative of behaviour in the repository itself, especially if monitoring is undertaken on a limited part of the repository or in a separate area such as a pilot facility. At the same time, a key principle within regulations for geological disposal is the requirement that monitoring must not undermine the safety provided by the multi-barrier system of the geological disposal system. For example, UK guidance on requirements for authorisation of geological disposal state that monitoring should not compromise the environmental safety case for a disposal facility, for example, by providing routes through which significant amounts of radioactivity might reach people [5]. Similarly, Swiss regulations require monitoring to be carried out in a pilot facility where conditions are representative of those in the repository itself, but which is spatially and hydraulically isolated from the repository, such that activities in the pilot facility do not adversely impact on the conditions in the repository.

Regulatory requirements on monitoring timescales differ from country to country. However, the challenge of monitoring slow processes occurring over long timescales in a repository is widely acknowledged. One possible approach to mitigate against this is to concentrate on monitoring processes during a transient phase of evolution, early on in the lifetime of a repository, for example, during the resaturation of disposal areas following their closure. Some regulators consider that there may be benefits, for ease of management, in amalgamating site characterisation, site investigation, monitoring and surveillance of a repository into one overarching programme. However, it is also recognised that these activities vary in their objectives and scope, and that it might therefore be more appropriate to consider them separately.

In some national programmes, regulators are significantly involved in working with implementing organisations to design and develop an appropriate repository monitoring programme. However, even in such cases, there is a distinction in responsibilities: the implementer will have responsibility for conducting monitoring and using it to demonstrate safety, whereas the regulator will be responsible for evaluating whether the monitoring system fulfils its objectives and is being implemented appropriately.

Clear use of terminology is important in the regulation of repository monitoring. The International Standards Organisation (ISO) and European Standards Organisation recommend a strict four-level hierarchy of terminology, as follows (in decreasing strength of emphasis):

- A requirement, which indicates that something shall be done.
- Guidance, which indicates that something should be done.
- Permission, which indicates that something may be done.
- A possibility, which indicates that something can be done.

This terminology is applied in the hierarchy of safety standard documentation that has been produced by the IAEA.

3.3 Theme 3: Monitoring Technologies: Feasibility and Limitations

The following oral presentations were delivered under this theme during Sessions S6D (focusing on monitoring barrier and repository component demonstrators) and S6T (focusing on monitoring technologies) of the International Conference and Workshop on Repository Monitoring:

- S6O1: José-Luis García-Siñeriz (Aitemin, Spain) summarised the review of the current state-of-the-art in monitoring technologies that was carried out under the MoDeRn Project, focusing on experience drawn from long-duration experiments and demonstrators carried out in European URLs.

- S6DO1: Stephane Buschaert (Andra, France) described the design and development of a large-scale *in situ* monitoring test section in the Meuse/Haute-Marne URL.

- S6DO2: Tobias Vogt (Nagra, Switzerland) described experiences monitoring thermo-hydro-mechanical effects in a full-scale emplacement experiment at the Mont Terri URL.

- S6DO3: Joachim Stahlmann (Technische Universität Braunschweig, Germany) discussed experiences from monitoring a test set-up for a sealing dam installed at the Morsleben repository in Germany.

- S6TO1: Hansruedi Maurer (ETH Zurich, Switzerland) described recent experiments and advances in techniques to monitor components of geological repositories using non-intrusive seismic methods.

- S6TO2: Thomas J. Schröder (NRG, The Netherlands) described investigations of wireless data transmission from the HADES URL to the surface that were carried out under the MoDeRn Project.

- S6TO3: Ignacio Bárcena (Aitemin, Spain) described a new wireless data transmission system based on high-frequency radio communication that has been developed under the MoDeRn Project.

- S6TO4: Friedemann Grafe (IBeWa-Ingenierurpartnerschaft, Germany) discussed experiences of wireless data transfer through salt host rock.

- S6TO7: Lou Areias (ESV EURIDICE, Belgium) set out plans to incorporate a new corrosion sensor within upcoming reduced-scale tests of the Belgian supercontainer.

- S6TO6: Norman Wagner (Institute of Material Research and Testing, Germany) discussed the technology, feasibility and limitations of using spatial time domain reflectometry for moisture monitoring in geological repositories.

The following poster presentations were delivered during Session S4 of the International Conference and Workshop on Repository Monitoring:

- S4P8: David Jaeggi (Swisstopo, Switzerland) described testing of a fibre optic system for long-term monitoring applications under *in situ* conditions in the Opalinus Clay of the Mont Terri URL.

- S4P9: Fidel Grandia (Amphos 21, Spain) discussed monitoring of radon gas emission distribution as a technique used to characterise gaseous releases from CO_2 storage sites, a technique that could be transferable to monitoring of a repository for radioactive waste.

- S4P10: Thomas Spillman (Nagra, Switzerland) presented the approach to, and results from, geophysical monitoring of a gas permeable seal experiment undertaken at the Grimsel Test Site in Switzerland.

- S4P11: Oliver Czaikowski (GRS, Germany) discussed and compared different methods for monitoring pore water pressure and pressure variations.

- S4P12: Kei Suzuki (RWMC, Japan) described the development a wireless data transmission system employing low-frequency electromagnetic radiation, and utilising miniaturised wireless transmitters and borehole type receivers.

- S4P15: Lou Areias (ESV EURIDICE, Belgium) discussed the application of Digital Image Correlation to detect the potential onset of micro-cracking in the concrete buffer of the supercontainer.

- S4P18 Reza Goudarzi (Clay Technology, Sweden) summarised measurements carried out as part of the prototype repository test at the Äspö Hard Rock Laboratory in Sweden.

- S4P19: Nicolas Linze (Université de Mons, Belgium) presented work to develop optical fibre vibration sensors based on light polarisation properties.

- S4P20: Alexey Faustov (SCK.CEN, Belgium) described the results of a distributed temperature measurement experiment employing fibre optic sensors, performed in a low-dose radiation environment of the sub-pile room under the material testing reactor BR2 vessel in Belgium.

The points below record the key areas of discussion following oral presentations under this theme.

<u>General Points of Clarification from Technical Presentations</u>
Regarding *in situ* monitoring sensors (discussed in Paper S6O1), it was noted that modern sensors typically employ improved mechanisms and materials that are expected to prolong the sensor lifetime under repository conditions compared to older designs. Older sensors used in experiments in URLs have already performed well for periods of over 15 years. Modern sensors would be expected to last for longer periods, although this remains to be demonstrated through long-running experiments.

The state-of-the-art concerning non-intrusive seismic tomography as a monitoring technique (discussed in Paper S6TO1) currently focuses on examining the elastic properties of pressure waves, and does not include consideration of shear waves. Analysis of shear waves could be considered in future developments of this technique, potentially as part of using seismic tomography to examine the anisotropic properties of a disposal system.

Regarding wireless through-the-Earth (TTE) data transmission from a repository to the surface (discussed in Paper S6TO2), it was noted that excavated spaces within the repository could be employed to maximise the size of the antenna used for data transmission. However the geometry of such excavations would affect the efficiency of signal transmission; use of a rectangular antenna rather than a circular antenna of comparable size would potentially reduce efficiency by up to ~20%. Key influences on the feasibility of wireless TTE data transmission include the electrical conductivity of the overlying rock and levels of noise/interference at the surface in the vicinity of a repository (e.g. from power lines, cars and local weather).

Corrosion sensors developed in Belgium (discussed in Paper S6TO7) for application in monitoring corrosion of the supercontainer overpack will be used during supercontainer half-scale demonstrator tests, with the objective of confirming that the supercontainer design will fulfil performance requirements. It is not currently planned to install corrosion sensors *in situ* within supercontainers emplaced within a Belgian geological repository. The corrosion rate of the carbon steel overpack within the supercontainer is expected to be very slow, and corrosion products are not expected to significantly affect the integrity of the supercontainer buffer. The long-term integrity of the overpack is intended to ensure that there are no radionuclide releases from the supercontainer into the surrounding near field during the thermal phase of the contained waste.

Approaches to calibrate measurements from spatial time domain reflectometry for moisture monitoring (see Paper S6TO6) were discussed. It would be desirable to calibrate this technique in order to convert readings obtained into physically meaningful quantities such as the water content of the disposal system component being monitored. However, it is currently only possible to calibrate this technique indirectly, for example in a laboratory, by examining the frequency dependent properties of different components of the disposal system as a function of conditions such as water content and temperature. The combination of various components exhibiting different electromagnetic properties in the disposal system itself, such as the host rock, porewater and overlying soil makes it difficult to convert readings from spatial time domain reflectometry into absolute physical quantities. This technique is therefore considered to be primarily useful to monitor for changes in the behaviour of a disposal system, such as progressive saturation of a repository near field, rather than to determine absolute values of, for example, pore water pressure.

Implications of Technical Presentations for Building Public Confidence

It was observed that aspects of the oral presentations given under Theme 3 and subsequent discussions were found to be complex by some of the audience at the conference. It was also observed that the manner in which messages from some of the presentations were presented, could have a negative effect on public confidence, if similar messages were presented during specific engagement events. Such aspects included:

- The presentation of technically detailed materials, which would be impenetrable to a lay audience. Use of such information to explain the objectives and outcomes from monitoring programmes is expected to be of limited value to building lay stakeholder confidence, and may even reduce confidence in the work of an implementing organisation. Lay stakeholders may find it difficult to understand the key implications of an overly detailed presentation, and, in situations where there is not a high level of trust in the implementer, may consider that important points are being either inadvertently or deliberately masked in technical details. Experts therefore need to be able to clearly explain what they are doing and why, and to target their discussions to a particular audience.

- The presentation of uncertainty inherent in the development of approaches and techniques for monitoring. From a scientist's perspective, initial uncertainties are a natural step in planning research, since they provide the basis for developing hypotheses to be tested. However, perceptions of uncertainty can vary, and therefore such uncertainties need to be carefully communicated (and put into context), particularly as a disposal programme develops in maturity and moves closer to implementation.

- Questioning and criticism of experts' work by each other. As with the last point, review and challenge of new research outcomes are considered to be key aspects of a rigorous scientific approach. However, such activities might undermine lay stakeholder trust in technical work, if it leads to an enduring perception that such work is often flawed.

The International Conference and Workshop on Repository Monitoring brought to together a large and diverse audience, and presentations in the technical sessions were mainly aimed at a technical audience, rather than at a wider group of stakeholders, some with a less technical background.

Therefore, it is not surprising that some issues of this nature were recognised at the conference. The comments and queries raised may also reflect the relatively novel nature of many of the techniques and approaches presented at the International Conference and Workshop on Repository Monitoring, which are at the forefront of technological developments relating to repository monitoring and reflect the current state-of-the-art, as well as participants' initially low level of familiarity with these novel developments.

Discussion of the feasibility and limitations of monitoring technologies is considered an integral component of advancing understanding of repository monitoring techniques through dissemination of work and is therefore central to the scope of the conference. Nevertheless, these observations provide useful insight to the perception of technically detailed material by a lay audience, and, given the importance of monitoring as a tool to build confidence, they would need to be considered as part of any plans to discuss similar material at a meeting or event targeted specifically at a lay audience.

Discussion during this technical theme highlighted that there tends to be a greater degree of confidence, amongst both lay and expert stakeholders, in the performance of purpose-built repositories for radioactive waste, compared to confidence in the performance of pre-existing facilities, such as mines, that have been modified for use as repositories. This is largely because the facilities have not been specifically designed for use as repositories, and the need to modify the facility designs to allow for safe waste disposal introduces an element of doubt in the mind of stakeholders.

4. Record of Workshop Discussions

This section provides a factual record of comments and opinions expressed during each of the six workshops held on 20-21 March. For each workshop, the discussion records:

- Key points from group discussion, based on notes taken during this discussion and feedback to plenary provided by the workshop chair.
- Points raised in the associated plenary discussion.

Each of the workshops involved a different group of participants. As such, there are some examples where differing opinions were provided in different workshops.

4.1 Workshop 1, Track 1: How to monitor?

Elizabeth Harvey (Galson Sciences Ltd), Jose-Luis Fuentes-Cantillana (Aitemin)

Discussion focused on the technical feasibility and limitations of monitoring technologies, based on the current state-of-the-art in each of the following areas:

- Wireless data transmission, including short-range and long-range transmission using radio frequency electromagnetic radiation, as well as alternative transmission systems not based on the use of radio waves.
- Options for long-term power supply to underground monitoring equipment.
- Durability of monitoring components, including susceptibility of *in situ* monitoring equipment to failure under the environmental conditions expected within the repository.
- Geophysical methods for monitoring, including consideration of monitoring equipment installed within the near field of a repository, as well as in the far field, e.g. in boreholes, at the surface, or from the air.

<u>Wireless data transmission</u>
The application of wireless techniques for data transmission within a repository could facilitate direct monitoring of the engineered barrier system whilst removing the need for cables or wires to pass through engineered and natural barriers. Cables and wires could provide a pathway for radionuclide migration and impact the long-term environmental safety case.

Short-range data transmission (e.g. across a plug or seal) could utilise high-frequency radio waves, whereas long-range data transmission (e.g. TTE) would typically need to utilise lower frequency radio waves. Both long-range and short-range data transmission systems need to be configured according to the repository design and layout.

The distance of rock through which data can be transmitted using high-frequency radio waves is of the order of a few metres. It could be possible to transmit data using high-frequency radio waves over greater distances by using intermediate relays. However, to ensure regulatory compliance, it would be important not to undermine the isolation function provided by the rock overlying a repository. One possibility might be to emplace intermediate wireless receivers/transmitters within a repository shaft or drift during the sealing and closure process.

Feasible distances for long-range TTE data transmission using radio waves depend on the electrical conductivity of the transmission medium, i.e. the host rock and overlying strata, including the nature of the pore water within the rock. In general, long-range data transmission using electromagnetic radiation is considered to have better prospects for successful application in hard, dry rocks, due to the tendency for signal attenuation in soft rocks with higher pore water content, although work within the MoDeRn Project has demonstrated the feasibility of low-frequency data transmission across 225 m of poorly indurated clay and overlying sandy aquifers.

There was more limited experience within the workshop of other wireless data transmission techniques besides those using radio waves, such as those using vibration (sound) waves. In general such techniques were expected to have higher power demands than available radio frequency systems. They were also not considered to be feasible in some geological environments, such as poorly-indurated clays.

Research into high-frequency and low-frequency wireless data transmission has focused on different phases of repository implementation. High-frequency techniques could be used following closure of individual disposal tunnels or disposal boreholes, by installing receiver equipment in the adjacent access tunnel. They are therefore primarily applicable during the post-emplacement period, but prior to complete repository closure. In contrast, low-frequency wireless data transmission would primarily be of benefit during the post-closure period, once there is no direct access to any part of the repository.

The expectation that wireless data transmission would typically not be required until fairly late-on in a repository implementation programme, potentially decades, or even centuries into the future (particularly for long-range techniques), led some workshop participants to question the need for extensive research on these techniques at this time. They argued that it would be preferable to postpone further work in this area until a point in time closer to when such techniques were actually applied, by which time, the state-of-the-art of relevant technologies may have advanced significantly. On the other hand, if an implementing organisation wishes to employ *in situ* monitoring during the post-emplacement and/or post-closure period as part of a wider monitoring programme, then it would have to demonstrate, at a relatively early stage in the licensing process, that it would be feasible to carry out the required monitoring, and design of the associated data transmission systems would need to be incorporated into the overall repository design. Further research in this area was therefore considered to be beneficial to confirm the feasibility of such approaches, as well as to ensure continued advancement of the state-of-the-art. Target areas for improvement include feasible distances for data transmission, improved transmission across difficult media, and improved approaches to manage signal interference and noise levels.

Current state-of-the-art wireless monitoring techniques are considered to be largely sufficient for application in a repository pilot facility, where data transmission over 5-10 m is likely to be required. However, there was uncertainty in the workshop over whether it would actually be necessary to employ wireless techniques within a pilot facility, or whether more conventional techniques employing wires/cables would be acceptable here.

<u>Long-term non-intrusive power supply</u>

A factor limiting the lifetime of *in situ* monitoring equipment (e.g. sensors and data transmission components) and hence, the feasible timescales for post-emplacement and post-closure monitoring, is the availability of a reliable long-term power supply.

Electrical batteries are widely available in a variety of forms. There is relatively limited experience on their long-term behaviour, and the maximum lifetime of existing batteries is currently expected to be a few decades. It was the view of workshop participants that advances in battery technologies between now and when they would be required to power remote wireless monitoring equipment in a repository (decades or centuries in the future) are expected to improve the battery lifetimes in the future. It was also recognised by the workshop that other, currently unforeseen power sources, suitable for long-term remote applications, may emerge during this period.

Generation of electrical power based on thermal gradients within the repository was considered by workshop participants to be a promising technology worth investigating further. The radioactive waste inventory to be disposed of within a repository offers an extensive source of potentially suitable radioactive decay, particularly in terms of high heat-generating inventory components such as spent fuel or HLW, and specific radionuclides such as strontium-90, which have already been used in thermoelectric generation for other applications such as satellites, space probes and unmanned remote facilities, and which are abundant in some radioactive waste streams. The thermal gradient accessible for energy harvesting is an important factor affecting the feasibility and efficiency of thermoelectric generation.

Realising thermoelectric generation from the waste in a repository could require adaptations to the design and layout of the repository, for example, changes in the waste packaging approach and/or changes in the distribution of different waste streams across a disposal area. Further research is required to improve understanding of how to apply this technique within a repository environment. Any required design adaptations would still need to comply with regulations applicable to radioactive waste disposal, and should not undermine the safety case for geological disposal.

Miniaturised nuclear reactors installed within a repository were also proposed by workshop participants as another option for a long-term power supply to monitoring equipment. This technology has been proposed as a small-scale generation route that could be applicable to supply power to e.g. individual towns and space stations. The implications of installing such devices on the safety case for a repository would need to be evaluated, but it was felt by some participants that this option would merit further investigation.

Durability of monitoring components

Sensor lifetime was a key area of discussion during the workshop. Experience of long-term sensor performance is available from the last 30 to 40 years during which sensors have been extensively developed and employed in a variety of industries. However, the timescales over which monitoring sensors in a repository are required to perform could potentially be longer than this. Moreover, the conditions in a repository for radioactive waste will be relatively aggressive (this could include, for example, high temperatures, an alkaline chemical environment and a high radiation field), which could reduce the lifetime of sensors compared to that observed in other applications. There is limited experience of the behaviour of relevant sensors under such harsh conditions, and this was identified as a key area requiring further investigation. It was also felt that tests which deliberately accelerate the degradation of wireless monitoring equipment could be used to identify weak points in designs, for improvement in the future.

There is limited experience of long-term electronic component performance in relevant environments. Electrical systems employed on the Voyager space probes have continued to function for over 30 years, despite the extremes of temperature and relatively high radiation environment they are exposed to. However, some degradation of thermocouples and other electrical components has occurred over this period, which has reduced the efficiency of the power supply to the probe below anticipated levels based purely on radioactive decay of the power source. This is recognised as an area of rapidly-advancing technology; the durability of new sensor types will therefore need to be tested as they emerge.

Glass fibre optic sensors have a relatively high chemical durability, although the polymer coatings surrounding some fibres are typically much less durable. The glass fibres themselves are susceptible to signal attenuation arising from irradiation, as well as hydrogen diffusion into the fibres, although some workshop participants observed that hydrogen diffusion could actually improve the resistance of glass fibres to further radiation damage.

Fibre optic sensors are a relatively recently-developed sensor technology, and experience of their application is therefore limited. Nevertheless, some relevant experience of the long-term performance of fibre optic sensors is available from their application in other industries, for example monitoring dam integrity in the vicinity of man-made reservoirs, although the transferability of this specific experience may be limited, given the different environmental conditions compared to those present in a repository.

Improved collaboration between research groups working on related projects could benefit further development of fibre optic monitoring systems. An example proposed in the workshop discussions was continued collaboration between the Belgian and French research groups that have been developing fibre optic monitoring sensors and monitoring systems during the MoDeRn Project.

Considerable transferable experience of the performance of relevant sensors and other monitoring equipment is thought to be available within the oil and gas industries, particularly in terms of employing monitoring systems in aggressive (i.e. corrosive and hot) underground systems.

Geophysical methods for monitoring

A variety of geophysical techniques are available to address a range of monitoring requirements. These can be employed with different levels of proximity to the repository itself, for example:

- Equipment installed in the repository itself, or in the surrounding near field.
- Techniques in the far field, for example in boreholes drilled from underground excavations, or based at the surface.
- Airborne techniques.

The resolution of data from geophysical monitoring equipment installed in a repository near field, for example, the results from cross-hole seismic tomography monitoring, depends on the frequency of the seismic source used, the distance between the monitoring boreholes, and the velocity structure of the near-field rock and engineered barriers being monitored. In general, increasing the resolution requires the monitoring boreholes (for sensor and receiver equipment) to be placed closer to the near-field rock and engineered barriers being monitored. This has obvious implications in terms of whether such monitoring techniques can be regarded as being truly non-intrusive, which is key to their potential application. Near-field geophysical monitoring techniques are therefore considered to be primarily useful for monitoring relatively large changes in repository characteristics, such as widespread saturation characteristics, rather than highly localised processes, such as the saturation of a small component of the engineered barrier system.

There are also similar inherent physical limits associated with the spatial resolution of monitoring results obtained from geophysical equipment installed on the surface overlying a repository. Workshop participants considered that it would be possible to monitoring large-scale processes, such as preferential flow paths, but that more localised processes would be difficult to observe using current state-of-the-art techniques. Some improvements in resolution could be achieved using sensors or sources installed in monitoring boreholes, provided this did not affect the isolation function of the rock.

Airborne and satellite-based geophysical techniques such as synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR) facilitate precise detection of ground movements at the Earth's surface. This has potential applications for safeguards monitoring (e.g. to detect unauthorised activities), as well as for monitoring large-scale processes such as thermal uplift. Such techniques have been employed to measure uplift associated with underground carbon dioxide sequestration tests.

As discussed previously, the feasibility of applying geophysical monitoring techniques tends to be strongly dependent on the characteristics of the host rock and overlying strata, with the exception of airborne techniques that monitor changes at the surface.

4.2 Workshop 1, Track 2: Why monitor?

Matthew White (Galson Sciences Ltd), Nicolas Solente (Aitemin)

International guidance on repository monitoring recognises that monitoring is undertaken to provide support to the post-closure safety case, to support operational safety, to ensure environmental protection and as part of safeguards. The workshop session on *why to monitor* therefore focused on the expected benefits that would be realised from repository monitoring.

<u>Influence of Costs on Repository Monitoring</u>
Considering why monitoring is undertaken may provide a basis for considering how much effort is required to deliver the monitoring programme, and how much money should be spent on monitoring. From the implementers' perspective, a regulatory requirement to undertake specific monitoring programmes must be addressed and it would not be appropriate for the requirements for specific monitoring activities to be challenged. However, society including the public may question the need to for expensive monitoring programmes.

Alternatively, monitoring could be considered as part of the optimisation of the repository system and may support decisions to use more cost-effective approaches to disposal of radioactive waste, or support decisions to close a facility earlier than planned, leading to cost savings. In terms of stakeholder engagement, the use of monitoring in optimising the disposal process may be a good message to communicate.

Therefore, optimisation of implementation and support for cost-effective delivery of the repository programme may be seen as reasons for undertaking repository monitoring.

<u>Monitoring, Knowledge Management and Post-closure Monitoring</u>
One of the objectives of a monitoring programme could be to provide an information source to future generations. It is expected that information collected at an early stage in the programme will be of use to future generations. This will require the strategies for monitoring and knowledge management to be integrated and to work together. In order to provide meaningful data to future

generations it will be necessary to record the decisions made in developing the monitoring programme.

These decisions may be different when different phases of the monitoring programme and the influence of the national context are considered.

The role of various involved parties, or “actors” (see Section 4.5 for further discussion of this term) can differ between different national programmes. This includes different responsibilities being assigned to implementers, regulators, and contractors working for both the implementers and the regulators. The social organisation of a country will also influence responsibilities, for example the division of roles between the state and industry.

It was proposed that the driver for undertaking post-closure would be to address any health concerns held by members of the public, and that this could be addressed by monitoring of the groundwater. The context for monitoring groundwater quality has to be considered, and some participants felt that groundwater standards could change in the future. The participants felt that, for some programmes, it would not be feasible however to monitor for the failure scenarios considered in the safety case. For example, failure scenarios considered in safety assessments undertaken by SKB consider processes and events that could occur in association with the next ice age, which is expected to occur in 20,000 years from now.

Baseline and Pre-closure Monitoring

Participants at the workshop recognised that commencing monitoring early was important. This would provide a baseline for understanding the significance of any data collected following emplacement of waste. The importance of monitoring prior to closure was stressed by one participant who felt that there would be no significant processes or events to monitor following closure.

Reasons why monitoring could be undertaken prior to closure mentioned by workshop participants included:

- To provide information to update the safety case – in this context, it was noted that the repository will probably be classified as an operational nuclear facility and will therefore have to provide an updated safety case every ten years. The updated safety case will need to be supported by data from monitoring.

- Demonstration of the safe operation of the repository.

- To learn as much about the disposal system as possible.

- To support decisions related to retrievability where retrievability is required in national regulations.

- To ensure the safety of workers and the public, especially to protect against health effects if there was a major accident by providing early notification of such an event.

Monitoring for Public Acceptance

One participant noted that new innovative visualisation tools were being developed to support communication to the public. Provision of data to populate such communication tools could be a reason for undertaking monitoring.

Another participant noted that, in some fields, there had recently been a shift from the concept of social acceptability to the paradigm of social responsibility. Adoption of this paradigm could imply that a reason for monitoring was the implementer decide that the public should be provided with additional data over and above that which the implementer themselves considered necessary or valuable. Alternatively, this could be interpreted as a responsibility not to undertake monitoring if it was of no value.

Workshop participants proposed that, in addition to understanding why monitoring should be undertaken, it was important for monitoring programme development to consider reasons why a proposed monitoring parameter should not be monitored, and to record these reasons as justifications in instances where such consideration led to the rejection of a monitoring parameter. In particular, it was proposed that monitoring that responded to "irrational fears" should not be undertaken, as this may only serve to provide tacit support to the fear. However, an alternative view expressed was that monitoring only the minimum necessary could appear arrogant to stakeholders.

<u>Importance of Defining Why Monitoring is Undertaken</u>

In conclusion, it was stressed that a clear definition of why monitoring was being undertaken was necessary for a successful monitoring programme to be undertaken. The reasons for monitoring should provide the basis for a robust selection of monitoring methods and locations. This would allow the data collected to be compared to the specific objectives defined and provide a context against which significance could be judged. In support of this argument, it was noted that there is a widely-held view that a large monitoring programme had been established in the local area following the Fukushima disaster but not all of this monitoring was of value to robust decision making. However, it was difficult to find a reason to stop monitoring a particular parameter once monitoring had started unless it was associated with a specific objective.

The discussion on why monitoring should be undertaken highlighted that the answer to this question may be different for different phases of repository. There appeared to be consensus about the drivers for monitoring during the early stages of repository implementation, but less consensus about the drivers later in the programme. Optimisation and cost-effectiveness were good reasons for undertaking monitoring. Monitoring could be used to support stakeholder engagement (including visualisation of the repository evolution) and stakeholders could potentially provide good advice on the development of the monitoring programme. However, as with all monitoring issues there would be different answers to the why question for different national programmes.

4.3 Workshop 1, Track 3: When and how long to monitor?

Peter Simmons (UEA), Jaap Hart (NRG)

This workshop was concerned with the timing of monitoring, with when, during the life of a repository, monitoring should be carried out and for how long it should be continued. The workshop chairman opened by noting that the questions of 'when' and 'how long' could not be decoupled from the questions 'why', 'how', 'what' and 'where' to monitor. He situated the questions in the context of a step-wise decision process by displaying a figure that summarised the phases of repository implementation and gave examples of major decision points (Fig. 4.1).

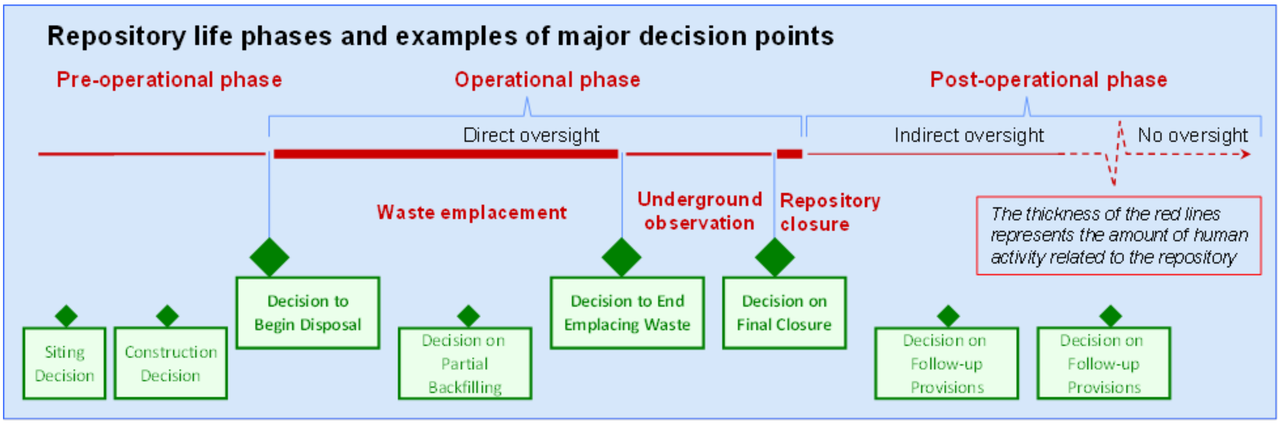

Figure 4.1 Repository life phases and decision points [5]

To stimulate discussion the chairman presented a series of quotations, taken from papers presented at the conference, from reports produced by international agencies and research groups, and from reports of the MoDeRn project itself, which offered a range of responses to the questions of 'when' and 'how long' to monitor. Associated questions suggested by the chairman included:

- What are the views of:
  - Regulators?
  - Experts?
  - Citizens and stakeholders?

- If demanded, how long is post-closure monitoring possible?
  - What are the implications of the technological state of the art (e.g. advances in wireless techniques in MoDeRn) for post-closure monitoring?
  - How long can monitoring programmes, or "oversight", be expected to be sustained, either technologically or institutionally?

The discussion ranged across a number of issues raised for participants by the question of when and for how long monitoring should be carried out.

For some stakeholders the questions of when and how long linked inevitably to the uncertainties and challenges associated with the very long time scales over which waste remained hazardous and the repository would evolve.

<u>When to begin monitoring</u>
One point upon which there was general agreement was that monitoring should begin as early as possible in order to establish baseline data and subsequently to provide as much information as possible about wasteform and repository evolution. It was also emphasised that monitoring had a role through all of the phases of repository development and implementation. There was also, however, some related discussion about where monitoring was to be conducted, with some participants distinguishing between monitoring within and outside a facility, and noting the different time scales over which, for technical and safety reasons, monitoring might feasibly be carried out at different distances from the waste once it is emplaced.

<u>Continued monitoring to provide societal oversight</u>
Although there was general recognition of the role that monitoring would play during the operational phase of a repository, discussion returned several times to the rationale for continuing

monitoring in the post-closure phase. Following presentations earlier in the day, there was discussion of the notion of 'oversight' and of its relationship to monitoring. Some participants were concerned to define these terms clearly in order to avoid any confusion between monitoring, understood as involving measurement and data collection, and oversight, understood as the continuous and extended involvement of society beyond repository closure. The notion of oversight was justified by reference to the continuing hazard presented by the waste, despite it being contained within a repository system several hundred metres below the surface, and the potential loss of regulatory credibility that would be associated with 'walking away' from a licenced facility after closure.

The call by some stakeholder participants for continued surveillance of a repository reflected concerns that there might be unexpected processes or events which could compromise safety. It was pointed out that no very long term management option is risk free. In response to this it was argued that consideration of all conceivable scenarios would ensure that these were addressed by the design concept but some stakeholders nevertheless expressed a clear wish for extended monitoring to provide 'early warning' of any adverse developments in the repository system. Although there was no agreement among participants on the necessity of post-closure monitoring or about its precise nature, with some referring to both repository and environmental monitoring in this context, it was agreed that if society demanded it and resources could be directed to developing the necessary technical means to do so, there was no reason why it should not within safety constraints.

For several participants the question of post-closure monitoring or of some form of oversight and continued institutional control raised the issue of preserving data records and of ensuring that future generations would be able to interpret them and understand their meaning. This would require the design of institutional arrangements capable of maintaining the societal capacities and competences necessary to do so. Against this call for continued institutional oversight and providing for the information needs of a future society, other participants argued that we are unable to envisage the future configuration and needs of society. It was pointed out that enormous transformations in the organisation of society have taken place over the past 300-400 years - and for some countries (e.g. Germany) even recent decades have seen dramatic change. It was argued that the lesson to be drawn from history is that societal futures are not predictable, suggesting that the maintenance of human institutions to provide oversight would be very uncertain over the extended timescales being discussed.

When to stop monitoring?

The discussion of how long to monitor also raised the question of when to stop. It was pointed out that a primary purpose of monitoring was to provide information to support decision making and that monitoring would therefore need to continue for as long as there were decisions still to be made. A slightly different view, expressed in relation to monitoring for the very specific purpose of providing early warning of unforeseen problems, was that such monitoring should be maintained only as long as there was the possibility of responding in some way, after which there was no longer any point continuing with it. A more general point made was that wider societal acceptance of repository safety and of the eventual cessation of monitoring was more likely if citizens better understood radiation and the measures for the containment of radioactive waste. It was suggested that a technical repository programme would need to be accompanied by a programme of continued education and engagement.

Technical challenges of long-term monitoring

A final strand of discussion when considering how long to monitor concerned the technical capacity to monitor over the long term. Several participants were sceptical about the durability of monitoring sensors, pointing to the eventual failure of any instruments. It was suggested that, for this reason, no manufacturer would guarantee performance of their instruments over the periods of time for which it would be required in a repository. This led one participant to argue that sensors should only be placed where they could be physically checked and replaced, in order to be able to distinguish anomalous readings due to instrument failure from any genuinely unexpected evolution of the repository system. Nevertheless, others voiced the expectation that there would continue to be new developments in knowledge and in instrumentation that would extend current capabilities for monitoring. The timescale over which repositories would be implemented provided opportunities for continued research and development. It was also proposed that working collaboratively with other industries could foster creative approaches to the problem, which might produce technical innovations that would make continued oversight possible. The nuclear batteries used in space craft were suggested as an example of an existing technology that might be explored, although it was also pointed out that the implications of any new technology for the safety case would also need to be considered.

4.4 Workshop 2, Track 1: How to use monitoring results?

Elizabeth Harvey (Galson Sciences Ltd), Brendan Breen (NDA)

This workshop considered what arrangements need to be in place for effective governance of a repository monitoring programme, and how monitoring results should be used. Associated questions raised by the workshop chairman to initiate discussion included:

- What is governance?
- Who needs to be involved in monitoring and who should be responsible? This topic was covered in more detail under Workshop 2, Track 2. Therefore, discussion during this workshop focused on who should be involved in governance arrangements, and how those responsible for governance may change over time.
- How can monitoring be carried out independently (if required)?
- How should the results from a monitoring programme be made publicly available and what associated requirements are there for processing and interpretation of monitoring data?
- How should monitoring feed into decision-making, particularly decisions on when to stop monitoring?
- What measures are required to respond to unexpected results?

Discussion during this workshop focused on the role of monitoring in providing stakeholder reassurance. The discussion therefore focuses on how repository governance, particularly in terms of managing an effective monitoring programme, can be used to build and maintain stakeholder confidence.

<u>What is governance?</u>
Governance implies on-going control, regulation and oversight of repository operation, waste disposal and associated monitoring activities. In this respect, there are notable synergies between the discussion during this workshop and the work of the NEA relating to oversight of a geological repository (see Paper S3O5 and Section 3.2 of these proceedings). Governance can be applied both

as part of the activities of the implementer (e.g. through good management and quality control practices), and also through external oversight activities, potentially at different hierarchical levels (e.g. by national regulators/government, through the EU, and/or through the NEA and/or IAEA). A key concept contributing to effective governance is that stepwise licensing of a repository can be used as a means of ensuring periodic review and on-going control of disposal activities.

The licence to construct, operate, and eventually to close a repository is awarded by government, or by the relevant nuclear regulators. However, its award is likely to require the buy-in of the local community. In order to build the trust of these stakeholders, it will therefore be important for long-term governance arrangements to be in place before the disposal implementer applies for a licence.

Effective governance of a monitoring programme requires the application of an objective and impartial viewpoint, without preconceptions of the outcomes of the programme. Governance mechanisms need to be stable to changes in political decision-making, including changes in local and national government, in order to maintain continuity over the long timescales of repository implementation.

<u>Who needs to be involved, including the impact of monitoring phases and timescales</u>

In the context of governance, it is important for each involved organisation to have a pre-defined set of responsibilities, prior to initiating activities at a disposal site. However, the scope and distribution of responsibilities will depend on a country's national context for monitoring, and are therefore difficult to define generically. There is also a need for flexibility to allow appropriate changes to governance practices as a repository implementation programme progresses. For example, it might be appropriate for there to be a gradual evolution in the responsibilities for records keeping and knowledge management, from the implementing organisation in the first instance, towards higher-level national or international organisations. Workshop participants proposed that the United Nations Educational, Scientific and Cultural Organisation (UNESCO), who are charged with the custody of aspects of human heritage, could be an appropriate international organisation to which responsibility for records keeping and knowledge management could be transferred.

It is important to ensure that knowledge and understanding is sustained and transferred across generations, particularly given the long-running nature of a repository programme. This includes communication of the historical motivation for undertaking specific monitoring activities, particularly if there is a desire for some form of post-closure monitoring to be undertaken, so that stakeholders in the future can make informed decisions as to whether such monitoring is still necessary.

Long-term engagement with stakeholders on the topic of repository monitoring may require an additional skill set focused on placing repository monitoring programme into context, and sustaining this knowledge and ability to explain the significance of results over the long term. Communication and education approaches should be designed to embed the concept of repository safety within individuals and into society for the future, recognising that institutions are unlikely to prevail over the timescales of interest. The workshop recognised that a challenge in achieving this was the potential for a loss of interest in a repository monitoring programme over time, particularly if there are no observable changes or unexpected results arising from the monitoring programme.

Pluralism, specifically the parallel interpretation of monitoring results by different organisations, groups or individuals was felt to be an important principle in support of confidence building.

Parallel monitoring of the WIPP by the CEMRC and by groups within the DOE were cited as examples of good practice in this respect.

How to ensure independence?

Assigning responsibility for repository monitoring to an independent organisation was initially felt by the workshop to be a key aspect of using monitoring for reassurance and confidence building. It was recognised that all organisations or groups with a stake in geological disposal would have their own perspective on safety, which might skew their approach to gathering and interpreting monitoring data. To counteract this, a body with no pre-existing stake in the geological disposal process could be needed, either to oversee monitoring activities, or to undertake them on behalf of other stakeholders.

The possibility of having a truly independent monitoring organisation or group was questioned. In particular, it was recognised that even if such a group were set up, with a wholly independent remit, the funding to enable it to operate would typically be routed via the implementing organisation (as is the case for DOE funding of the CEMRC) or via waste producers. This could undermine the perception of its independence in some countries. Independence from political processes, particularly changes in local and national governing bodies, was also felt to be crucial for ensuring continuity in measurement approaches, given the potentially long-running nature of a repository monitoring programme.

What was felt to be more important than the true independence of a monitoring organisation, was the ability for stakeholders to trust that a nominated organisation responsible for monitoring would carry out monitoring objectively, without bias, and provide open, honest reporting of results.

The choice of organisation responsible for monitoring, and the mechanisms used to ensure satisfactory independence in its approach, will therefore depend on the national context of the country in question. Depending on the particular situation, the most appropriate group to carry out monitoring might be the nuclear regulators (or associated supporting organisations), the repository implementers (if there is sufficient trust in their behaviour) or a completely separate organisation, possibly funded via a route that does not undermine confidence in their independence.

How to use results

A key requirement proposed by workshop participants for building confidence is that all of the raw results obtained from a monitoring programme should be made publicly available, preferably without any form of pre-processing or filtering of data. Such an approach could be seen to maximise the transparency of the monitoring programme, and might facilitate independent analysis of monitoring by groups or individuals not affiliated to a repository implementation programme. Workshop participants felt there might be benefit if stakeholders could make their own interpretations of monitoring data, which could either confirm the interpretations made by the organisation responsible for monitoring, or offer a different interpretation for discussion. This approach recognises that the interpretation of raw data is sometimes rather subjective (workshop participants remarked that in some cases, subject experts could offer different interpretations of a data set), and acknowledges the value of alternative views.

At the same time, it was felt that guidance should be offered on the possible interpretation of monitoring data. Processing and interpretation of the meaning of monitoring data should be carried out by experts, and their interpretation of the significance of the data should also be made publicly available, accompanied by clear explanations of the assumptions made in interpreting the data, and the rationale for the conclusions drawn.

Combining these two approaches demonstrates a willingness to communicate monitoring results and their interpretation to interested stakeholders so that it can be understood by all parties, but also offers the opportunity for independent scrutiny of the interpretations made.

Deciding when to stop monitoring

Consistent with a step-wise process for licensing repository activities (as mentioned above), it is generally acknowledged that closure of a repository would not be approved until there was confidence that the disposal system was performing largely as expected, and that it would continue to ensure safety through passive measures over the long term. It therefore follows that after closure there would be no technical basis for carrying out any further monitoring, and that any monitoring beyond this point would be undertaken purely to address societal requirements. This philosophy reflects the principle of not placing a burden for waste management onto future generations.

The implicit associated change in the main objectives for monitoring that would occur following closure, could have the effect of changing the location of monitoring activities, for example, from non-intrusive monitoring of barrier performance in the near field, to monitoring for public reassurance (e.g. safeguards monitoring or environmental monitoring) at the surface. In particular, it is anticipated that environmental monitoring (e.g. of groundwater or aerial discharges) may continue when other forms of monitoring have stopped, probably as part of existing national monitoring programmes.

Regulators or government would be responsible for deciding when to approve repository closure and hence, when to stop monitoring to support the long-term safety case. However, it is expected that the opinions of local stakeholders would be sought as part of this decision-making process.

After closure, local communities could have a continuing, and potentially more significant role in directing a monitoring programme if they felt that continued monitoring was important for their reassurance. Such monitoring could potentially continue for many years, until local communities had sufficient confidence in the long-term safety of the repository. Local communities are therefore expected to take the final decision on when to stop monitoring. This does not indicate a burden placed on future generations, since they would only be undertaking monitoring at this stage voluntarily, for their own reassurance.

Responding to unexpected results

Various principles were suggested for responding to unexpected monitoring results, which were considered to be part of ensuring good governance of a monitoring programme and wider repository implementation activities. These included:

- Recognising that results that could affect the assumptions and arguments in the safety case could occur, and clearly setting out the range of reasons why they may occur.

- Putting in place contingency planning for responding to unexpected monitoring results. This should include a sliding scale of responses, depending on the implications of the results for the safety case.

- Communicating contingency plans to stakeholders.

- Setting trigger values or early warning systems to enable rapid identification of unexpected results and appropriate response before there is a significant issue.

- Responding quickly to unexpected results to avoid any escalation in the potential impact of any detrimental processes that might be occurring.

- Clear communication of unexpected results to stakeholders.

- Clearly explaining the significance of unexpected results and involving stakeholders in discussing appropriate response measures. It was suggested that obtaining monitoring results that are outside expected ranges (e.g. outside pre-defined bounding values) might trigger an increase in the frequency of stakeholder engagement and communication activities.

A key challenge for governance is to formulate effective responses to monitoring results that are completely unexpected and cannot reasonably be foreseen. Some flexibility in the approach to respond to unexpected results is therefore needed. It was also noted that options for responding to unexpected results will evolve, and become more limited as the repository implementation process progresses, and particularly, as repository operation moves towards closure.

4.5 Workshop 2, Track 2: Who should be involved in monitoring?

Matthew White (Galson Sciences Ltd), Anne Bergmans (UA)

The discussion in this workshop session focused on the roles and responsibilities, and issues associated with the different actors involved in monitoring. The discussion considered three different groups of actors:

- Implementers and regulators.

- Advisory bodies.

- Public stakeholders.

<u>Implementers and regulators</u>
In general, it is expected that the implementer will undertake monitoring and evaluate the results and that the regulator will perform checks on the monitoring undertaken by the implementer and the use of the monitoring results in decision making.

The workshop recognised that there is concern on an international basis on the availability of competent scientists to act as advisors to regulators. The EU Sustainable network of Independent Technical EXpertise for radioactive waste Disposal (SITEX) Project was mentioned. This project is aiming to establish the competence for supporting regulatory reviews of safety cases. The work of the SITEX Project will include definition of the competence required to support such reviews, and will then provide recommendations on how to develop and maintain it. Existence of such expertise would be valuable in the future when regulators are seeking to review implementer’s monitoring programmes.

The independence of implementers and regulators was discussed. It was agreed that it was acceptable for implementers and regulators to undertake joint research activities, but that decision-making processes should be strictly separated. This issue is captured in the EC Directive on the disposal of radioactive waste. It was also agreed that no one group has the right to ownership of basic scientific understanding, and, therefore, it was appropriate for implementers and regulators to work together on some specific issues, for example development of processes and features affecting repository evolution. Therefore, there may be areas of repository monitoring research where implementers and regulators could work together, such as research on monitoring technologies.

The workshop session discussed whether there was any need for independent monitoring to be undertaken in addition to the monitoring undertaken by the implementer. There was no consensus on this. However, it was recognised that environmental monitoring around a GDF could, and perhaps should, be undertaken by national monitoring organisations, i.e. organisations responsible for monitoring groundwater quality or food standards. Such environmental monitoring could also be undertaken by new, specialist monitoring organisations such as the CEMRC.

Advisory bodies

Advisory bodies were considered to be a good organisation for providing independent expert guidance to a repository programme. An advisory body could play a role in monitoring by undertaking periodic reviews of the programme (rather than being involved on a regular basis).

However, the independence of advisory bodies was questioned during the workshop discussion. The members of advisory bodies are likely to be of similar backgrounds to individuals in implementer and regulator organisations. Advisory bodies are likely to discuss repository programmes with, and provide advice to, government. Therefore, there is a potential for local stakeholders to lack confidence in advisory bodies. The example of the Committee on Radioactive Waste Management (CoRWM) - an advisory body in the UK - was raised. Some stakeholders in the UK have raised questions about members of CoRWM, although the structure of the organisation itself has been broadly accepted.

There is a requirement for balance in the membership of advisory bodies. During its existence, the membership of CoRWM has changed from members with general expertise to specific knowledge of scientific issues. This reflects the progression of the repository implementation programme in the UK. It means that members of advisory bodies would have to have appropriate knowledge of monitoring to be able to advise on monitoring issues.

The independence of advisory bodies was discussed. It has been observed in several programmes that there is no possibility of having a totally independent view, as all individuals will be affected by their history and current circumstances.

Public stakeholders

The discussion of the SITEX Project recognised that public stakeholders may also want access to independent advisory groups. A workshop on the requirements from stakeholders is planned for the SITEX Project.

In terms of public involvement in monitoring, it was noted that local public stakeholders would rather have trust and confidence in implementers and regulators than have to be involved actively. In particular, local stakeholders are volunteers and do not have a professional involvement in repository programmes; they want to maintain a balance between involvement in the repository programme and other activities.

Associated with the issue of the extent of involvement, the workshop recognised that the representativeness of local stakeholder groups is variable. Typically, stakeholder groups consist of older men, and it is difficult to involve younger people and women. However, for long-term projects, it would be desirable to involve individuals over long periods, meaning that it would be beneficial to have public stakeholders involved from a young age.

An example of the type of involvement that public stakeholders may value was provided based on experience in Belgium. A licence application for disposal of LLW in a near-surface facility was submitted in January 2013. The implementer is undertaking extensive consultation with the local public through a partnership forum. Each month the implementer presents one section of the licence application to the forum and answers questions. A similar type of involvement of local stakeholders in monitoring programmes could be envisaged. The local public were aware that holding these workshops represented a significant investment of time and money from the implementer. The local public were also aware that there were on-going discussions between the implementer and the regulator, and were supportive of this.

It was noted that, in Switzerland, engagement with public stakeholders had begun at the earliest stages of site selection. This experience implies that local stakeholders could be involved, perhaps through exchange fora, at the earliest stages of development of monitoring programmes, i.e. during development of plans for baseline monitoring.

The extent to which local stakeholders may input to the development and review of monitoring programmes is likely to depend on the nature of engagement on the overall repository programme. As an example, it was considered that the decision to use a pilot facility in the Swiss programme was a message that Nagra were open to inputs and proposals on monitoring.

<u>Summary</u>
The key conclusions from the workshop discussion were as follows:

- The implementer, regulator and others all have a role in monitoring: the implementer does the monitoring, the regulator checks the approach and the results, and other stakeholders input opinions and provide further oversight.

- Monitoring is part of the wider safety case; identifying who would be involved depends on wider groupings developed within the safety case framework, as it is difficult to concentrate on monitoring alone.

- SITEX is an example of an international regulator initiative to develop independent groups capable of reviewing safety cases, and, by extension, could be used in reviewing monitoring programmes.

- If the regulator and implementer are undertaking similar work, there is a need to communicate the ways in which they can work together and where separation would be ensured, e.g. research versus assessment/evaluation.

- The nature of, and representation on, advisory bodies depends on who is driving programme - the programme may be government-led or implementer-led.

- It should be recognised that true independence may be difficult to achieve, and it may be better to recognise that all actors have an agenda.

- Efforts should be made to broaden the representativeness of advisory bodies and public stakeholder groups.

- Active processes of transparency are important.

- Environmental monitoring is done now and will continue to be done by environmental monitoring organisations in the future – so national monitoring organisations have a role in repository monitoring but this is not currently integrated into monitoring programmes. This also means that active roles in repository monitoring is not just about involving local stakeholders.

- Involving local stakeholders in monitoring is a challenge as it requires effective communication and explanation from the developers.

- There is a range of examples from existing nuclear and non-nuclear programmes, for who can be involved in monitoring programmes and these examples provide a useful resource for national programmes to consider.

4.6 Workshop 2, Track 3: What to monitor and where?

Alastair Clark (NDA), Michael Jobmann (DBE-TEC)

The aim of this workshop session was to stimulate general discussion rather than identify a list of monitoring parameters, and the following questions were posed (the first three concern 'what to monitor', whilst the fourth and fifth questions concern 'where to monitor'):

- Should we monitor all parameters that can technically be monitored to get as much information as possible?

- Should monitoring be constrained to processes that are described in a site-specific features, events and processes (FEPs) catalogue and identified as significant in the safety case, or should monitoring be more comprehensive and include site evolution in general?

- Should implementers only monitor processes that can be related to safety functions?

- Should monitoring be carried out across the whole of a repository, in order to ensure that all processes occurring can be monitored, or should monitoring only be carried out in a limited area of the repository, or in a pilot facility, on the assumption that this is representative of all other disposal areas.

- Which engineered barriers need to be monitored, to confirm that they continue to function appropriately, and where should the equipment for monitoring these engineered barriers be installed?

Parameter choice through modelling

Modelling during the development of a safety case can help to identify key monitoring parameters by providing information on the scale of physical and chemical phenomena that may occur during the evolution of the repository. For example, key monitoring parameters have been identified for the German salt environment through consideration of 30 years of modelling results. The spatial and temporal resolution limitations associated with modelling must be accounted for when determining what parameters could be included within a monitoring programme, i.e. the robustness of parameter choice is dependent on the scope of modelling. Confidence in parameter choice will be limited where natural processes are relatively complex or there is a lack of available data which results in relatively high uncertainty. Monitoring cannot be expected to provide a definitive representation of sub-surface processes; it is a representation with residual inaccuracy.

It was agreed that URLs can be used to provide evidence about natural processes. For example, evidence of the rate and extent of concrete crack propagation gathered at the Mol URL, has been applied wider in the Belgian programme.

Most programmes are at the research and development stage so the extent of experience from actual repository sites is currently limited, and, for some programmes, non-existent. Monitoring programmes will only be optimised following site characterisation and during construction to ensure that monitoring is based on the fullest possible understanding of site characteristics. Nonetheless, the development of monitoring programmes during research and development should define key parameters to monitor during operational and pre-operational phases.

The cost of monitoring should be proportionate to the programme cost. Therefore, monitoring should concentrate on parameters that are going to provide most benefit for decision making and other programme goals. A comparison was made by workshop participants, who noted that waste acceptance criteria are typically based on a relatively narrow range of parameters.

<u>Where to monitor?</u>
Monitoring of the near field and far field may be undertaken following closure for public acceptance and confidence reasons. It was suggested that given the current technical limitations of monitoring it is perhaps easier to monitor in the region close to the near field, which was defined in the workshop as the 'middle field'. However, some participants felt that there were good prospects for monitoring the near-field, citing recent advances in non-intrusive geophysical techniques.

Repository monitoring will be undertaken over long periods, and this requires the monitoring programme to evolve in response to development of knowledge on the repository evolution and also in response to developments in repository monitoring technologies. There is good precedent of monitoring supporting the development of knowledge. For example, Nagra and Andra have witnessed examples of self-sealing of clay host rocks in the excavated damaged zone around underground tunnels in URLs.

To stimulate more specific discussion, an example of engineered barrier system parameters that could potentially be monitored after emplacement was presented (Fig. 4.2). It was noted that methods for monitoring the proposed parameters were well-known and had been applied for 20-30 years. Therefore, there is good experience on which to develop engineered barrier monitoring systems.

The proposed monitoring system illustrated in Fig. 4.2 includes measurements in a dummy canister to determine pressure and pore pressure increase, and measurements above and below the borehole plug to check for its tightness.

Regarding the possibility of monitoring radionuclide migration following closure, workshop participants noted that, if such monitoring was to take place, it should focus on the radionuclides of most concern to the safety case.

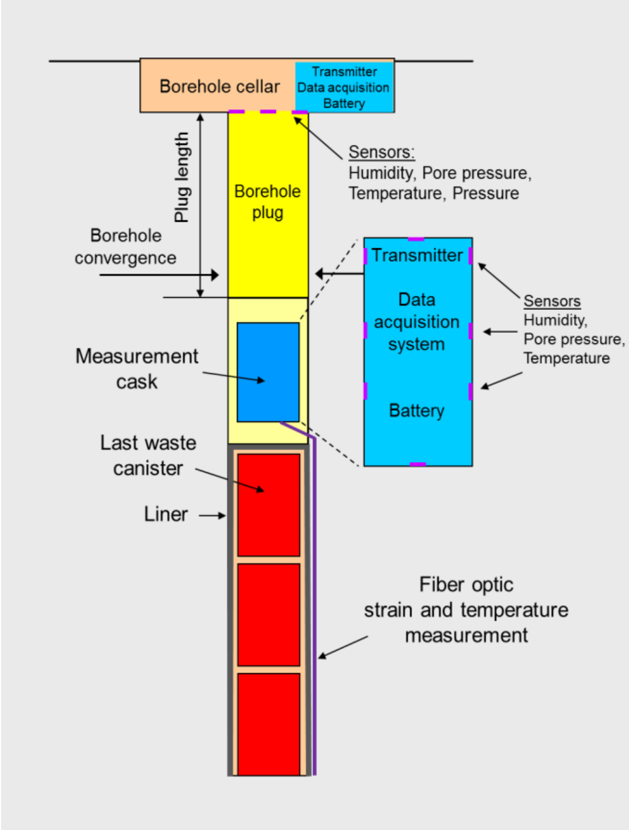

Figure 4.2: Parameters that could be monitored in a disposal borehole in the German disposal concept for geological disposal of HLW and spent fuel.

Workshop participants suggested that post-closure monitoring could be used to verify that repository-derived radionuclides do not enter the food chain/biosphere. However, other workshop participants argued that the engineered barrier system would provide better performance than assumed by those proposing monitoring of radionuclide migration, and therefore suggested that such monitoring was not necessary or worthwhile.

The workshop participants agreed that a set of baseline monitoring parameters should be established by each national programme and that these parameters should be monitored until the end of institutional control. A period of 200 years for such monitoring was proposed. It was suggested that a list of possible monitoring parameters could be proposed on an international basis, and that each country could use this list as a starting point for developing national parameter lists focusing on the national context of their own programme. It was noted that the national context would affect the selection of monitoring parameters in each national programme.

One of the workshop participants suggested that implementers should start with a site-specific parameter list and that over time some parameters may be phased out while some will become more prominent depending on specific information requirements. Flexibility in the parameters monitored is needed over a repository lifecycle; e.g. parameters associated with the performance of the sealing system will be most important in the period after their emplacement when the most significant transient processes are occurring.

It was noted that the MoDeRn Project is producing a reference monitoring framework. This framework was based on the philosophy that monitoring programmes should be sufficiently flexible to incorporate learning and continued development of technology.

The philosophy behind the proposed use of a pilot facility in the Swiss national programme was discussed. The approach to be adopted with the pilot facility was to concentrate on representative boundary conditions and processes but that this does not mean Nagra would not also eventually monitor in the main repository too. Monitoring in the pilot facility and emplacement of waste in the main repository would be conducted in parallel.

Aspects of Why to Monitor?

One of the possible drivers for developing a monitoring programme discussed in the workshop was to support decision to reverse the disposal process or to continue with it. The workshop participants commented that both the French and Swiss national programmes are designing the repository with the possibility of retrievability in mind. It was commented that the response to retrieve waste or leave it in should be based on risk assessment (i.e. the potential consequences). The retrieval of toxic waste from disposal sites near Basel, Switzerland was cited as an example of the use of monitoring to support decisions on reversibility of a disposal process.

Other workshop participants stated that the monitoring was undertaken to support optimisation of operational practices and repository design. In this respect, monitoring would be regarded primarily as a tool for confidence building rather a tool for mitigating failures. It was proposed that implementers should look to other industries (e.g. the oil and gas industry and the chemical processing industry) and learn lessons from monitoring case studies.

It was also recommended that implementers should adopt a complimentary, concentrated approach to monitor to understand both localised processes and regional (e.g. network of seismic system sensors) processes.

A key reason for monitoring in the view of participants at the workshop was to ensure that the repository performance lies within the range of conditions assumed in the safety case. Therefore, a response plan was required should the monitoring programme demonstrate behaviour outside of the range assumed. The workshop discussed ICRP principles associated with radiological exposure (Table 4.1), noting that one principle is to move materials or people in the event of 'exposure situations' [6].

Table 4.1: Examples of radiological exposure as a function of disposal facility evolution [6]

Radiological exposure situations as a function of disposal facility evolution and presence and type of oversight			
Disposal facility status	**Type of oversight**		
	Direct oversight	**Indirect oversight**	**No oversight**
Design-basis evolution	Planned exposure situation	Planned exposure situation	Planning exposure situation
Non-design basis evolution involving significant exposures to people and the environment	Emergency exposure situation at the time of exposure, followed by an Existing Exposure situation	Emergency exposure situation at the time of exposure, followed by an Existing Exposure Situation	Emergency and/or Existing Exposure Situation

Inadvertent human intrusion	Not relevant	Not relevant	Emergency and/or Existing Exposure Situation

5. References

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

[2] European Commission (2004). Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste. European Commission Project Report EUR 21025. EC, Luxembourg.

[3] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) (2010). Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste, as at 30 September 2010.

[4] ICRP (2011). Annals of the ICRP: Radiological Protection in Geological Disposal of Long-Lived Solid radioactive Waste, Draft Report for Consultation, 4838-8963-9177.

[5] Environment Agency and Northern Ireland Environment Agency (2009). Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation.

[6] ICRP (1997). Annals of the ICRP: Radiological Protection Policy for the Disposal of Radioactive Waste. ICRP Publication 77, ISBN 008 042 7499.

Appendix A. Detailed Conference Programme

Monitoring Developments for Safe Repository Operation and Staged Closure

International Conference, Luxembourg , 19-21 March, 2013

Day 1
19 March, 2013

13:00	**Welcome & Introduction**			
	KEYNOTE ADDRESS AND OVERVIEW OF THE MoDeRn PROJECT			
	Session 1, co-chaired by the European Commission and Andra		Conference room M6	
13:10	Keynote: Monitoring and long term safety	P. Zuidema	Nagra, Switzerland	S101
13:40	Overview of the MoDeRn project: A reference framework for developing a monitoring programme -Presentation of the three themes	N. Solente	Andra, France	S102
	THEME 1- IMPLEMENTERS PERSPECTIVE : PROGRAMMES AND CASE STUDIES ON MONITORING			
	Session S2, chaired by Nagra		Conference room M6	
14:00	MoDeRn – A Case Studies	M. Jobmann	DBE Technology GmbH, Germany	S201
14:20	Confirmation Monitoring of Repositories in the United States	S. W. Wagner	Sandia National Laboratories, USA	S202
14:40	Monitoring strategy of Cigéo reversible disposal	S. Buschaert	Andra, France	S203
15:00	Monitoring of the planned repository for spent nuclear fuel in Sweden	J. Andersson	SKB, Sweden	S204
15:20	Development of the UK's Geological Disposal Facility Monitoring Programme	B. Breen	NDA, United Kingdom	S205
15:40 16:00	**Discussion**			
16:00 16:30	**Coffee Break**			
	THEME 2 - MONITORING : THE WIDER PERSPECTIVE, THE REGULATORY AND STAKEHOLDERS VIEW POINT			
	Session S3, chaired by University of East Anglia		Conference room M6	
16:30	Different views on monitoring and the governance of repository development and staged closure	A. Bergmans	UA, Belgium	S301
16:50	Monitoring for Geological Disposal: A stakeholder's viewpoint	G. Lauwen H Sannen	STORA, Belgium	S302
17:10	Environmental Monitoring of the WIPP-A Deep Geological Repository for Transuranic Waste	P. Thakur	Carlsbad Environmental Monitoring & Research Center, USA	S303
17:30	Monitoring and science programmes as "demonstrators" of safety	M. Meyer	CNRS, France	S304
17:50	Oversight of a Deep Geological Repository and the Role of Monitoring – Some preliminary findings by the RK&M Project of the NEA	C. Pescatore	NEA/FSC	S305
18:10 18:30	**Discussion**			
From 18:30	**Session S4: Poster Session & Cocktails**		Jean Monnet building, 1st floor	

Day 2 am

20 March, 2013

THEME 2 - MONITORING : THE WIDER PERSPECTIVE, THE REGULATORY AND STAKEHOLDERS VIEW POINT

Session S5, chaired by Enresa

Conference room M6

8:30	The draft Safety Guide on "Monitoring and Surveillance of Disposal Facilities"	K. Moeller	International Atomic Energy Agency (IAEA)	S5O1
8:40	MoDeRn – Regulatory view View on Monitoring of spent Fuel Geological Disposal in Finland	J. Heinonen	STUK, Finland	S5O2
8:55	Monitoring requirements in the Swiss regulatory framework	A.-K. Leuz	ENSI, Switzerland	S5O3
9:10 9:25	**Discussion**			

THEME 3 - MONITORING TECHNOLOGIES : FEASIBILITY AND LIMITATIONS- TECHNOLOGY

Session S6 & S6 Demo, focus on components & barriers, chaired by NDA

Conference room M6

9:25	State of art of monitoring technology for repositories: instrumentation performance obtained from long duration experiments	J.L. Garcia-Siñeriz	AITEMIN, Spain	S6O1
9:45	Design and development of large scale in situ monitoring section test in the French URL at the CMHM	R. Farhoud	Andra, France	S6DO1
10:00	Monitoring THM effects in a full scale EBS/host rock system – first experiences of the FE-Experiment in the Mont Terri URL during construction and ventilation phase	T. Vogt	Nagra, Switzerland	S6DO2
10:15	Monitoring of Sealing Dams – Experiences from a Test Set-up at the Repository ERAM, Germany	J. Stahlmann	Technische Universität Braunschweig, Germany	S6DO3
10:30 10:45	**Discussion**			
10:45 11:10	**Coffee Break**			

Session S6-Tech, focus on technology, chaired by Aitemin

Conference room M6

11:10	Monitoring High-Level Radioactive Waste Repositories with Non-intrusive Seismic Methods	H. Maurer	ETH Zurich, Switzerland	S6TO1
11:25	MoDeRn: Wireless Transmission of Data from the HADES Underground Laboratory to the Surface	T. Schröder	Nuclear Research and consultancy Group (NRG), Netherlands	S6TO2
11:40	New wireless data transmission system based on high frequency radio communication: design, development and testing results under repository conditions	I. Bárcena	AITEMIN, Spain	S6TO3
11:55	Wireless data transfer in salt rock	F. Grafe	IBeWa-Ingenieurpartnerschaft, Germany	S6TO4
12:10	Reduced scale tests to assess corrosion of a steel overpack in the Belgian Supercontainer	L. Areias	Euridice, Belgium	S6TO7
12:25	Spatial Time Domain Reflectometry (Spatial TDR) for Moisture Monitoring in Geological Repositories – Technology, Feasibility, and Limitations	N. Wagner	Institute of Material Research and Testing (MFPA) at the Bauhaus-University Weimar, Germany	S6TO6
12:40 13:00	**Discussion**			
13:10	**Closure of plenary sessions and introduction to workshops**			
	Lunch			

Monitoring Developments for Safe Repository Operation and Staged Closure

Workshops

Day 2 pm
20 March, 2011

Time	Session wp1-1 Conference room M3	Session wp1-2 Conference room M4	Session wp1-3 Conference room M5
15:00	**How to monitor ?** Feasibility & limitations	**Why Monitor ?** **Driving force ?** **Do we need it ?**	**When & How long to monitor ?**
	Jose-Luis Fuentes (Aitemin)	**Chairs** Nicolas Solente (Andra)	Jaap Hart (NRG)
17:00	Liz Harvey (GSL)	**Rapporteurs** Matt White (GSL)	Peter Simmons (UEA)

Day 3
21 March, 2011

Time	Session wp2-1 Conference room M3	Session wp2-2 Conference room M4	Session wp2-3 Conference room M5
09:00	**How to use results** Monitoring & governance	**Who is involved ?** Roles & responsibilities	**What & where to monitor ?** Parameters, spatial distribution & justification
	B. Breen (NDA)	**Chairs** Anne Bergmans (UA)	Michael Jobmann (DBETech)
11:00	Liz Havey (GSL)	**Rapporteurs** Matt White (GSL)	Alastair Clark (NDA)

11:00	Coffee break
11:30	A, B, C Sessions reporting (Chairs) — Conference room M6
12:00	Discussions
12:10	D, E, F Sessions reporting (Chairs)
12:40	Discussions
12:40	General conference conclusion Alan Hooper, General Rapporteur
13:10	Closure & adjourn

EURATOM

MODERN
Monitoring Developments for Safe Repository Operation and Staged Closure

AEN NEA

Appendix B. List of Participants

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MONITORING IN GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE:

OBJECTIVES, STRATEGIES, TECHNOLOGIES AND PUBLIC INVOLVEMENT

Appendix C. Full Conference Papers

C.1 Session S1: Keynote Address and Overview of the MoDeRn Project

Monitoring and long term safety – the view of a practitioner based on more than 25 years of experience

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Summary

In this paper, a broad overview is given of the different aspects of monitoring in the stepwise process of repository implementation. The paper addresses both technical and societal aspects. Although monitoring is very useful in providing information on specific phenomena related to long-term safety, there are inherent limitations with respect to the demonstration of overall system performance due to the long time scales involved. Furthermore, there remain some technological challenges with the instrumentation for monitoring which are still under investigation. Monitoring can also be an important element in the interaction between the technical experts and society at large. However, in the interaction with society great care is necessary to ensure that no undue expectations are raised about the possibilities to confirm the behaviour of the repository with respect to long-term safety. Finally, a few remarks are made about the evolution of monitoring over the last ~25 years.

1. Introductory remarks

In this paper, a broad overview on the different issues related to monitoring with respect to long-term safety is given. The paper is written by a practitioner with more than 25 years of experience (a large fraction of which as head of science & technology) in an implementing organization. Although the view is that of a practitioner and not a scientist, it tries to reflect the views of the different fields of relevance such as science, technology, sociology, etc. It is not a review paper, but rather the personal view of the author.

For the purpose of this paper, monitoring is defined as “continuous or periodic observations and measurements of parameters and indicators/characteristics (i) to evaluate the behaviour of a system or a subsystem and/or (ii) to evaluate the impact of the system or subsystem on its environment.”

There exists broad agreement that monitoring provides important contributions to successful implementation of geological repositories. Monitoring starts already in the early phases of repository implementation by providing information for decision-making for site selection and for the selection of the repository concept. Monitoring will take place in all phases of repository construction and operation both to confirm the adequacy of the system and of the operating procedures and to help in the decision-making regarding possible measures for optimization or for corrective actions. Monitoring will also provide input to decision-making to fully close a repository and may continue even after closure. Eventually, however, monitoring will most likely stop as society may lose interest in such monitoring activities and the institutional program to follow the evolution of the repository will cease, likely well before the end of the time span over which the repository has to provide protection of humans and the environment from the hazards of the radioactive waste. Therefore, there is broad agreement that monitoring cannot be a part of the system that ensures long-term safety; the repository system must be based on passive barriers and must be safe without any monitoring activities.

As can be seen from several waste disposal programs, success in bringing repository projects forward requires repository projects of high technical quality based on a sound scientific and technological program, but, equally important, it also requires broad societal support. To discuss monitoring, it is thus worthwhile to look at the role of monitoring in the scientific-technological program for implementing repositories but also at the meaning and usefulness of monitoring for society and how monitoring can contribute to the needs of society.

2. Monitoring as part of the scientific-technological program for implementing geological repositories

Monitoring in science and technology is broadly established. Science disciplines such as climatology, astronomy or biology – just to mention a few – strongly rely on the analyses of more or less long records of measurements to bring scientific understanding forward. In technology, monitoring is very widely used and can be considered as “good engineering practice” – see e.g. the use of periodic or continuous measurements for technological systems such as engines (e.g. in airplanes), complex buildings (e.g. deformations of large dams), etc. But also in other fields, monitoring is essential - see e.g. the monitoring of stock exchange rates and the use of monitoring records for deciding whether to buy or to sell a title.

When discussing monitoring for repository implementation, it is considered useful to have a look at the different aims of monitoring. Monitoring can be used as a tool for research in the sense that one collects basic data “just to see”, as it is often done with very long-term scientific data series (e.g. climate, seismicity, geodesy). When focused on more specific questions, monitoring of experiments or of a specific situation in nature is often used to clarify a specific issue related to our scientific understanding e.g. through comparison of results from (a priori) predictive modeling with measurements relevant to the issue, a process called model testing or “validation”. Furthermore, monitoring is broadly used to confirm proper performance of a specific system, often without the need to capture all the underlying scientific aspects. These different aims of monitoring should then be looked at in the context of decision-making in the stepwise process of repository implementation. In the very early phases, monitoring of “just to see” may take place and this can also continue but has normally no direct input to decision-making. Monitoring related to geological phenomena (e.g. periodic geodetic measurements to quantify potential differential vertical and horizontal movements, monitoring seismicity to detect neotectonically active zones, etc.) may be used in decision-making for site selection. Here, also monitoring of experiments in first generation URLs may contribute to the decision because such experiments may provide input to setting priorities on different host rocks options.

In parallel to site selection, monitoring is widely used in the RD+D-programs because much of the experimental work involves monitoring – either in lab programs or in experimental studies in first generation URLs. This work will in several programs continue in parallel to repository construction and may eventually become part of the program to assess and confirm the long-term performance of the repository system. During actual repository implementation, monitoring will be important. This includes the establishment of a base line and then periodic observation to determine if any changes occur with respect to this base line. Such changes can reflect the system behaviour for phenomena that are also relevant to post-closure safety. Thus, the monitoring of changes with respect to a base line may not only be relevant for potential liability issues but may also be relevant as input to system behaviour related to post-closure safety.

Monitoring is also part of the site characterization program and is part of the work in the site-specific second generation URL where experiments are made to characterize the (site-specific aspects of the) host rock and/or to confirm engineering aspects. These experiments are similar to those already made for RD+D purposes in first generation URLs. This may include migration tests, heater tests, gas transport through the host rock, properties of the EDZ, etc. Also repository construction is monitored in detail as it is done with other underground construction work and as it is considered to be "good engineering practice". By doing so, it is ensured that the repository is built to specifications (and to meet the requirements of long-term safety) and such monitoring activities may also lead to a decision to modify the work process (e.g. change of excavation method to reduce the extent of the EDZ). Furthermore, monitoring may also include the observation of indicators relevant for post-closure safety such as the response of the geosphere to disturbances such as draining the underground e.g. as a response to the sinking of a shaft.

A very much desired goal of monitoring of the geological repository is – as in other applications – the demonstration that the overall system performs as planned. Thus, the desired ultimate goal is to demonstrate that the repository is able to retain essentially all radionuclides in the near field of the repository or in the surrounding geosphere until they have decayed away. This is, however, not possible, because the time needed for decay of a significant part of the radionuclides is by far too long to be monitored. Therefore, the assessment of appropriate performance of the repository has to focus on evaluating the performance of individual safety barriers of the repository system under conditions as they will exist in the long-term when eventually some radionuclides will be released from the (breached) canisters. However, it will take a long time until such conditions are reached. For a typical HLW repository (Swiss project), saturation of the bentonite for example will take in the order of approx. 100 years. But even then it will not be possible to measure the retention properties of the bentonite; due to the containment of the waste (spent fuel or vitrified HLW) in a long-lived canister no radionuclides would be released that could migrate through the bentonite backfill and the (near-by) host rock. But even in the hypothetical case that radionuclides would be released much earlier, their migration velocity would be so slow that nothing can be measured within reasonable time spans. Thus, within the overall repository system it is not possible to monitor the performance of the transport barriers in a direct manner. However, the transient behaviour of the overall system – starting with excavation of the emplacement rooms – can be monitored and includes (example: HLW repository) observation of deformations of the emplacement rooms, resaturation of the bentonite backfill combined with build-up of swelling pressure, de- and resaturation of the host rock surrounding the emplacement rooms and temperature evolution in the near field; other phenomena are expected to be hardly detectable. Although these early phase phenomena cannot be directly used for assessing long-term performance, they are useful indicators in assessing the evolution of the system towards the relevant long-term status and can provide confidence that the early transient phenomena are not unduly affecting the long-term performance of the barriers. Furthermore, complementary to monitoring the overall system or parts thereof, there exists the possibility to perform experiments in the site-specific URL to test specific phenomena related to performance of the repository barrier system. This may include migration experiments (both for the backfill and the host rock), gas release tests, heater tests, etc. Monitoring of such long-term experiments may provide very useful results for the performance confirmation program.

Despite the limitations on what can be monitored for the overall system, it was decided in Switzerland to foresee a so-called “pilot facility” as part of the repository that is a duplicate of the main facility. The main facility will contain the majority of the wastes and will not be monitored, while the pilot facility will contain a small but representative fraction of the wastes under conditions replicating those in the main facility. This pilot facility will be used for monitoring to derive additional information for the decision for the eventual final closure of the repository. Although monitoring of the pilot facility aims at collecting confirmatory information, it should also be able to detect any “unexpected developments”. Keeping this in mind, it may be necessary to broaden the range of parameters to be monitored to be ready “to detect the unexpected”. Most important for decision-making is, however, not to look at in-situ monitoring of the “pilot facility” in isolation but to combine it with dedicated experiments (in the in-situ rock laboratory or somewhere else), scientific studies and – probably most important – monitoring any progress of science in the areas relevant to post-closure safety. All the information from these different sources needs to be periodically analysed and the meaning of any findings assessed and documented (e.g. within a so-called “periodic safety evaluation” as they are required e.g. for NPPs in Switzerland). All the information is expected to be used also in the eventual decision to close the repository.

Besides these remarks on the general issues and challenges related to monitoring, there are also many practical issues and challenges related to the technology needed for monitoring. Technology is of key importance because technology determines what can be measured with what precision and with what reliability over the long timescales envisaged (in Switzerland on the order of one hundred years). With respect to technology it is important to be clear about the parameters / variables that can be measured, about the spatial resolution of the measuring devices (e.g. in heterogeneous systems, over what volume is the measurement averaged). Then, practical issues like access (boreholes, etc.) for data transfer and energy supply versus the possibility of wireless data transmission and the availability of in-situ power sources need to be discussed in the context of the importance of disturbances of the monitoring device and its connections to data acquisition and power systems. This also includes an evaluation of the possibilities for non-intrusive instrumentation (e.g. geophysical monitoring techniques). When considering the long timescales involved in monitoring, issues like drift of measuring devices and the need for calibration, reliability/longevity and the possibility for repair or replacement (without creating undue disturbances) must be considered. Much experience on the strengths and weaknesses of the different monitoring devices is available through their use within (long-term) experiments in the numerous underground research laboratories. Future experiments in such underground research laboratories are an ideal approach and will be used to test newly developed monitoring devices and to gain experience regarding their long-term performance.

Finally and very important is also the issue of potential impact of monitoring on the barriers for passive long-term safety. There is broad agreement that no compromises should be made with respect to long-term safety to allow for more easy monitoring. This boundary condition further reduces the possibility with respect to monitoring.

To summarize, there exists a clear understanding on the phenomena that can be monitored in the different phases of repository development. According to the current understanding, the possibilities to directly monitor the overall performance of the implemented system at large are very limited; thus the wish to directly check the proper functioning of the overall system cannot be fulfilled. Furthermore, there are also limitations with respect to the technology available today, some of the limitations are inherent but others are subject to further technology development.

3. Societal needs

As mentioned, successful implementation needs besides a sound scientific and technological program also the support by society. Society needs confidence and trust in the performance of a repository in order to be comfortable with a decision "to go forward". The level of confidence and trust needed to go forward will increase as the decisions get more binding within the stepwise implementation program. The steps in such a program go from choice of waste management concept to selection of site and design towards start of construction and operation and eventually closure of the repository. A significant part of society is at least implicitly, sometimes also explicitly, aware that they cannot understand all the details about a repository and therefore, confidence and trust are based to a large extent on "the overall picture" that besides factual information also considers the process of repository implementation and decision-making and the behaviour of the key stakeholders. Furthermore, for the layman the complex scientific arguments and models assessing the future evolution of the repository are difficult to understand and it is even more difficult for the layman to judge whether he can trust the results of these complex models. In that sense, measurements that confirm (or contradict) predictions are much easier to understand ("did you measure what the models predicted?") and therefore, monitoring results can be really helpful. However, equally important are the arguments that the measurements are relevant for the key question at hand: "is the repository safe?" Because of the difficulty to identify performance indicators that can be reliably monitored and at the same time are relevant for safety, it is important to ensure that society is already involved in the process to define the monitoring program. Thus, society can be made aware of what can be done (and what not) and how the experts work on this issue. Being involved already at an early stage and observing the process for an extended time period provides an opportunity for society to develop confidence in the way the technical experts handle the issue.

Thus, there is a clear need to involve society already in the site selection process. There should be the possibility to follow actual work and adequate information should be made available. Already during site investigation, the possibility for impact of characterization work on the environment may be an issue and thus, in some programs a monitoring program is implemented to record the effects of field work. A powerful instrument to ensure that the needs of the local population are sufficiently respected in this phase is the implementation of a supervisory commission or a support group that follows the field activities and takes note of the results of the monitoring program and is also informed about the broader picture on how the data are used and how the decision-making will progress. The supervisory commission has been a useful instrument already in the early phases of the Swiss program. It is expected that such a supervisory commission will also be used during the actual implementation of the repository.

Monitoring will continue also after construction of the repository. This is important for society because this is a clear signal that the implementer and the authorities still care about science also after construction and start of operation of the repository. Such a long-term monitoring program is a clear commitment towards readiness for continued learning and to have the necessary vigilance. For society, it is very important to have clarity on how the monitoring results are to be used in the decision-making process and what the possibilities are to implement optimization measures or to take corrective actions if the monitoring results indicated the need for it. In all stages of repository development, society in several countries wants to be ensured that in the most extreme case, it would be possible to retrieve the waste and such requirements are therefore formulated in the laws of these countries (e.g. Switzerland).

As discussed in the first part of the paper, there are scientific-technological limitations on what can be monitored with respect to post-closure safety in a direct manner. To ensure full transparency, it is important that society is aware of the strengths and weaknesses of monitoring and also broadly knows how the information gathered by monitoring can be used to re-evaluate post-closure safety. Thus, it is important that the process of deciding on the phenomena to be monitored and the underlying overall strategic thoughts are at least in the broad sense discussed with and transparent to (the representatives of) society; ideally these representatives should already be involved in the discussion phase when the detailed monitoring program is being developed.

Once the monitoring program is defined and underway, it is important that the information is available in an adequate format and that a suitable process to disseminate and discuss the results is in place that also considers the needs of society. Thus, periodic reporting is essential. More recently, it has internationally also been discussed in how far other organizations than the operator and the authorities should be involved in the collection of information, its analysis and reporting.

To summarize, it is felt that society will profit from monitoring not only by receiving “hard information” but also through the process and the corresponding direct contacts with the implementer and the authorities; society will get a better understanding through the interaction with the implementer and the authorities in the discussion of the results and the corresponding broader aspects. However, great care will be necessary to ensure that no wrong expectations are raised about the possibilities to check in a direct fashion the actual behaviour of the repository.

4. Conclusions

Monitoring provides important contributions to the successful implementation of geological repositories and addresses both technical and non-technical stakeholder expectations. However, there are inherent limitations on what can be achieved with monitoring in the direct demonstration of performance of the overall repository system with respect to long-term safety. Besides these inherent limitations, there are also technological challenges with respect to the monitoring devices. Nevertheless, monitoring provides important information in the stepwise implementation process. Monitoring is also an important element for society and can provide a suitable platform to enhance the interaction between society and the technical experts. In the interaction with society, however, it is also important to be realistic regarding the strengths and weaknesses of monitoring.

Looking back over the last 25 years, the author sees a clear evolution of the use and role of monitoring in repository implementation. Already in the 80’s, monitoring as “good engineering practice” was fully established. This covered aspects during construction and operation of the repository. Monitoring as part of RD+D activities was also foreseen from the beginning (e.g. migration experiments). Over the years monitoring with respect to post-closure performance became more important. In parallel to the evolution of the technical-scientific issues, involvement of society and the consideration of societal needs have turned into a new additional focus of monitoring over the last ~15 years. The focus of society, however, is more narrow than that of science and technology at large, which looks at the whole range of applications during all the different stages of repository development, whereas society typically puts the emphasis on in-situ monitoring of the implemented repository.

Overview of the MoDeRn project: A reference framework for developing a monitoring programme

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Abstract

This paper provides an overview of the MoDeRn projects main goals and results. The main goal of this collaborative, European Commission 7th Framework project is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during the staged approach of the disposal process. It should be noted that the MoDeRn project recognizes the diversity of monitoring activities that will be required in a repository, in particular related to operational safety and environmental impact assessment. The projects emphasis, however, is on verifying – with the aim of confirming and possibly enhancing the prior license basis for safety and pre-closure management options – expected repository system evolutions (i.e. natural environment and engineered system evolutions) during a progressive construction, operation and closure phase that may last on the order of a century. To achieve this goal, 18 partners representing 12 countries and including 8 Waste Management Organizations joined their efforts since 2009, and have developed a “roadmap to repository monitoring”.

MoDeRn has progressed on both the associated Process issues – why to monitor, how to develop a program, and how to use monitoring results – and Technology issues – technical requirements and constraints, technology state-of-the-art, and focused R&D and in-situ demonstrators. To achieve progress on process issues, the basis for a structured development of monitoring programmes was established, focused on justifying and proposing key objectives; how to attain them; and how to use monitoring results to assist decisions of disposal process management. Their application was tested through developments of case studies in various host rocks. Furthermore, the results of a focused sociological study provide a basis for associated stakeholder engagement activities as well as a better understanding of whether and how monitoring will contribute to enhancing confidence in and acceptance of the disposal process.

To achieve progress on the technology issues, an overview of typical technical requirements and constraints was developed. Further on, a technical workshop involving other monitoring Research and Technology Development (RTD) projects was hosted to identify RTD techniques that enhance our ability to monitor deep geological repositories. An overview of monitoring technology state-of-the-art was

established and several focused R&D and in-situ monitoring experiments were launched.

Introduction

MoDeRn is a four year international collaborative research project[1] (2009 – 2013) addressing the question of how repository monitoring can contribute to the technical safety strategy and quality of the engineering of geological disposal facilities for long lived radioactive waste and spent nuclear fuel, as well as contribute to public understanding of and confidence in repository behavior.

The term *Monitoring* refers to a generic activity and the need is felt to provide a concise definition of what is referred to as *Monitoring* in the context of performance verification and confirmation. Based on prior (IAEA 2001, ETN 2004) definitions, the MoDeRn project defines the term monitoring in the context of geological disposal of radioactive waste 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 thus to support decision making during the disposal process and to enhance confidence in the disposal process."

The overarching motivations for this activity are to enhance confidence of implementer, expert and lay stakeholders during construction, operation and closure of the repository, and to assist the decisions that must be taken during this stepwise disposal process. Project partners have thus decided to remain close to prior definitions as proposed in [9] and in [10], adding the reference to these overarching motivations.

Spent nuclear fuel and long-lived radioactive waste must be contained and isolated for very long periods, and current schemes for its long-term management involve disposal in deep geologic repositories. The successful implementation of a repository programme for radioactive waste relies on both the technical aspects of a sound safety strategy and scientific and engineering excellence as well as on societal aspects such as stakeholder acceptance and confidence. Monitoring is considered key in serving both ends.

The increased interest in monitoring the repository prior to closure is consistent with a general consensus that future work is required after receipt of a license to construct and operate. It is expected to contribute to a transparent disposal process acceptable to stakeholders and to provide further basis supporting a future decision to close the repository. This is consistent with socio-political feedback received on earlier disposal program developments. From these, a consensus appears to have emerged, that an informed, stepwise approach provides an acceptable basis permitting progress from a licensing stage through progressive construction, operation and ultimately closure of a repository (see e.g. [1], [2], [3], [4], [5], [6], [7], [8]).

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[1] There are 18 MoDeRn project partners representing organisations responsible for radioactive waste management in 7 EU countries (Andra, DBE TECH, Enresa, NDA, Posiva, RAWRA, SKB), Switzerland (Nagra) the US (Sandia) and Japan (RWMC) as well as organisations with specialist expertise in monitoring (Aitemin, Euridice, NRG, GSL, ETH Zurich). Three partner organisation offer specialist experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organisations, industry) in highly technical issues (UA, UEA, UGOT).

Several national programs and international cooperation led to a better understanding of why, what and how to monitor. International cooperation is reported in the International Atomic Energy Agency (IAEA) Technical Document on monitoring of geological repositories [9] and by the European Commission (EC) within a Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste [10]. In addition, the IAEA has recently requested a review by Member States on its draft safety guide DS357 on Monitoring and Surveillance of Waste Disposal facilities [11]. A fairly comprehensive overview of the current developments on monitoring within individual national programs is provided in [12] and [13].
To further build upon these prior and parallel developments, the European Commission has decided to include the Topic *Strategies and technologies for repository monitoring* in its 7th Framework Program to request corresponding proposals. A Grant (Agreement n°232598) was awarded to the collaborative MoDeRn project, whose main goal is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during the staged approach of the disposal process and to provide a clear description of monitoring strategies, taking into account a variety of physical and societal contexts, available monitoring technology, and feedback from both expert and non-expert stakeholder interactions.

It should be noted that the MoDeRn project recognizes the diversity of monitoring activities that will be required in a repository, in particular related to operational safety and environmental impact assessment. The projects emphasis, however, is on verifying expected repository system evolutions (i.e. natural environment and engineered system evolutions) during a progressive construction, operation and closure phase that may last on the order of a century. This aims at confirming and possibly enhancing the prior license basis for safety as a pre-requisite to obtaining an authorization to close the repository. It also aims at providing data to re-evaluate options available for managing a stepwise disposal process prior to its closure, for instance the option of waste retrieval.

The various activities undertaken in the course of the project contributed to defining a detailed panorama of both the Process issues – why to monitor, how to develop a program, and how to use monitoring results – and the Technology issues – technical requirements and constraints, state-of-the-art of available technologies and focused R&D and in situ demonstrators, achieving a detailed description of:

- National contexts, structured in a set of societal and physical boundary conditions which may influence some of the upstream decisions for geologic repository monitoring.
- technical requirements on monitoring activities as well as an assessment of the state-of-the-art of relevant technology responding to these requirements, and of the Research and Technology Developments in the field of data transmission
- Stakeholders' engagement activities in relation to the monitoring of facilities for the geological disposal of radioactive waste. Monitoring is considered as a combined socio-technical activity, driven as much by social and institutional innovation as by technical innovation.
- Demonstration of innovative techniques conducted in situ within underground research laboratories, with the objective of providing new or enhanced monitoring approaches specifically responding to some of the design requirements of a repository.

- Case studies, providing an analytical and practical evaluation of relevant monitoring aspects on the basis of a generic repository design, in salt, clay and granite host rock, taking into account various monitoring concepts. Case studies aim to illustrate the potential design of corresponding monitoring systems and possible approaches to prevent and detect measurement errors. The case study will also show how unexpected repository evolutions may be handled
- A Reference Framework, as guidance for the development of a geological disposal monitoring programme, the design of monitoring systems to implement such a programme, the use of monitoring results and their contribution to the governance of a stepwise disposal process and the progressive updating of the monitoring programme within that stepwise process.

All these subjects are thoroughly developed in specific thematic documents, available on www.modern-fp7.eu

Keeping in line with the 3 conference themes, broad results of the MoDeRn project will be further described and presented below. These themes are:

- Implementers perspective: programmes and case studies on monitoring
- Monitoring: the wider perspective, the regulatory and stakeholders' viewpoint
- Monitoring technologies: feasibility and limitations

Implementers perspective: background, programmes and case studies on monitoring

Building on the results achieved in the process and technologies sections of the project, a reference framework is proposed, with the objective of developing and proposing a structured process to provide guidance for implementers on how to develop, implement and use a monitoring programme, while acknowledging the diverse national contexts.

Boundary conditions

The project has taken the position that there are a variety of factors that influence the decisions each waste management organization will take with regards to monitoring. They are introduced here and are regarded as "boundary conditions" which condition such decisions on monitoring. A distinction is made between societal boundary conditions and physical boundary conditions. The former address the way society may influence decisions on monitoring (see also 0 **Monitoring**: the wider perspective, the stakeholders' viewpoint). The latter address conditions, needs and constraints for monitoring related to the physical environment of the repository and of the waste itself.

Societal boundary conditions to monitoring decisions can be interpreted very broadly, and include **legal and regulatory frameworks**. the national frameworks provide a basis for what needs to be included in the monitoring program, but most often tend to be relatively general in their terms, with no detail on how monitoring should be carried out. Mention may be made of a stepwise implementation process, but no details are available on how decisions at each step should be taken. Some regulations may include specific requirements for implementation strategies, e.g. the Swiss regulator calls for monitoring to be conducted in a pilot facility [14]. The French guidelines [15] also address monitoring to inform reversible disposal management.

Physical boundary conditions refer to key elements of the repository system, i.e. the inventories describing quantity, content and conditioning of the waste, the natural environment and the engineered system.

In disposal concepts designed for different types of natural environments, the isolation of radioactive waste from the biosphere is based on different components of a combination of engineered and natural barriers. Monitoring prerogatives for each rock type vary as a function of waste and rock properties in concert with disposal concepts, with greater or lesser emphasis placed on mechanical stability, hydrogeological evolutions and associated transport properties.

The overall engineered system includes considerations of overall layout, thermal management, as well as specific barrier performances to contribute to the basis of the safety case and of operations. Monitoring implementation strategies, need to be adapted to environmental conditions, to construction procedures, and levels of accessibility of these units. Of particular importance is the need to preserve safety function performances.

Reference framework

An obvious conclusion from the National Context analysis is that any technical specifics of a monitoring program must be tailored to and developed within its national context. The overall process, however, to conduct such developments proceed along common steps.

The project aims to provide advice on how monitoring might be integrated within the repository programme - by proposing a *Monitoring Reference Framework* as a structured approach to follow from development, to implementation and operations of a monitoring programme, providing guidance on:

- How monitoring objectives may be developed and their role in the disposal process understood: to develop these objectives into clear information requirements which can then be related to key safety functions and thus to processes and parameters to be monitored;
- How monitoring systems may be designed and what strategies may help in attaining the monitoring objectives – to assess technological feasibility, implementation strategies and technical limitations, with an outlook for further R&D, and more generally the potential for added value from a monitoring programme as well as an assessment of its limitations for informing the disposal process;
- How monitoring should be addressed as part of the overall governance of the disposal process by providing general notions on how monitoring results would inform and thus contribute to management decisions, how they would be evaluated against prior expectations, and how the particular case of monitoring results deviating from such prior expectations (the *unexpected* or *deviating* results) could be addressed; and
- How monitoring might contribute to stakeholder confidence – to discuss how the evidence expected from testing the validity of the licence basis prior to closure, the process overall and specifically the roles different stakeholders may play, could contribute to enhancing confidence in the disposal process.

The *MoDeRn Monitoring workflow* (Figure 2) illustrate this approach and provides an overview of key steps to consider when developing a monitoring program.

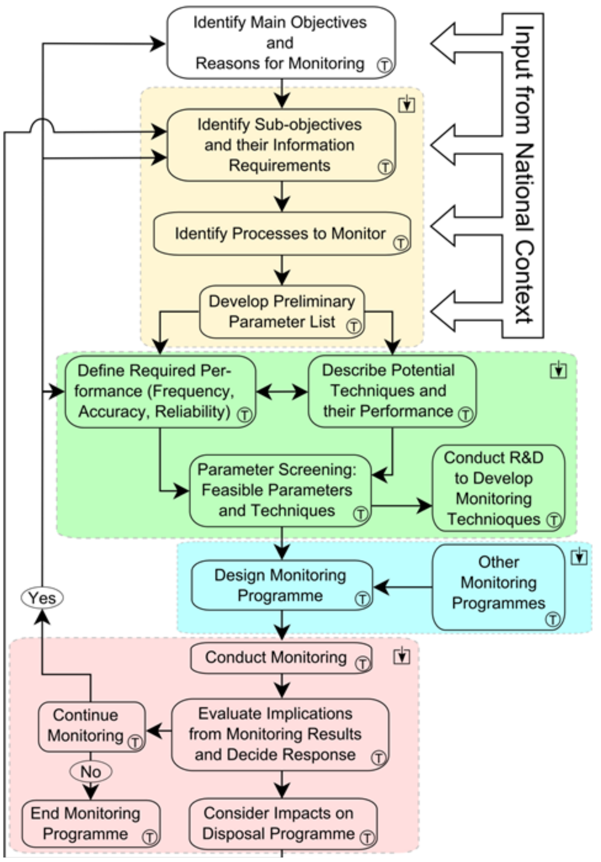

Figure 1: Summary flowchart of key steps in developing and using a monitoring program

The *MoDeRn Monitoring Workflow* identifies three key stages in developing and managing a monitoring programme:

1. Analysis of overarching goals and objectives and relating these to processes and parameters to identify a preliminary parameter list for monitoring.
2. An analysis of requirements and available monitoring technology to design a monitoring programme.
3. Conducting a monitoring programme and using the results to inform decision making.

The first and most important step is to understand Monitoring Objectives and thus to establish what needs to be monitored, and for what reason. The MoDeRn project proposes that the two overarching motivations for developing a monitoring program and conducting monitoring are:

- To support decision making throughout the disposal process, and
- To enhance confidence in and thus acceptance of the disposal process

In the context of substantial prior knowledge available and at a time in the development process when a national program has already submitted a License Application, both of these translate into the main objective for a monitoring program: To confirm the basis for expected/predicted behavior of the repository system.

Here to confirm is the hoped-for conclusion that monitoring results will support. It pre-supposes prior steps to verify the actual basis and to evaluate any consequences of this basis on expected/predicted behavior. These are carried out to verify the basis for expected performances:

- To support the basis of the long-term safety case, and
- To support pre-closure management of the repository.

These main objectives must then be analyzed to ultimately define what to monitor, that is to provide a set of technical monitoring objectives which designate those processes and parameters that are to be monitored within the repository. For this, it is essential that the implementing organization makes use of available knowledge and understanding, based for instance on decades of science and technology research programs, as well as on site characterization and monitoring of site baseline conditions. Through iterative developments of site characterization and a science and technology program, repository design, process model developments, safety analysis and performance assessments, the link between what is important to safety and to pre-closure management and the associated processes and parameters has already been established. Select processes and parameters of engineered and natural repository components, illustrated in Fig 2, would then be monitored.

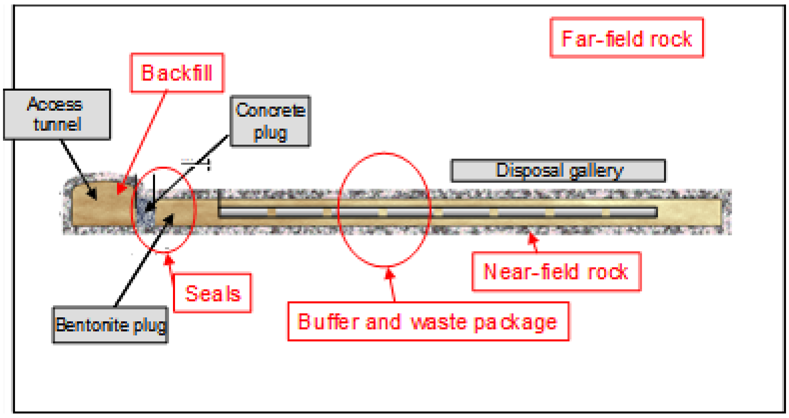

Figure 2: Typical engineered and natural repository components subject to monitoring

Prior to addressing technological requirements, three key issues deserve further consideration:

- Monitoring will be limited due to the timescales of certain slow processes;
- Monitoring results should be representatives for repository and component performance; and
- The special issue of post-closure monitoring.

Analysis of these in a given context will provide a basis to provide a realistic assessment to what extent monitoring might provide further support to the disposal process, and also what specific aspects cannot be answered directly through monitoring. Presenting this in a transparent manner will prevent making exaggerated claims, which might in the future discredit the value of monitoring.
Some processes operate at typical **timescales** which are substantially higher than a century. They will thus not be accessible to direct confirmatory monitoring. This consideration could be addressed in previous experiments, by providing for artificially accelerated transients (e.g. forced resaturation). Assuming that in-situ repository evolutions will not be subjected to any artificial acceleration, monitoring of very slow natural evolutions would at best provide

information limited to detecting initial evolutions, which might in certain cases provide confirmation that adequate process models were selected, or to confirming the absence of significant evolution. This is the case e.g. for far field responses in host rocks having very small transmissivity. It is also the case for near field and engineered barrier evolution to their long term, post closure configuration (e.g. very slow seal resaturation and swelling).

The potential added value of in situ monitoring, however, remains substantial, if it provides in-situ data over several decades, to add to prior experiments typically conducted over shorter timescales.

Monitoring data are expected to be representative for the basis of safety. Although it is theoretically possible to perform monitoring exhaustively on all components of the repository, this approach is not realistic. Therefore, an argument should be developed to support that **select monitored locations** and components provide such representative results. This will typically be based on considerations of homogeneity of the natural environment and of the controlled homogeneity of manufacture and construction of engineered components. Conversely, the impact of any heterogeneity should be addressed when designing a monitoring system.

The issue of post-closure monitoring is often required in principle, without specifying what might be expected. From today’s perspective, this may be a sensible request if it is focused on surface-based, environmental monitoring or on nuclear safeguards, or if it is focused on long-term monitoring of far-field hydro-geological response to the repository. Any requirements specifically focused on processes within the repository may seem in contradiction with the current perspective that performance confirmation monitoring related to long term safety is conducted prior to closure of the repository.

Indeed, the decision to definitely close a repository – at least from today’s perspective – is preceded by a century of experience with disposing waste, managing a repository and obtaining confirmatory information from in-situ monitoring and from a parallel long term science and technology programme, and confirmation and re-evaluation of the safety case prior to closure. It might then be argued that, should additional residual questions remain concerning the long term safety of the repository, then the decision to close the repository would be postponed. Conversely, if all stakeholders agree on having confidence in the long term safety, it may be more difficult to associate this view with a request for further monitoring.

It is, however, not the responsibility of today’s stakeholders to decide for and in place of future stakeholders – repository operations are typically considered over timescales on the order of a century. In any event, the future context and motivations cannot be well appreciated today.

It is noted that, in the event post-closure, in-situ monitoring would be called for, organizations are currently developing wireless, through rock transmission technology that may be able to respond to some level of in-situ post-closure monitoring.

Monitoring is limited by available technology. A realistic development of a monitoring program must thus consider available monitoring technology and strategies to implement the monitoring program. In particular, environmental conditions and the requirement to monitor over extended periods of time impose specific technical requirements on monitoring systems [16]. Analysis should highlight technological shortcomings that may still represent an obstacle in meeting monitoring objectives, and propose improvements by conducting several focused RTDs. In a repository, these may also address the need to avoid detrimental impact of monitoring on pre-closure/post-closure performances.

Case studies to test the proposed approach

The general approach to developing a monitoring program must rely on work conducted with specific examples, as provided by the national contexts and further developed in specific case studies. These tackle all relevant monitoring aspects by considering a system design based on different monitoring concepts and adapted to different specific host rocks and engineered barriers.

Work has progressed by defining the cases to be studied as focused on the three most commonly considered host rocks – i.e. salt, clay and granite, as well as three different disposal concepts – i.e. the German, French and Finnish concepts (Fig 3). This enables the most relevant monitoring issues for final repositories of high-level heat generating radioactive waste to be addressed. An initial draft developing possible monitoring processes and parameters for all three cases was developed as a basis for further discussions, and corresponding monitoring systems are being proposed.

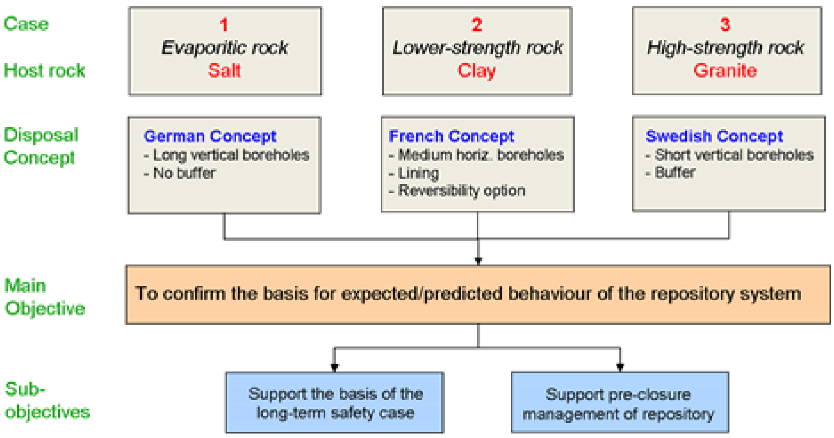

Figure 3: Case studies developed within MoDeRn

Monitoring efforts are generally intended to confirm that the properties of the natural environment are as anticipated (i.e. consistent with site characterization) and that changes to these conditions are within limits applied in the design and licensing process. This may call for:

- Verification of expected hydrogeological properties;
- Verification that favorable properties are preserved, minimally altered, or understood sufficiently during construction and operation;
- Verification of thermo-hydro-mechanical response in the near field to construction, operation and partial closure;
- Verification of far field response, if any, due to construction, operation and closure.

In crystalline rock, the long-term integrity of the waste containers and the behavior of the bentonite buffer provide an important contribution to safety, so that the near-field groundwater flow and groundwater chemistry are emphasized. This type of formation is characterized by blocks of tight rock suitable for waste deposition surrounded by fractures or fracture zones. Monitoring may thus also contribute to the knowledge of host rock heterogeneities. In sedimentary or saline rock, the concept relies more on the homogeneity, sorption capability, and extremely low hydraulic conductivity of the host formation. In the latter case, therefore, the average hydraulic properties on larger scale, and of the backfilled and sealed access tunnels, ramps, and shafts, are vital.

Any structural health monitoring requirements are strongly dependent on the host rock, on the chosen ground support, and on the chosen operational strategy, especially duration of needed emplacement operations and duration prior to a local closure stage (i.e. the end of local operation and access needs). While usually not an issue for high strength crystalline rock, these are likely to give rise to monitoring objectives in the lower strength saline or sedimentary rocks, if access and waste transfer and emplacement capacities have to be ensured for long operational periods.

Monitoring: the wider perspective, the stakeholders' viewpoint

A significant part of the project is devoted to provide a basis for stakeholder engagement activities in relation to the monitoring of facilities for the geological disposal of radioactive waste. The report views monitoring as a combined socio-technical activity central to the pursuit of safe repository operation and staged closure. The project studied expert views on monitoring, the role of monitoring in building stakeholder confidence, and monitoring as a socio-technical activity, focusing on the basis for social trust.

Expert Views on Monitoring

The investigation of expert views of monitoring drew on two sources of data: key international technical documents and interviews with 18 experts (mainly technical specialists) from radioactive waste management and research organisations.

For the experts interviewed, monitoring is about collecting information on the repository system, mainly for purposes of decision-making. More specifically, it is about observing through measurements the behaviour and impact of the repository system. For the technical partners in the MoDeRn project the focus is on confirming that repositories will perform as required and that the basic safety assumptions are correct. In addition, however, assurance and confidence building were mentioned by all respondents as being one of the main drivers for monitoring, to assure the implementer and the regulator, and also to reassure the public and build confidence in the repository. It must be noted however, that the expert stakeholder has not yet a clear knowledge of the lay stakeholders' anticipation in terms of monitoring, due to limited interactions between both groups.

A specific theme for expert stakeholders is the post-closure monitoring. It is seen as a major challenge for R&D, particularly if this were to involve monitoring of internal or near-field processes.

Monitoring processes within the repository while maintaining the principle of passive safety by developing non-intrusive monitoring techniques seems inadequate to many respondents who explicitly refer to post-closure in situ monitoring as unrealistic and potentially counterproductive.

In addition to answering the question of *how* to monitor safely, however, there is also continuing discussion about *what* should be measured, i.e. which specific processes – or parameters that, in the relatively short period before closure, would provide data conclusive enough to accurately predict future system behaviour. This has both implications for post-closure and pre-closure monitoring. The general position taken by the experts interviewed, was that it will be possible to identify measurable parameters that would enable them to validate (and if need be adjust) the models on which they build their safety cases, but only a very few.

Stakeholders, Monitoring and Confidence

Based on a review of literature on citizen and stakeholder engagement with monitoring examples from the nuclear sector and from other contexts, often related to *environmental* monitoring, the project reported positive effects for stakeholders, typically local citizens and community organisations, and for their relationships with experts, regulators and decision makers, . Reported outcomes include increased confidence in programmes, operators, regulators and scientific experts, and the added value of enhanced social capital and community capacities, although not all of these could be shown to have resulted in all contexts.

The prevailing paradigm for geological disposal today is one of continuous vigilance. The societal question of how much vigilance is enough and how should it be organised is a societal question that cannot be answered from a technical-expert perspective alone. Lay stakeholder views on what monitoring can and should contribute to long-term safety of a repository are likely to differ to those of experts, due to fundamentally different views on what it means to stay vigilant and for how long, and less confidence that it is possible to ensure (safe) long term repository behaviour. These doubts arise for many reasons, but are at least partially based on known cases of institutional and technological failure. Another reason is the concern that some risk will remain due to the impossibility of foreseeing all contingencies; yet expert statements on repository safety that do not acknowledge such uncertainties may not be perceived as trustworthy.

It may be easier for social actors to commit to the successive stages of concept development, siting, licensing, construction and operation, if the provisional nature of their trust is acknowledged and there is at each stage the opportunity to evaluate and reconsider their commitment.

Monitoring can also help to demonstrate that the operator of the disposal programme is aware that there are uncertainties involved and is willing to take appropriate precautions. By introducing the notion of retrievability or reversibility into law, however, some countries are already moving towards an adapted sociotechnical solution: one that still relies on achieving passive safety, but which recognises that this end point may be further away than initially planned and, subject to future societal decisions, may not be final.

Monitoring technologies: feasibility and limitations

The third axis of the project is technology, with contributions from the project partners through:

- a presentation of the state of the art in monitoring techniques
- Technological demonstrators built and operated in situ
  RTD centered on wireless transmissions and networks, non-intrusive techniques and fiber optics

Reporting on **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 a realistic description of what and how monitoring can be implemented and an informed discussion on current, technical limitations. Based on the latter, the implementer can further recommend where future R&D would be most beneficial and where only alternative implementation approaches can provide some monitoring information (e.g. from comparable long-term experiments instead of in-situ monitoring).

Emphasis 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.

The SotA description is a synthesis of the existing knowledge on applicable monitoring technologies based on two main sources: namely the applicable knowledge and experiences provided by the project partners, and the results of the Troyes Monitoring Technologies Workshop, 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 infrastructure
- Gas storage
- Hydrocarbon exploration
- CO2 sequestration and storage

The technical requirements for the monitoring of a repository are 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 proposed, including a preliminary list of parameters of interest for repository monitoring programs. Parameters identified are:

- 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

However, this list cannot be considered definitive at this stage. The applicable monitoring technologies have been structured in the following sections:

- Repository-based monitoring
- Borehole-based monitoring
- Surface-based moitoring and
- Remote sensing monitoring systems

There are different approaches **repository-based monitoring**. 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.

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 (however in this case, applicability of results to disposal cells must be demonstrated)

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.

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.

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. 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, or time-lapse 3D, in which surveys are undertaken in 3D modes and repeated over time. The current standard application of 4D technology is he monitoring of fluid movements in thick sandstone sequences in marine environments. Other techniques considered for monitoring include seismic refraction surveys, gravity surveys, acoustic emission and microseismic magnetic and electro-magnetic methods, ground-penetrating radar, soil-surveying and GPS measurements and surface leveling.

Remote monitoring makes use of 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. The techniques will acquire information on both the physical layout and the physical properties of the location being surveyed, with a possibility of repeating the measurement to detect changes (interferograms), such as terrain elevation changes. Resolution and surface of area covered vary considerably between methods, which can use acquisition platforms such as aircrafts (manned or not), balloons, satellites

Research and Technology Developments (RTD) on selected topics was carried out by the project teams. Main axis for research is the wireless transmission of data and networking, and power sources for sensors, in both cases to avoid the use of connecting wires and related sealing issues, as are developing capabilities for measurements in a deep geological repository construction and operation environments, including fiber optics scattering, and improving processing seismic resolution.

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

The four **demonstrators** developed and implemented for MoDeRn project are:

- Testing and Evaluation of Monitoring Systems (TEM), undertaken at the Grimsel Test Site (GTS) Underground Rock Laboratory (URL) in Switzerland, to demonstrate the feasibility and to develop an effective strategy to employ full-waveform inversion as a monitoring tool in the closure stage of an individual disposal cell.
- Application of ZigBee monitoring technology in the GTS URL, aimed at demonstrating the potential of using wireless sensor and transmission networks underground, part of which would be immersed in solid material (buffer, concrete, rock, etc), and to manage corresponding energy needs for inaccessible immersed network sensors (nodes).
- Monitoring of the PRACLAY large-scale heating experiment in the HADES URL in Belgium, using:
    - microseismic measurements, to improve the treatment of signals to gain an understanding of (1) the evolution around the gallery due to excavation/lining and heating and (2) imaging of a water-bearing concretion layer,
    - Fiber-optic based sensing techniques; in particular distributed sensing for minimal cable-feed through, long-term reliability in harsh conditionsand extensometry,
    - additionally, the wireless data transmission from the HADES URL to the surface was tested, in particular (1) proof-of-principle for magneto-inductive data transmission and verification of the used models, (2) optimizing of energy usage and (3) demonstration of bidirectional data transmission
- Integrated monitoring of a disposal cell demonstrator in the Bure URL in France. The overarching objective is to evaluate the feasibility of hydro-mechanical monitoring. With experiments were designed to evaluate the instrumentation 1) placed on the inside of the cell liner and in the void space between liner and rock to monitor hygrometric evolutions, 2) located the near field to identify coupled hydro-mechanical near field response to cell construction and to monitor near field hydraulic pressure evolution as the near field tends to a new equilibrium and 3) in the cell liner to evaluate the potential of robust sensor and wiring emplacement and to detect and monitor mechanical deformations in response to the progressive liner loading by the host rock.

Conclusion

The results of the tasks performed are providing a basis for a a 'roadmap for repository monitoring', and aim at providing a shared international view on how monitoring programs may be developed to respond to specific national needs at the various steps in the disposal process. A better understanding of the role of monitoring contribution to verify safety and pre-closure management, and of its contribution to confidence in the disposal process
A website (www.modern-fp7.eu) provides updated information about progress as well as access to relevant publications.
Statements on monitoring should remain cautious and realistic regarding the added value it is expected to deliver to aid decision-making and the success of the disposal process, as a certain number of limitations of monitoring can be recognized. This should be understood as a recommendation both to pursue efforts in reducing such limitations, to evaluating whether or not they are acceptable, and most of all to provide transparent communication on them. These limitations are primarily related to five considerations:

- Monitoring is limited in time, and even in a very favourable monitoring environment where in-situ data may be obtained over a timescale spanning a century, some natural evolutions operate on substantially higher timescales and will not be detectable;
- Monitoring is limited in space, as practical considerations of disposal process management may constrain their application to limit any undue interference of monitoring activities with operations and partial closure on all repository components;
- Monitoring is constrained by the requirement to preserve favourable properties for long term safety and monitoring activities cannot reduce the expected performances of the natural environment or of the engineered barriers;
- Monitoring is constrained by local environmental conditions and monitoring systems must be designed for durable operations under possibly harsh conditions, e.g. within the waste disposal unit;
- Monitoring is constrained by available technology and certain specific parameters may not be directly accessible for in-situ monitoring.

For all of these, it is important to achieve a balance between the added value monitoring can bring to a transparent and informed management of the disposal process, and the potential risk to operational activities and to long term safety.

In-situ monitoring over a century scale provides an unprecedented opportunity to observe engineered barrier and natural environment evolutions; confirmatory activity related to very slow, long term evolutions may be conducted successfully using indirect means, e.g. by confirming that key intrinsic properties (e.g. geochemical conditions) are consistent with baseline data and/or that local environmental properties are consistent with model assumptions.

A thorough understanding of the natural environment and quality control of produced and constructed engineered barriers, combined with adapted in-situ monitoring implementation strategies, can provide an adequate basis to confirm representativity of monitoring results.

Monitoring implementation strategies can be developed to provide both required in-situ data and preserve required barrier performances, if necessary by including wireless transmission systems, by providing for a partial dismantling of monitoring systems, or by allowing for waste retrieval of a monitored disposal unit whose performances can no longer be guaranteed.

Monitoring in comparable environmental conditions of high temperature, pressure and water content has been conducted in URLs and available experience combined with a dedicated R&D program allow further enhancing durability of available monitoring equipment.

Implementation strategies may provide for long term, in-situ representative testing in a dedicated environment made accessible for sampling after several decades of evolution to compensate for the lack of technological ability for direct sensor-based in-situ monitoring, and an ongoing technology R&D program may enhance the ability for direct monitoring of certain parameters.

Acknowledgements

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References

[1] Andra 1998. In: Proceedings of an International Workshop on Reversibility: Scientific and technical bases for the reversibility of geological disposal, Paris, November 25-27 1998.

[2] FOE 2000. Disposal Concepts for Radioactive Waste – Final EKRA Report. Federal Office of Energy, www.bfe.admin.ch.

[3] SKB 2004. Monitoring during the Stepwise Implementation of the Swedish Deep Repository for Spent Fuel. SKB Report R-04-13.

[4] NWMO 2005. Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel (Final Study). NWMO Report. www.nwmo.ca.

[5] Loi n°2006-739. Loi de programme n° 2006-739 du 28 juin 2006 relative à la gestion durable des matières et déchets radioactifs, France.

[6] Andra 2009. Options de réversibilité du stockage en formation géologique profonde. Andra report n° C.NT.AHVL.09.0005.

[7] Aparicio, L. (Ed.) 2010. Making nuclear waste governable: Deep underground disposal and the challenge of reversibility. Springer. Andra.

[8] OECD/NEA 2010. Reversibility and Retrievability (R&R) for the Deep Disposal of High-Level Radioactive Waste and Spent Fuel – Intermediate Findings and Discussion Documents of the OECD/NEA R&R Project (NEA/RWM/PROV).

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

[10] EC-Thematic Network 2004. Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste. European Commission Project Report EUR 21025, EC, Luxembourg.

[11] IAEA 2011. Monitoring and Surveillance. IAEA Safety Standards for Protecting People and the Environment. Safety Guide No. DS 357 – Draft submitted to Member States. IAEA, Vienna.

[12] MoDeRn 2011a. National Monitoring Contexts Summary Report. MoDeRn project report, www.modern-fp7.eu.

[13] MoDeRn 2011b. National Monitoring Contexts Country Annexes Report. MoDeRn project report, www.modern-fp7.eu.

[14] ENSI 2009. Spezifische Auslegungsgrundsätze für geologische Tiefenlager und Anforderungen an den Sicherheitsnachweis. Richtlinie für die schweizerischen Kernanlagen ENSI-G03. Eidgenössisches Nuklearsicherheitsinspektorat (ENSI), Villigen, Switzerland.

[15] ASN 2008. Guide de sûreté relatif au stockage définitif des déchets radioactifs en formation géologique profonde. Autorité de Sûreté Nucléaire (ASN), France.

[16] MoDeRn 2010a. Technical Requirements Report. MoDeRn project report, www.modern-fp7.eu.

C.2 Session S2: Theme 1: Monitoring – Implementers' perspectives: Programmes and case studies on repository monitoring

MoDeRn – Case Studies

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Summary
In this paper, generic disposal concept in rock salt (Germany) and clay (France) are used as an example to discuss the design of a repository monitoring system. The approach used is based on a generic structured approach to monitoring – the MoDeRn Monitoring Workflow – which is being developed and tested as part of the MoDeRn project. As a first step in the study, the requirements on the monitoring program were identified through consideration of the national context, including regulatory guidelines, host rock properties and waste to be disposed of. The safety concept identified the key safety components, each of them having specific associated safety functions. The safety functions can be related to the list of processes related to the future repository evolution. By screening this list, all processes that potentially can affect the safety functions have been identified. In a next step the parameters that would be affected by the individual processes were determined, leading to a preliminary list of parameters to be monitored. By evaluating available techniques and monitoring equipment, this preliminary list was investigated with respect to its technical feasibility at the intended locations. Prior to final system selection, potential impacts of the monitoring system on safety or other measurements are evaluated. To avoid potential pathways for fluids that may compromise the integrity of a barrier, considerations on the application of wireless data transmission systems and techniques for autonomous, long-term power supply were given.

Introduction

Monitoring involves continuous or periodic observations of parameters to help evaluate the behaviour of the disposal system. Preliminary guidance on monitoring, in particular the high-level

Within the MoDeRn project, a structured approach – the *MoDeRn* Monitoring Workflow - was elaborated to provide a generic methodology for the development and implementation of a monitoring programme that takes into account specific national boundary conditions [1]. The workflow allows the linking of high-level monitoring objectives to the detailed selection of monitoring technologies and sensor placements. The MoDeRn Monitoring Workflow is illustrated in Figure 1, and contains the following steps:

- Objectives, processes and parameters: In the first step in the *MoDeRn* Monitoring Workflow, the objectives for the monitoring program to be developed are identified and, through analysis of the disposal program assessments and safety case, processes to monitor are identified and linked to a preliminary list of monitoring parameters

- Parameter screening: In the second step in the *MoDeRn* Monitoring Workflow, the preliminary parameter list, monitoring locations are selected and the parameter list is screened for technical feasibility, considering the specific technical requirements for the monitoring of each process. Research and development may be undertaken to feed into the technical feasibility of monitoring specific processes.
- Monitoring programme design: In the third step in the *MoDeRn* Monitoring Workflow, the monitoring programme design is specified to a level of detail that monitoring can be undertaken. The design of the monitoring programme would consider: (i) management of uncertainty in the performance of the monitoring techniques, (ii) defining data management approaches, (iii) defining data analysis and interpretation methods, (iv) specifying performance measures and trigger levels for the monitoring programme, including agreement on response plans to be undertaken should data exceed trigger levels, (v) integration of the repository monitoring programme with other monitoring programmes that might be collecting data of relevance (e.g. national groundwater quality monitoring programmes).
- Monitoring programme implementation: In the fourth step in the *MoDeRn* Monitoring Workflow, monitoring is conducted and the results are used to support decision making within the wider repository programme. Monitoring may be used to support a decision to move to the next stage of the repository programme (e.g. to submit a licence application, and to close the repository), and will also feed into updates to the implementation process, such as changes to the design and changes to the monitoring programme.

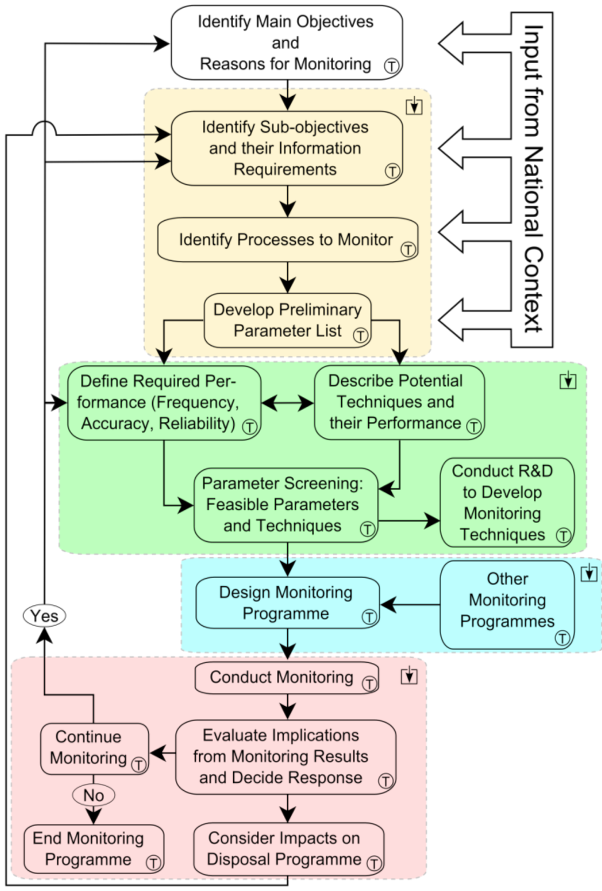
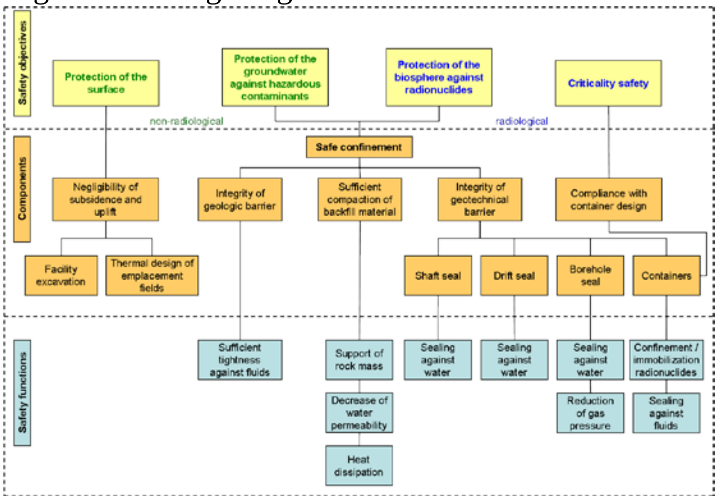


Fig. 1: The MoDeRn Monitoring Workflow

In the case study, modular-based principle monitoring systems for a repository in salt (German concept), clay (French concept) and granite (Swedish/Finish concept) are discussed based on the approach provided by the *MoDeRn* Monitoring Workflow. The first two cases are addressed in this paper.

1. Identification of parameters relevant to monitoring

In the ***German concept (case 1)*** the safety objectives are considered within part of the safety assessment and can be related to three safety components named: "safe confinement", the "negligibility of subsidence and uplift" and the "compliance with the container design". Figure 2 shows the safety objectives and their relation to the safety components. Each of the three can be subdivided into several safety components, e.g. the core element "safe confinement" comprises the components "integrity of the geologic barrier", "sufficient compaction of the backfill material", and "integrity of the geotechnical barrier". The latter can be attributed to the individual engineered barriers shaft seal, drift seal, borehole seal, and containers. The safety functions allocated to the individual barriers are listed as well. In addition to a decrease in water permeability (hydraulic), support of the rock mass (mechanical) and dissipation of the container heat (thermal) have to be provided for by the engineered and geological barriers.



When based on the safety functions that can attributed to the individual components, monitoring can support the safety strategy of a disposal concept by providing meaningful data acquired under full-scale in-situ conditions. To do so, the *MoDeRn* Monitoring Workflow foresees in a first step to identify the parameters suitable to demonstrate compliance with the safety functions.

Fig. 2: Relationship between safety objectives, safety assessment components, and safety functions for the salt rock HLW disposal concept

The safety functions of the assessment components given in Figure 2 can be related to physical and chemical processes taking place in a repository. These processes are described in a site-specific catalogue of features, events and processes (FEPs) [2]. The FEP catalogue can be used to identify those processes that could significantly affect the safety functions of a component. In order to be able to define a proper monitoring strategy for a process identified by this method, the parameters relevant for the process need to be identified. When performing this analysis for each of the safety functions in Figure 2, a list of all parameters relevant to monitoring can be generated (a more detailed description of the identification process can be found in [3]).

In the ***French concept (case 2)*** there are three overarching safety functions:

SF1: *Counter water circulation*. This function aims at limiting the transfer vector “water” eventually responsible for the dissolution and transfer of radionuclides.

SF2: *Limit radionuclide release and immobilize them in the repository*. This function aims at limiting the source term of eventual radionuclide migration in the given hydraulic conditions that is waste form dissolution, the released radionuclide solubility and their potential mobility.

SF3: *Delay and reduce concentration of radionuclide migration outside of disposal cells*. This function considers requirements that may contribute to delay and reduce ensuing radionuclide migration (based on repository design, siting and host rock properties).

Each of the three major functions and associated requirements to preserve favourable properties relies (Figure 3) on a combination of such favourable site properties, engineered barrier performances, the adequate management of thermal, mechanical or chemical perturbations, and overall siting and layout features.

SF	Contributing Feature/Component	Preserve favorable…	Feature/Component to preserve …
SF-1 Transport vector	Host formation (monitor?) Layout (verify)	Repository scale permeability	Thermal management (monitor) Ratio of excavated rock (verify) Backfill (monitor?) Residual voids in cells (verify) Self-healing (monitor?)
	Seals (monitor)	Near-field permeability	Construction (verify) Ground support (monitor) Contact with near-field (monitor) Self-healing (monitor?)
SF-2 Source term	Thermal management (monitor) HLW disposal package (monitor) Water in cell (monitor) Chemical management (monitor?) Waste form (???)	Near-field geochemistry: Solubility, sorption	Ground support materials (verify)
SF-3 Transport	Host formation (verify?) Layout (verify) Closed infrastructure (???)	Permeability – Diffusion coeff Near-field geochemistry: Solubility, sorption Repository scale geochemistry	Cf. SF-1 Cf. SF-2 Thermal management (monitor)
	Surrounding formations (verify?)	Permeability	Borehole seal (?)

Fig. 3: Main Safety functions and their link to favorable site properties

The latter siting and layout features can be confirmed by direct confirmation (inspection…) at the outset of construction. There is no perceived need to associate further monitoring to them. Favourable site properties – note that this refers to the unperturbed site - may be subject to a confirmatory activity, which may be assimilated to a continuation of site characterization to further enhance and/or confirm said properties.
Expected engineered barrier performances, specifically those of waste disposal packages, seals and plugs, are subject to performance confirmation.
The risk of perturbations to expected host formation and engineered barrier performances is addressed through appropriate thermal, mechanical and chemical management. Note that this includes all aspects addressed under the function “preserve favourable host formation properties”. All of these are subject to monitoring in relation to the barriers expected performances. In the particular case of mechanical management, engineered support structures (mechanical support for seal, backfill, and residual voids at closure…) are used and may be subject for monitoring.

Associated monitoring considerations to SF1 will have an emphasis on the seals and as warranted their support structures and near-field. Meeting the overall layout features will be verified upon construction and this does not warrant further monitoring.
Associated monitoring considerations to SF2 will have an emphasis on the thermal management and water tightness of HLW disposal packages. The possible monitoring of parameters characterizing the chemical environment needs to be further evaluated, given that chemical equilibrium influencing dissolution and release may not be reached until a distant future. Imported complexion agents, e.g. as waste by-products, are identified prior to emplacement and this does not warrant further monitoring.
With regard to SF3 the specific transport conditions from disposal cell to access shafts/ramps are currently being addressed in relation to seal performances.

2. Monitoring locations and feasibility screening

As a next step, locations for the monitoring devices need to be identified. Furthermore, suitable monitoring techniques and equipment have to be selected. For the general placement strategy, it is assumed that it is advantageous to implement monitoring systems in one representative emplacement field and not scattered over the entire repository. In [4], the use of a pilot facility is considered to be a possibility to monitor relevant parameters in a representative environment and – at the same time – to gain insight into the behaviour of the waste emplaced without compromising the operation of the actual repository. Following this line of reasoning, in this case study the monitoring activities are envisaged only for one part of the generic disposal facility, the so-called field “East 1” (Figure 4). East 1 is selected, because it will be the first to be filled with waste containers and which will be backfilled and sealed. While emplacement continues in the other emplacement fields, it would be possible to gather data from this representative, sealed “monitoring field”. Thus, the evolution of an entire field could be monitored during the operating phase of the repository.

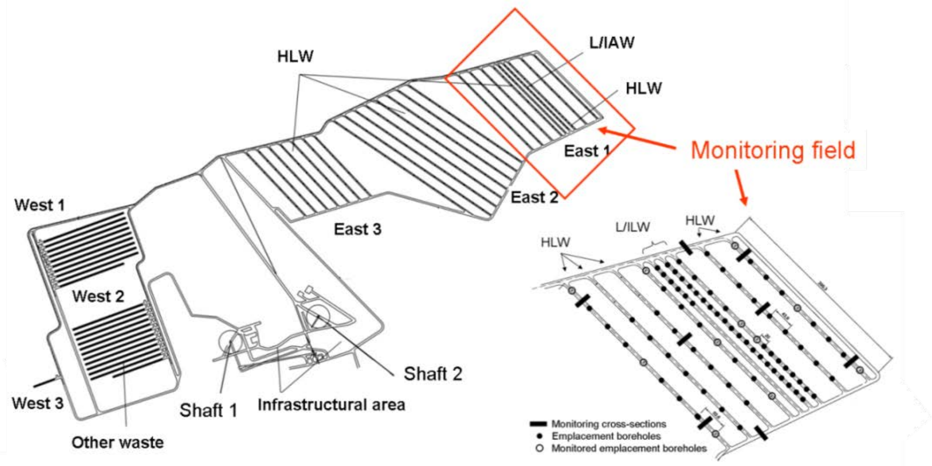


Fig. 4: Draft of the emplacement fields for the vertical borehole disposal option. Status: January 2011.This draft was prepared within the scope of the Preliminary Safety Analysis Gorleben (VSG) and will be further refined as the VSG continues [5] (slightly modified).

Figure 4 (right) shows an enlargement of field East 1. This field is designed for high-level waste (HLW) as well as low-level waste (LLW) and intermediate-level waste (ILW). The black dots indicate emplacement boreholes. The emplacement boreholes indicated with a circle are selected in this study as potential locations for monitoring. These boreholes are either located in the centre of the field so that they are exposed to the highest possible heat development or in the edge of the field so that they are exposed to the highest inhomogeneities of the thermo-mechanical development of the monitoring field.

The exact placement of monitoring equipment within the limited space of the emplacement boreholes is a relevant question. As discussed above, the placement of monitoring equipment within a seal is not considered, because this could potentially impair the safety function of the seal. Instead, the placement of monitoring equipment, including power supply, data acquisition systems and sensors, in a dummy canister at the top of an emplacement borehole is foreseen, directly below the borehole seal (Figure 5). Equipped with sensors on the outside of the canister to measure temperature, moisture, pore pressure, and total pressure, this canister would monitor the conditions at the bottom of the borehole seal. As the gap between the canister and the borehole wall is only a few millimetres, any fluid flows through the seal would be detected, especially if several sensors will be placed on the circumference of the canister. The monitoring data will be transmitted via wireless transmission system (see next section) to the borehole cellar at the top of the borehole (Figure 5). The borehole cellar is used to store the power supply, data recording, and transmitting devices. In the current disposal concept, there are no special requirements on the backfilling of the borehole cellar, so this may be a suitable site for placing monitoring equipment. There will be a need, however, to demonstrate that degradation of the monitoring equipment in the long-term will not affect long-term safety. Additional sensors can be placed at the interface between borehole cellar and borehole plug.

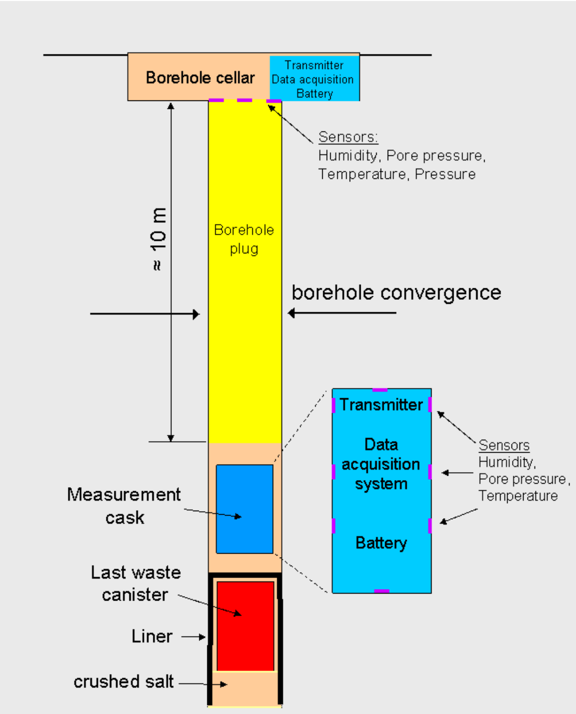
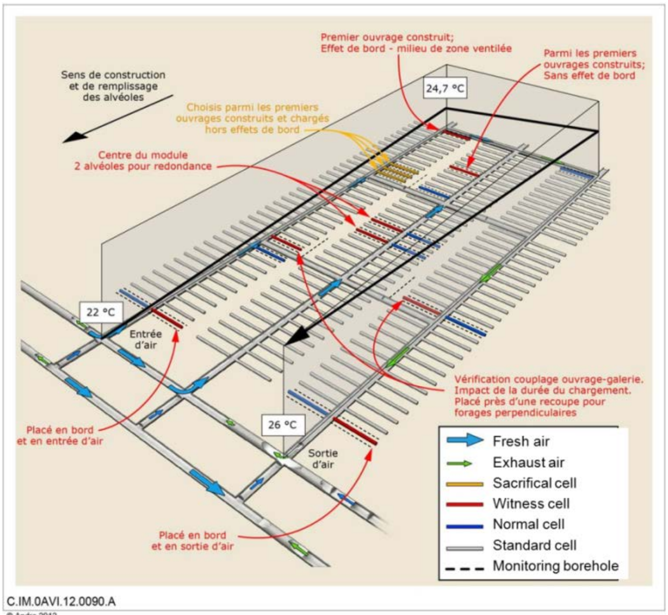


Fig. 5: Schematic diagram for monitoring the borehole seal

Drift and shaft sealing components can be monitored in a similar way, with sensors embedded at both ends of the plug but not within the sealing components. In addition, three monitoring modules in form of monitoring cross-sections will be installed in different distances from the plug on both of its sides. These cross-section modules are intended to demonstrate that no brine moves through the barrier and to measure the crushed salt compaction process in the drift. Furthermore, these cross-section modules can be equipped to measure humidity, pore pressure, compaction pressure and rock displacement. Modules to monitor the geomechanical behaviour of the host rock and the crushed salt due to the increase of temperature can be placed in the monitoring field as well in order to compare the rock behaviour in the monitoring field with that next to the sealing constructions.

A feasibility screening for the example case yields that most of the parameters identified to characterize safety-relevant processes can be measured with monitoring equipment currently commercially available [3]. Some parameters have been screened out because placing of monitoring equipment may impair important barrier functions. For instance, measuring the radial rock displacement is not a technical problem, but an emplacement borehole at the location of the plug it is not allowed because no holes should be drilled into the host rock at barrier locations. However, as discussed in the next section, one of the main challenges for setting up a monitoring programme is not on the level of sensors or data acquisition systems but on the ability to transmit the monitoring data wirelessly and to provide an autonomous power supply for the monitoring equipment for several decades. Thus, part of the feasibility screening is to investigate the possibilities of data transmission and power supply and will be discussed in the next sections.



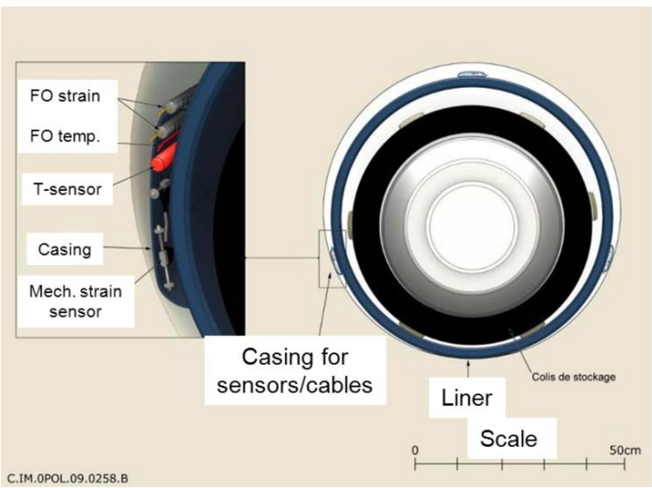
In the French case (case 2), on the scale of the HLW disposal unit, the monitoring strategy must meet the following objectives: (i) Checking the interaction between the storage cells and the access galleries, linked in particular to the gradual loading of the module, and its consequences on interactions with the access galleries, linked to the ventilation flow, (ii) checking the effects of waiting time between the construction of a cell and its loading (between 1 and 10 years) on changes in processes H, M and H-M from one cell to another, (iii) checking the peripheral effect linked to the presence or otherwise of neighboring cells (cells side-by-side or end-to-end).

Given these three main objectives, the monitoring strategy anticipates the integration of an initial module constructed from witness cells distributed respectively (i) in the core of the module and at its edge (ii) along the length of the access gallery (in an air intake and an air return) and (iii) along the module (first cells loaded against the last cells loaded). With some witness cells able to meet both objectives (Fig 6), a pooling of resources had made it possible to restrict the number to 9 witness cells (out of approximately 200 in the case of the Andra 2009 architecture) within the initial waste disposal module.

Fig. 6: Emplacement module and monitoring cells

This is not a definitive figure and will be amended over time as containers arrive, and adapted to the storage and operational design choices. Cell instrumentation would be supplemented by observation and monitoring in the galleries. For example, an optical fiber providing distributed temperature measurements would contribute to monitor gallery ventilation, and the expected 4°C temperature increase along access gallery (depending on ventilation direction). Concrete liner monitoring is also planned.

In each of the monitoring cells show in Figure 6 liner monitoring plays an important role. Monitoring the liner in addition to the boreholes and the in-cell environment through the radiological plug would enhance the design of the overall monitoring system by providing further information on relevant evolutions. In particular, the progressive loading of the liner can be characterized in this way, which is also indicative for mechanical changes in the rock. It also allows verifying the prior assessment basis for the design of the liner, i.e. that loading is homogeneous, thus precluding the risk of buckling. This is also part of the assessment basis for long-term safety, as waste disposal packages must remain intact during the exothermic period.
Temperature monitoring is planned (Figure 7) to contribute to verifying the assessment basis for long term safety, by allowing verifying whether prior predictions for the duration of the thermal period and the expected thermal peaks are consistent with monitoring results - as well as verifying the conditions to be expected in the event of waste retrieval.



Feasibility of such instrumentation is a major challenge. On the one hand, the ability of the instrumentation to withstand dose rates, which remain significant, even on the external surface of the liner, is an identified risk of degradation of the monitoring devices. On the other hand, the sensors and their cables must withstand very large stresses during liner pushing operations.
HLW demonstrator in the Andra URL showed optical fiber sensor survived

liner excavation. Such sensor is expected to detect the location of clay break-outs and progressive pressure loading on the liner.
Fig. 7: Sketch of liner instrumentation

Trade-off between robustness and sensitivity is a challenge, still under evaluation making use of the demonstrator realized in the Andra URL.

Instrumented cross-sections provide precise but local measures that would be combined with indications of overall distributions provided by distributed temperature and strain fiber optic sensors. Their purpose would be to verify the distribution of the mechanical loading and changes to it. Monitoring devices would be covered with a protective cap welded on to the liner. This technique is used in civil engineering for instrumentation in the foundation of structures with steel piles. Many technical solutions are presently being studied.

Monitoring device could also be incorporated into grooves. However, this would affect the basis for the safety assessment, which partially relies on the thickness of the liner. For this reason, installation in grooves would only be allowed within highly instrumented "sacrificial structures", a concept dedicated to monitoring even waste reversal processes. Finally, cables could be replaced by radio transmitters, if battery life were improved, especially at the expected high temperatures.

3. Data Transmission

When thinking about monitoring of processes within the underground facilities of a final repository for high-level radioactive waste, especially after its closure, an important aspect to consider is the transmission of monitoring data out of the monitoring field or up to the earth's surface.

In 2001, IAEA [4] emphasized that when developing a monitoring concept, the benefits from having dispose of monitoring data need to be balanced against potential detriments resulting from the process of monitoring. This is especially important when monitoring in the vicinity of geotechnical barriers, where installation of monitoring equipment (i.e. instruments and cables) may result in potential pathways for radionuclide migration. This leads to the requirement that all monitoring activities must be implemented in such a way that they are not detrimental to long-term safety [6]. For the generic German concept in rock salt, the following <u>principles</u> apply when implementing technical measuring and/or monitoring systems:

- *Preferably no installation of sensor systems within geotechnical barriers*
- *No cables running through the geotechnical barriers*
- *No cables running along access drifts backfilled with compacting crushed salt*
- *No cable connection from the repository to the surface*

During the past years some institutions and companies have started to develop wireless data transmission systems with the intention to send data through geotechnical barriers and host rock. Corresponding tests are currently running at different underground research laboratories [1]. In addition, a few systems exist world-wide able to send data out of underground excavations, mainly mines, to the earth's surface. In several cases, transmission distances up to 600 m have been claimed. The maximum transmission distance depends on the rock through which the signal is being transmitted and can thus only be seen as an indicative value. In case of the German generic concept, the depth level of the repository is assumed to be 870 m. It is obvious that the development of a wireless connection to the earth's surface will in that case be a challenging task.

In above ground applications wireless transmission systems containing several relays stations have successfully proven their ability to transmit monitoring data over long distances by data hopping from relay station to relay station [7]. In principle, such a system is conceivable for underground through-the-earth systems as well. Data recorded within the monitoring field would be transmitted along a chain of relay stations to the shaft and up to the surface in several stages. In a closed and sealed shaft the installation of relay stations requires a careful location of the stations between different sealing elements within the shaft.

A conceivable alternative to relay stations located in the shaft would be the use of a borehole drilled from the surface to the outer area of the repository. Such a borehole would not intersect the main host rock at the emplacement level and would be separated horizontally from the underground facilities by a distance of approximately 200-300 m. A receiver located at the repository depth within the borehole could receive data through the earth from the repository and transmit the data via cable or using wireless methods via relay stations to the earth's surface. Using this approach relay stations can be located a safe distance away from the repository and shaft. However, the safety case will need to demonstrate that there is no significant impact from risks that an open borehole is not abandoned without backfilling, or that the monitoring borehole provides a pathway for radionuclide migration.

4. Self-Sufficient power supply

In the generic disposal concept, a minimum operating period of 25 years is assumed. Furthermore, monitoring is intended to continue during an institutional control period after repository closure of 100 years. Systems for monitoring, data-acquisition and wireless data transmission in backfilled or sealed areas must therefore have a long-term self-sufficient power supply. Such a long-term self-sufficient power supply can be achieved by using radionuclide batteries [8, 9] or betavoltaic batteries [10]. Radionuclide batteries convert heat into electric current and they are autonomous, maintenance-free, and can continue to release energy for long periods of time. The performance of radionuclide batteries have been proven during several space missions (e.g. the Cassini-Huygens space probe). The durability of betavoltaic batteries depends on the half-life of the radioisotope used to provide the energy source. Betavoltaic batteries work similar to solar cells but instead of using photons they use beta particles from the radioactive decay to directly produce electrical current. Tritium-based prototypes of betavoltaic batteries have already been developed and successfully tested, whereas prototypes using nickel isotopes, which could provide a usable half-life of approximately 100 years, are still to be developed. Betavoltaic batteries are rather simple and robust and can be used in rough and high temperature environments where normal chemical batteries can hardly be used. This type of batteries is thus a promising technology to realize self-sufficient power supply of monitoring systems supposed to run over several decades.

5. Discussion

Based on both regulatory requirements as well as for reasons of public acceptance, monitoring of a geologic repository is not limited to just the operational phase but may continue after closure of the facility. There is a broad international consensus that the development of a monitoring concept for a repository particularly for the post-closure phase needs to carefully weigh the benefits obtained from collected data against potential negative impacts associated with collection of the data [4, 6, 1]. In this context the following aspect has been shown to be relevant for the case study performed:

- To ensure that the integrity of a geotechnical barrier, i.e. sealed boreholes, shafts, and drifts, does not impact the long-term safety function of the barrier, monitoring systems should not be installed within the barrier. However, this has shown not to be a relevant limitation, because it is not the barrier itself but its functional performance as a sealing system that needs to be monitored.
- The same is true for disposal canisters: for reasons of waste handling and radiological safety, monitoring systems should not be installed directly on the outer surface or integrated into the disposal canister as such installations could result in points of weakness and thus affect barrier integrity. As consequence, monitoring should be conducted through observations of the area surrounding the disposal canister.
- The establishment of a dedicated monitoring network initiated at the earliest practicable time will lead for the considered case to a monitoring period of at least 25 years. Subsequently, a post-closure monitoring period of 100 years is assumed. Because repairs or replacement of defect components is not possible during the post-closure case, system robustness is a relevant design criterion in order to meet the monitoring performance objectives. Sensors used in construction monitoring have demonstrated reliable performance over several decades: Bordes & Debreuille [11] analyzed the long-term performance of nearly 7,000 sensors over a wide range of applications. Their analysis showed that malfunctions preferentially occurred during the initial period of use with a significant decrease in failure rates over time. In other words once a sensor is properly functioning it will likely continue to function properly. Despite these reliable performance indicators for purposes of repository performance monitoring the sensors used must provide both a redundant and diversified capability to offset potential system failures to the greatest extent possible. In the case of a large borehole disposal as considered in this paper, not every borehole can be monitored, because such a system would be logistically difficult to implement and disproportionately vulnerable to potential failures. Therefore a representative subset of emplacement boreholes should be considered for performance monitoring.
- In many cases, monitoring data collected during both the operational and post-closure periods need to be transmitted using wireless systems. Although several systems exist around the world, specifically those used in mining to establish communication with trapped miners, the signal transmission ranges of the current known systems is significantly limited, especially in rock formations. Several tests are currently underway to study the transmission of such signals in Belgium, Sweden, and in Switzerland [1]. Similar studies designed to estimate the potential for success are also needed in the German case.
- Battery technologies are available that allows an autonomous power supply operating over several decades. In order to determine which battery concept is best suited for the outlined monitoring concept, the electrical power requirements for each individual component of the monitoring system needs to be determined. This requires early-on development and consideration of the monitoring concept and associated equipment requirements.
- In order to be able to collect data on the performance of repository emplacement areas in the operational and post-closure phase, appropriate monitoring systems must be installed already at the start of emplacement activities. Therefore decisions regarding post-closure monitoring must be made early-on in the development of a repository.

In conclusion, the case study has shown that monitoring of safety relevant processes in a geologic repository does not represent an insurmountable task. However there are still many technological open questions that need to be addressed.

6. Acknowledgements

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References

[1] *MoDeRn (2011)*: MoDeRn - Monitoring Developments for safe Repository operation and staged closure (www.modern-fp7.eu).

[2] *Buhmann, D., Ebert, S., Keller, S., Kreienmeyer, M., Krone, J., Mönig, J., Tholen, M., Weber, J.R., Wolf, J. (2008):* Überprüfung und Bewertung des Instrumentariums für eine sicherheitliche Bewertung von Endlagern für HAW - ISIBEL -, Abschlussbericht, FEP-Katalog, Gemeinsamer Bericht von DBE Technology, BGR und GRS, Peine.

[3] *DBE TECHNOLOGY GmbH (2011):* MoDeRn – processes and parameters, draft internal project report, DBE Technology, Peine.

[4] *IAEA (2001):* Monitoring of geological repositories for high-level radioactive waste. IAEA-TECDOC-1208. ISSN-1011-4289.

[5] *Bollingerfehr, W., Filbert, W., Lerch, Ch., Tholen, M. (2011):* Vorläufige Sicherheitsanalyse Gorleben, Endlagerkonzepte für die VSG (AP5), Berichtsentwurf Stand 31.03.2011, DBE Technology, Peine (unveröffentlicht).

[6] *EC (2004):* Thematic Network on the role of monitoring in a phased approach to geological disposal of radioactive waste – Final report, European Commission project report EUR 21025 EN.

[7] *Feltrin, G. (2010):* Data intensive long-term monitoring with wireless sensor networks, Monitoring Technologies Workshop, Université de technologie de Troyes (UTT), France, 7-8 June.

[8] *Bennett, G.L. et al. (2008):* The general purpose heat source radioisotope thermoelektric generator : a truly general-purpose space RTG, Space Technology and Applications Internationale Forum – STAIF, American Institute of Physics 978-0-7354-0486-1.

[9] *Böttner, H., Nurnus, J., Schubert, A., Volkert, F. (2008):* New high density micro structured thermogenerators for stand-alone sensor systems.

[10] *Olsen, L.C. (1994):* Review of betavoltaic energy conversion, Washington State University, Richland, USA.

[11] *Bordes, J.L., & P.J. Debreuille (1985):* Some facts about longterm reliability of vibrating-wire instruments Transportation Research Record. No. 1004: 20-26.

Confirmation Monitoring of Repositories in the United States

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Summary
The United States has unique experience developing and implementing confirmation monitoring programs for nuclear waste repositories. This extensive experience provides wide exposure regarding why, what and when to monitor as portrayed in two accomplished programs. These comprehensive case studies include the Waste Isolation Pilot Plant or WIPP, a repository for transuranic defense waste in a bedded salt formation, and the Yucca Mountain Project, a repository situated in volcanic terrain for civilian spent nuclear fuel and high-level waste. Along with the significantly different disposal missions, the breadth of repository monitoring experience includes two different regulatory frameworks and reflects a maturation process as confirmation monitoring evolved.

Conducting science and developing a highly regulated facility necessitates an awareness of design, licensing, construction, and operations, as well as external influences. The long-term strategy must continue to support the licensing basis effectively, societal input, a responsive performance confirmation program, and appropriately scoped elective scientific investigations. A long-term testing and monitoring strategy for repository science will continue for the life of the repository project as an integral part of the licensing processes consistent with statutory and regulatory constraints. Elements of the science program that are directly incorporated into a license application and demonstrative of the safety case, such as performance monitoring, are a critical part of the broader science program.

The Environmental Protection Agency (EPA) standards for the WIPP included radioactive containment requirements that were to be demonstrated through performance assessment (PA) and multiple assurance measures that were intended to add confidence that the repository would perform as predicted. Compliance monitoring was included as one of these assurance measures to detect deviations from expected performance. The EPA also required analyses of the effects of disposal system parameters on the containment of waste in the disposal system to be used to develop pre- and post-closure monitoring plans. A parameter was considered significant if it affected the system's ability to contain waste or the ability to verify predictions about the future performance of the disposal system, which is the basic premise of compliance monitoring parameters at WIPP. The Department of Energy (DOE) analyzed disposal system parameters that were developed from the PA as well as a list of parameters provided by the EPA against their importance to disposal system performance or to radioactive waste containment. The WIPP experience included performance evaluations during the site-characterization phase, which helped focus experimental activities toward repository performance and public assurance considerations. The monitoring program has been acceptably and fully functioning since WIPP operations started in 1999, including discovery and reconciliation of conditions that were outside the parameter range used for modeling. The WIPP confirmation monitoring program has

served to increase public confidence through a better understanding of the disposal system [1].

The approach that ultimately identified testing and monitoring activities for the Yucca Mountain repository license application used risk information to focus attention on issues important to public health and safety. The far-reaching process involved with development of the safety case provided opportunity to approach confirmation activities as they evaluate information used as input to models, or evaluate whether observed behavior is consistent with expected or modeled performance. The enduring testing and monitoring program was reviewed, evaluated, and updated as needed to reflect new technical, programmatic, and regulatory information and maintain consistency with the licensing documents. Development of the performance confirmation process and its accomplishments over the life of the Yucca Mountain project provides an informative case study that contrasts with the WIPP experience. The license application submitted in 2008 contained an updated total system PA, which included the latest assumptions and technical information available. The safety case as supported in the performance calculations identified influential parameters for potential monitoring. Thus, the performance confirmation plan included in the license application submitted to the regulatory authority for construction authorization related elements within the plan to the regulatory requirements. The monitoring activities and specific parameters were checked by statistical techniques to evaluate their influence on post-closure performance of the natural and engineered barriers. Assurances were made to provide a breadth of investigations sufficient to evaluate the performance basis of the license application and to provide for continued evaluations into the future [2].

1. Introduction

Repository performance confirmation links the technical foundation of repository science and societal acceptance. Among the countless aspects of monitoring, performance confirmation holds a special place, involving distinct activities combining technical and social significance in radioactive waste management. International interest in repository monitoring is exhibited by the European Commission Seventh Framework Programme "Monitoring Developments for Safe Repository Operation and Staged Closure" (MoDeRn) Project [3]. The MoDeRn partners considered the role of monitoring in a phased approach to the geological disposal of radioactive waste. Sandia is a member of the MoDeRn team and draws upon its experience in helping to develop a common framework. As repository plans advance in different countries, the need to deliberate upon monitoring strategies within a controlled framework has become more apparent. The MoDeRn project pulled together technical and societal experts to assimilate a common understanding of processes that could be followed to develop a monitoring program. Experience from two repository programs in the United States sheds light on how performance confirmation has been executed. Lessons learned can help the next generation of performance confirmation.

A testing and monitoring program develops along with other maturing components of a repository science program. Upon licensing, performance confirmation objectives become de facto monitoring requirements because parameters are expected to be predicated on the most influential elements of the safety assessment. Performance confirmation testing and monitoring are conducted to evaluate the adequacy of assumptions, data, and analyses that led to the findings that permitted construction of the repository and subsequent emplacement of the wastes. Two key aspects of a successful program are: (1) selection of the parameters to be measured or monitored, and (2) determination of the conditions for which the regulatory authority would be notified regarding measured and monitored information that differs from the technical baseline. Performance confirmation is a binding commitment to the regulator that is accomplished in the licensing process.

2. Development, Implementation and Evaluation

A hierarchy for developing a performance confirmation program is sketched in **Error! Reference source not found.**, which describes similar strategies developed in Belgium and the USA [4]. At the highest level, national statutory and regulatory framework governs strategic choices. The high-level policies are often called boundary conditions, as reflected in **Error! Reference source not found.**. Strategic choices for each country context would include the geologic formation, the waste inventory and the concept of disposal. After the requirements are established, the methods of implementation, evaluation and feedback are defined at increasing levels of detail. The figure illustrates how requirements were evaluated and implemented for performance confirmation of Yucca Mountain in the United States. In **Error! Reference source not found.**, the assessment basis that might be used in other repository programs may involve similar processes as applied in the Yucca Mountain assessments shown in the lower right as feeding back into the requirements.

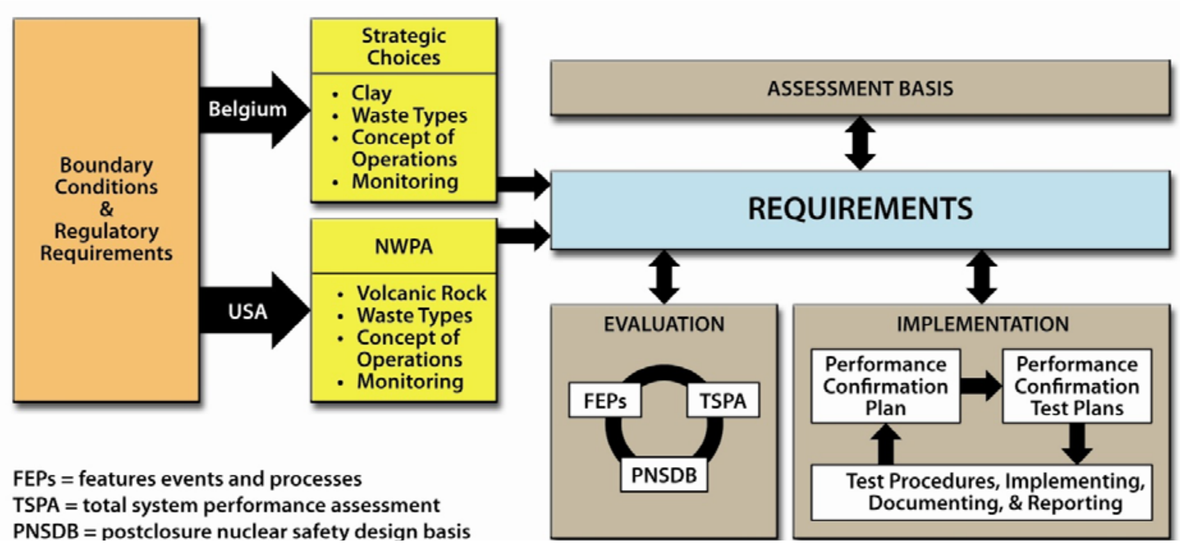

Figure 0-1: Summary flowchart of key steps in developing and using a monitoring program

Confirmation parameters for any repository program will involve appreciable technical input, which must be objectively justified. Test parameters to be monitored or measured for performance confirmation are derived from sources such as those illustrated in **Error! Reference source not found.**. Note these parameter sources are the same as those used for the technical assessment and evaluation illustrated in Figure 1. In **Error! Reference source not found.**, the PA sequence shown on the left-hand side identifies many of the most important parameters influencing risk and dose. Similarly, the design basis for post-closure safety as shown on the right-hand side identifies parameters and characteristics of features and components important to barrier capability. If it is possible to test or monitor these quantities, they could become candidates for inclusion in the confirmation program. Candidate

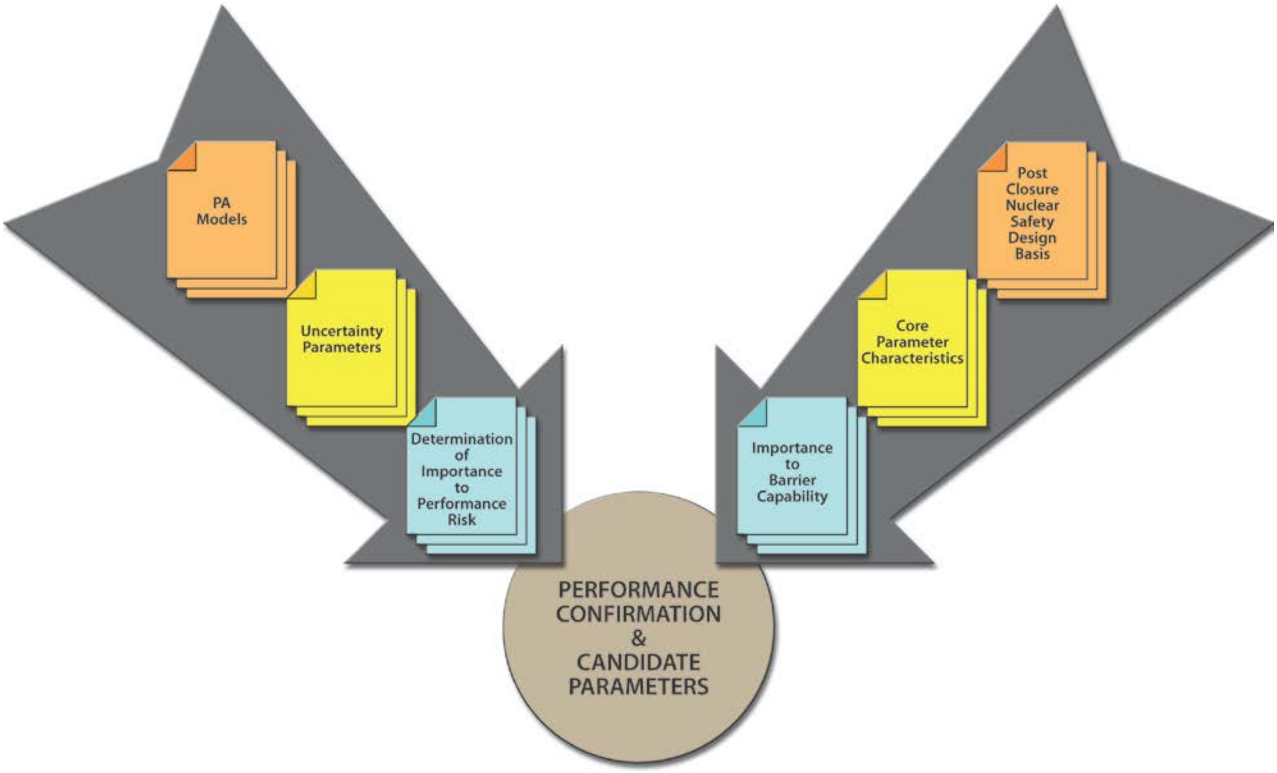

Figure 0-2: Sources used to identify performance confirmation parameters

The Electric Power Research Institute [5] outlined an eight-stage approach for performance confirmation, which relies on the selection of parameters subject to testing based on their sensitivity to repository performance. It is imperative to recognize the enormous amount of work that must be completed before parameters are selected for performance confirmation activities. Along with parameter selection are data quality objectives, trigger values, and objective justification, which are taken up as part of implementation and evaluation.

Implementation of performance confirmation activities is an iterative process of test plan development, deployment, acquisition of data, evaluation of the data relative to the licensing arguments and then using results to guide further activities. The overall testing and monitoring program is expected to develop jointly with stages of repository advancement and refinement of the understanding of the repository system.

Performance confirmation testing and monitoring are implemented using a specific test plan, which is usually initiated and justified by a principal investigator, who works for the implementing organization (licensee). Based on the safety case, the principal investigator(s) will establish parameters, data quality objectives, and ranges for confirmation testing and monitoring. The diagram shown in **Error! Reference source not found.** incorporates the eight steps identified by EPRI [5] in the implementation process. **Error! Reference source not found.** further illustrates the iterative assessment process associated with performance confirmation implementation. Individual test plans are developed, reviewed, authorized, and implemented. These requirements are then translated into a structured set of testing and monitoring needs that address long-term repository performance and support the decision-making process. Detailed requirements for individual monitoring or testing activities describe the parameter’s importance to barrier capability, specify an acceptable (expected) parameter range, and describe the procedure and actions required for handling results outside of the expected range.

Performance confirmation programs are developed and implemented under the provisions of strict quality assurance requirements. Specific requirements for testing and data management are developed in monitoring test plans and implementing procedures. These test plans contain sufficient detail to conduct the test, as well as describe applicable functional and test-specific requirements. Approved plans provide the primary means to reach a documented consensus on all aspects of a test or experiment, including design, cost, schedule, interface controls, and data management. These plans are used for review and documentation of the test effort and serve as an agreement between the principal investigator, the test implementing organization, and the authorizing management.

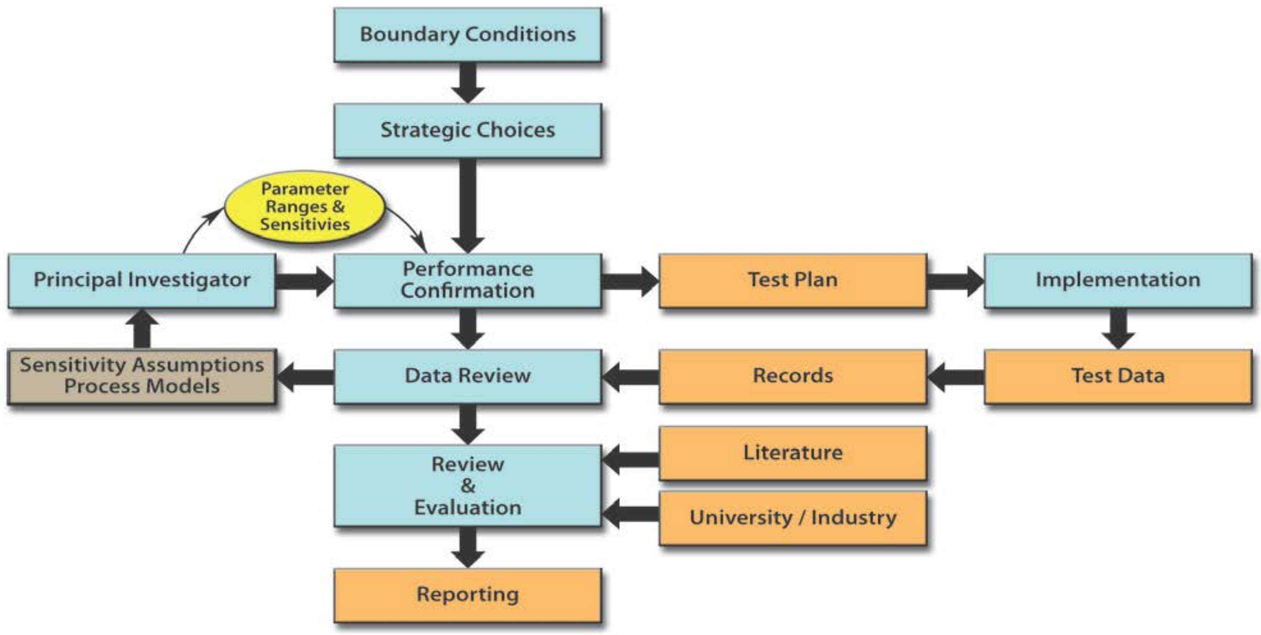

Figure 0-3: Implementation of a performance confirmation program

Enhancing the technical baseline by testing and monitoring can confirm or challenge assumptions made in performance predictions supporting the licensing submittal. Results that call into question the adequacy of assumptions, data, or analyses in the baseline information will initiate additional examination and evaluation. The repository program must adapt to inevitable changes, which are anticipated from technical advances, possible design alternatives, or similar circumstances. An evaluation of changes with respect to the post-closure technical performance is a recognized part of change control management. The testing and monitoring program includes a process to reevaluate, reexamine, and modify activities in a flexible and responsive manner.

3. Performance Confirmation for the Waste Isolation Pilot

The WIPP is a U.S. Department of Energy deep geologic repository sited in salt beds in Southeast New Mexico for the permanent disposal of defense-generated transuranic waste. Performance confirmation is an important part of the WIPP project, because it is used to analyze current conditions of the repository and its surroundings to ensure that the repository's long-term radioactive waste containment predictions are valid. The regulatory certification is related to the parameters, assumptions, conceptual and numerical models that are used to predict the potential radioactive waste containment performance of the system. The concept of performance confirmation for the WIPP is one that has evolved since the first repository work was initiated decades ago and has played an important role in assuring adequate repository performance both now and in the long-term. The WIPP mission has progressed from a pilot project to an operational disposal facility and will progress to eventual site closure when disposal operations are completed.

At the time WIPP was originally sited it was believed that site characterization and a technical performance demonstration would provide most of the answers needed and would ensure stakeholders that the repository would be safe. The U.S. Congress gave regulatory authority over the radioactive components of WIPP waste to the EPA as well as the responsibility to publish WIPP-specific certification criteria. Additionally, stakeholder and state authorities wanted to be involved in the project and negotiated a formal agreement between the DOE and the State of New Mexico in 1981. These agreements included, among other things, a list of experimental activities, waste limitations and monitoring requirements that were to become elements of a performance confirmation program [1].

Once finalized, the EPA standards included radioactive containment requirements that were to be demonstrated through a probabilistic PA. The standards also included a requirement for multiple assurance measures that were intended to add confidence the repository would perform as predicted, specifically through monitoring. The monitoring requirements thus became elements in the WIPP's performance confirmation program.

For WIPP certification, information was needed to build a robust and defensible PA model. Site characterization included in situ and laboratory experiments on the host rock, geologic structure, hydrology, seals designs, actinide chemistry, gas generation and many other aspects of the system. These activities created varying amounts of information that provided the foundation for licensing. To help stream-line resources and scientific research a decision-analysis tool called the Systems Prioritization Methodology (SPM) was used to help prioritize the important parameters and experiments needed for PA and the compliance demonstration. The SPM multi-attribute analyses used knowledge of existing experimental programs, existing models and sensitivity analyses to determine what elements were the most uncertain and sensitive to demonstrating compliance with the EPA standards. The SPM included input from stakeholders, oversight groups, and the regulator and used this information within the prioritization. The program produced important data and confirmatory information that was used to finalize conceptual models, parameter ranges and numerical model implementation in a compliance PA that ultimately demonstrated the repository would meet EPA disposal standards.

The EPA included requirements in its disposal standards for a monitoring program that met the common definition of performance confirmation. The intent of such a program was to use various techniques that continually challenge the certification basis used to satisfy the safety case for a repository. The purpose of the program is to provide additional assurance that the repository will safely isolate waste from the biosphere as predicted. The DOE qualitatively and quantitatively analyzed potential PA parameters to determine what aspects of the system could be monitored to meet the EPA's requirements. DOE used EPA guidance to develop the following criteria to assess performance confirmation parameters:

- Address significant disposal system

- Address an important disposal system concern,
- Obtain meaningful data in a short time period,
- Not violate disposal system integrity, and
- Complement other existing environmental monitoring programs.

The results of the analysis identified ten parameters that met the criteria. The analyses were documented in the DOE's Compliance Certification Application to the EPA [6]. The parameters chosen relate to human activities in the surrounding area, groundwater hydrology, geotechnical performance, waste activity and overburden subsidence. The confirmation program using these ten monitoring parameters has been in operation since 1999 and the results reported annually. The program has been verified by the EPA to meet their assurance requirements and is reassessed at each five-year recertification cycle. The program has proven beneficial in identifying conditions that are outside PA expectations. Specific changes have been made to PA models as a direct result of this performance confirmation monitoring program [1].

4. Performance Confirmation for Yucca Mountain

The extensive process involved with development of the safety case for Yucca Mountain provided opportunity to approach performance confirmation in assorted ways. The fundamental premise was always understood: confirmation evaluates information used as input to models, or evaluates whether observed behavior is consistent with expected or modeled performance. Before the move to rescind the Yucca Mountain license application, the enduring confirmation program was reviewed, evaluated, and updated as needed to reflect new technical, programmatic, and regulatory information and maintain consistency with the licensing application arguments. Development of the performance confirmation process and its accomplishments over the life of the Yucca Mountain project provide an informative case study.

The license application submitted in 2008 contains an updated total system PA, which includes the latest assumptions and technical information available to the project. The safety case as supported in the PA identifies the influential parameters for potential monitoring. To ensure consistency between the confirmation program developed by the decision analysis techniques and the PA supporting the license application, an evaluation was performed at the time of the license application submittal. The adequacy of the confirmation activities is summarized in the Yucca Mountain Safety Analysis Report (SAR) [7], which can be found on the web (http://www.nrc.gov). This evaluation confirmed that the existing performance confirmation activities provide a breadth of investigations sufficient to evaluate the performance basis of the license application and provide for continued evaluations into the future.

The approach that ultimately identified the performance confirmation activities used risk information to focus attention on issues important to public health and safety. The evaluation methodology is described elsewhere, such as SAR [7]. The process applied the so-called risk triplet (*What can go wrong? How likely is it? What are the consequences?*) to a set of parameters identified by subject matter experts. The decision analysis practice thereby initiated with subject matter experts identifying key natural system and engineering parameters of interest to the definition of performance confirmation, together with methods of data acquisition.

The performance confirmation information that was included in the license application submitted to Nuclear Regulatory Commission (NRC) for the repository construction authorization relates the elements of the performance confirmation program to the regulatory requirements. Although the multiattribute decision process is described in detail and documented in reports, the selection process was subjective in many respects, and perhaps not as objectively transparent as desired from a technical or stakeholder perspective. The existing performance confirmation activities support the post-closure PA of the natural and engineered barriers and provide adequate coverage to confirm the licensing basis [8].

In September 2011 NRC released its findings on the performance confirmation section of the SAR. The NRC Technical Evaluation Report on the Content of the U.S. Department of Energy's Yucca Mountain Repository License Application Administrative and Programmatic Volume is publicly available on the NRC website (pbadupws.nrc.gov/docs/ML1125/ML11255A152.pdf). The NRC finds that the performance confirmation program is consistent with the NRC's Yucca Mountain Review Plan (YMRP): *The SAR includes a description of the Performance Confirmation Program, which evaluates the adequacy of the supporting assumptions, data, and analyses in the SAR…On the basis of the NRC staff's review of the SAR and other information submitted in support of the SAR, the NRC staff notes that DOE has provided a reasonable description of its Performance Confirmation Program that is consistent with the guidance in the YMRP.*

5. Discussion

The concept of disposing radioactive waste in a geologic repository today involves a thorough understanding of numerous technical, political, regulatory, societal and economic elements. Many of these elements overlap and solving all relevant issues necessary to site, operate and decommission a disposal facility should be done with knowledge of each element's requirements and impacts. Performance confirmation is one tool that can help to coordinate many of these elements into a program that actively investigates what is thought to be adequately understood about the system and what information is lacking. A performance confirmation program is used to determine ways to challenge and verify those areas that are thought to be understood and to find ways to understand those areas that are not well understood.

Prioritization of parameters for the monitoring program should be traceable back to the safety and feasibility statements (and hence, the FEPs of the disposal system) in terms of their importance to barrier capability and waste isolation. These relationships can be derived by statistical post processing of the computations comprising the safety PA. A performance confirmation program evaluates information used as input to models, or evaluates whether observed behavior is consistent with expected or modeled performance. It is understood that such a testing and monitoring program should remain as consistent as possible with the license application baseline information. To achieve that goal, the performance confirmation plan would continue to be reviewed, evaluated, and updated as needed to reflect new technical, programmatic, and regulatory information.

Performance confirmation programs have been used twice at WIPP, first during site characterization and PA development and later in a compliance monitoring program. At first, only certain technical aspects of the system were deemed important because it was a scientifically-based, government project. Early site characterization work was designed to gather information about the geology and hydrology of the area and the mechanical properties of the natural barrier. The information would be used in a PA to determine the long-term containment performance of the disposal system. A performance confirmation element identified experimental and analytical programs that could be used to reduce uncertainty, confirm sensitive assumptions, and provide useful data. The performance confirmation program provided data to justify the adequacy of the information used in PA to demonstrate compliance with EPA's containment requirements.

Performance confirmation will continue to be used in the WIPP's post-closure period for at least 30 years and likely up to the end of the 100-year institutional controls period. As the technical documentation for the repository matures throughout the operational period, the currently planned post-closure monitoring program will need to be reassessed prior to implementation. However, the intent of the program will be the same as it was for the previous programs, to ensure the ultimate goal of the repository. This goal is to safely isolate waste from the accessible environment and ensure public and environmental safety.

All repository post-closure analyses will have a number of models developed from FEPs analyses. Models, parameters, and processes used for the Yucca Mountain license application were evaluated in advance of the license application. Parameters were identified whose uncertainties have significant effect on dose to the reasonably maximally exposed individual over the regulatory periods. The parameters in PA models that are most significant were identified and then weighed against planned testing and monitoring activities [8]. Model results derive from particular parameter distributions and other assumptions. Therefore, the testing and monitoring details, including justification, parameter ranges and condition limits, can be gleaned from the PA baseline. These and other analyses provide the foundation for a transparent selection of confirmation parameters.

Once parameters are selected, expected ranges, condition limits, and other related information can be developed using the risk-informed knowledge base and documented in specific test plans. The principal investigator develops expected ranges to capture the input set provided to the PA, as documented in analysis/model reports and technical data input packages. The expected ranges allow for natural or measurement-related variability and include values used for the PA analyses. These considerations assure that results remain acceptable if the measured values remain within these ranges. A substantial margin is likely to exist between condition limits outside the expected range and values influencing barrier functionality or compliance with performance objectives. The condition limits are based on the PA model, validity conditions, importance to barrier capability, the results of uncertainty and sensitivity analyses, and evaluation of available data.

6. Conclusions

There are many categories of testing and monitoring programs required to design, construct, operate, and close a nuclear waste repository. These include: performance confirmation testing and monitoring; design construction and operations testing; licensing specification testing; security, safeguards, and emergency testing; regulatory directed testing; natural and engineered systems testing and evaluation; health and safety effluents monitoring; and elective science and technology testing. Documented results of many of these testing and monitoring programs will be required to satisfy the regulatory requirements for the repository. The criteria by which activities will be evaluated for inclusion into a given category of the testing and monitoring programs, the functions each category addresses, and the current list of activities in each category will be developed at the appropriate time and for the intended purpose. Performance confirmation is a specific element among these many programs.

Sandia National Laboratories was the Science Advisor for the WIPP Program and the Lead Laboratory for the Yucca Mountain License Application and therefore entered into the MoDeRn agreement to share actual performance confirmation monitoring experiences. As the licensee for both WIPP and Yucca Mountain, DOE supplied the technical bases for the models used in the PA. In turn, the PA constituted an essential element of the safety case for compliance certification or license approval for WIPP and Yucca Mountain, respectively. Performance confirmation provides data to verify the adequacy of the information presented in the certification or license application. Despite the differences in mission, geologic setting and regulatory authority, the basic workings between the safety case PA and performance confirmation are analogous. In the case of the WIPP repository, the compliance monitoring program has been successfully implemented and is evaluated and reported annually. Although the license application for Yucca Mountain has been halted, a transparent and technically objective course forward has been identified for its performance confirmation program.

Experience with the WIPP and Yucca Mountain nuclear waste repository programs involved dissimilar media, EPA versus NRC regulators, unlike waste inventories and differing disposal concepts. However, both programs embrace a performance confirmation strategy and from these experiences guidance can be rendered for future considerations:

- Parameters should be demonstrably linked to the safety assessment.
- In some manner, confirmation begins during site characterization but formally becomes a commitment when it is included in a license submittal.
- Individual test plans require detail including acceptable ranges and relevance to PA.

The phased nature of repository development allows progressive development of monitoring approaches. The overall Yucca Mountain testing and monitoring program envisioned at the point of license application was flexible relative to the stage of repository development. Elements of the performance confirmation program started during site characterization and are expected to be continued over the life of the project. The regulatory nature of specific confirmation test plans necessitates that sound technical roots be interrogated for their definition, particularly with regard to selected parameters, ranges, and reportable conditions. A parallel and complementary elective testing program is instrumental in quantifying the appropriate parameters for some confirmation activities.

Monitoring adds to public confidence because it demonstrates that the repository is responding as expected and as represented in the licensing application, or, in the event that measurements reveal potential problems, it demonstrates transparent and responsible program management, assuming corrective actions are prompt and effective. A goal for a successful testing and monitoring program includes public outreach and includes a process to reevaluate, reexamine, and modify activities as the state of understanding changes. These are vital points to consider, because the WIPP experience suggests change to a confirmation practices is not easily achievable.

The U.S. repository programs have been conducted openly and inclusively for many years. WIPP has enjoyed a successful compliance monitoring history since operations started, while the performance confirmation plan for the Yucca Mountain license application was found reasonable and consistent with regulatory expectations. In the process of analyzing and compiling the license application for the Yucca Mountain repository, a clear path for performance confirmation within a long-term testing and monitoring strategy emerged. Experience developing performance confirmation in a licensing framework for two mature geologic repositories in the United States has the potential to guide other such work if the lessons are indeed learned and applied.

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References

[1] Wagner, S.W. (2012), "Performance Confirmation Strategies for the Waste Isolation Pilot Plant – A Historical Perspective from an Operating Disposal Facility," WM2012 Conference, Phoenix, Arizona, USA.

[2] Hansen, F.D. (2011), "Repository Performance Confirmation," SAND2011-6277, Sandia National Laboratories, Albuquerque, New Mexico.

[3] www.modern-fp7.eu

[4] NOCA (2009) Long-Term Testing and Monitoring Strategy—Final Report. Issue No. 1, 43641390//SNL-URS.

[5] Electric Power Research Institute (2001), "Performance Confirmation for the Candidate Yucca Mountain High-Level Nuclear Waste Repository," EPRI TR-1003032, Palo Alto, California.

[6] Department of Energy (1996), "Compliance Certification Application 40 CFR Part 191 subpart B and C," U.S. Department of Energy Waste Isolation Pilot Plant, DOE/CAO-1996-2184, Carlsbad, NM, U.S. Department of Energy.

[7] Department of Energy (2009), "Yucca Mountain Repository License Application Safety Analysis Report, Chapter 4: Performance Confirmation Program," DOE/RW-0573, Update No. 1, Docket No. 63-001, Washington, D.C., U.S. Department of Energy Office of Civilian Radioactive Waste Management.

[8] SNL (Sandia National Laboratories) (2008), "Performance Confirmation Plan," TDR-PCS-SE-000001 REV 05 ADD 01 ACN 01, Las Vegas, Nevada, Sandia National Laboratories.

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Monitoring strategy for a reversible waste disposal facility (Cigéo)

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Summary

After having concluded a feasibility study of deep geological disposal for high-level and long-lived radioactive waste in 2005, Andra was charged by the Planning Act n°2006-739 to design and create an industrial site for geological disposal called Cigéo, which must be reversible for at least a century-long period. Within the framework of this geological repository project, the monitoring system must obtain the information required to run the disposal operation and ensure waste reversibility. Concepts are concordant with steps of progressive construction, emplacement and closure of disposal cells.

To achieve monitoring objectives and needs, an overall monitoring strategy has been completed, which includes waste package characterization prior to emplacement and monitoring of disposal structures and the surface environment. To develop adaptive solutions, studies and evaluations have been undertaken on (i) the monitoring strategy with respect to global distribution of instrumented structures within the repository and design of monitoring units, (ii) research and development to adapt, complete and qualify the sensing devices, and (iii) specific tests and large-scale experiments in an underground research laboratory.

This paper will detail the first two points, especially in the context of reversibility, which have been ranked following a Failure Modes, Effects and Criticality Analysis methodology (FMECA). The FMECA consisted of identification and ranking of each perturbation that may occur during waste retrievability, through a step-by-step procedure to reveal each potential weakness. The FMECA also involved feasibility and performance of sensors. Examples will be presented to illustrate this methodology.

The monitoring system design is then developed, considering each perturbation and based on a combination of in-situ instrumentation and non-destructive methods, in order to obtain a high degree of confidence in measurements. To optimize sensor distribution, we take into account both the repetitive design of disposal cells and the homogeneity of the rock properties. The technology selection partly relies on classical and proven approaches, which have been adapted to the specifications of geological repository, by taking into account available feedback in the monitoring of tunnels, confinement areas of nuclear power plants and dams. To complete the requirements of this system (robustness, non-invasiveness, and above all reliable functioning over relatively long periods of time), that present substantial challenges for most available monitoring equipment, we are carrying out specific R&D actions, based on more recent and innovative technology. Main R&D results will also be illustrated.

1. Introduction

After having concluded a feasibility study a of deep geological disposal concept for high-level and long-lived radioactive waste in 2005, Andra was charged by the Planning Act n°2006-739 to design and request construction licensing for an industrial disposal facility called Cigéo which must allow retrieval of some or all of the emplaced waste (reversibility) for at least a century. Within the framework of this project, monitoring must furnish the information needed for facility operation and managing reversibility, structured in accordance with progressive disposal cell construction, waste emplacement and closure. This stepwise process also allows progressively updating and optimizing the design of future repository components. In-situ monitoring data derived from periodical structure reevaluations also contributes to operational and post-closure safety analyses, providing information required for validating (and enhancing) the process understanding underlying long-term safety evaluations.. Current understanding and predictions are based on experimental results obtained in surface and underground research laboratories, as well as on modelling and simulations.

2. Overall monitoring strategy

In order to achieve these objectives and needs, Andra is developing an overall monitoring strategy based on waste package characterization prior to emplacement and monitoring of disposal structure behavior over time, the latter including monitoring of all the parameters (T-H-M-C-R for Thermic / Hydraulic/ Mechanical / Chemical/ Radiological parameters) in every structure type: intermediate-level-waste (ILW) disposal cells, high-level-waste (HLW) disposal cells, access galleries, access shafts and seals.

The overall strategy is based on taking advantage of the complementarities of the different available monitoring techniques by progressively putting more emphasis on visual inspections and on non-destructive tests, , while decreasing the number of embedded sensors. This requires that sensor layout be optimized and spatially distributed based on a carefully selected, well-structured approach which takes advantage of the similarity between structures, in particular the kilometers of access tunnels and the thousands of disposal cells for long lived HLW.

The monitoring strategy takes advantage of the expected similarity of certain foreseen phenomenological evolutions based on the general homogeneity of the host rock and assuming similar behavior for all disposal cells containing the same type of radioactive waste. This leads to a strategy based on monitoring of a sequence of structures, of progressively decreasing density of embedded instrumentation, complemented by several “sacrificial” structures. Each type of structure has a precise function as regards monitoring:

- Echelon 1 of instrumentation (or “Witness”) structures are chosen amongst the first ones built and must fulfill all technical monitoring goals. Witness structures will also be chosen based on their specific location in the facility in order to test different situations (see details in §4).

- Echelon 2 of instrumentation structures contain less instrumentation and are monitored less frequently relative to “witness” structures considering more specific and focussing technical goals.

- Echelon 3 (or “Standard”) cells are generally not instrumented, and only contain essential equipment needed for insuring operational safety. They would be the target of occasional inspection and control.

- HL waste retrieval tests are planned for in some “sacrificial” cells. These cells will also offer the possibility of carrying out visual inspections, destructive analyses and sampling on construction materials. Such cells are planned to be dismantled because of the potential degradation of their component performance resulting from the testing process.

The question has been raised as to how to position monitored structures in order to ensure that the monitoring results are representative, i.e. correctly account for the spatial variability of the disposal facility (see below). This is important if the data is to be usable for verifying the hypotheses used as basis for assessing safety and reversibility performance.

In order to maintain a reasonable density of embedded sensors, an equilibrium must be found between monitoring needs and the constraints of monitoring equipment implementation. In order to do this, two solutions have been developed to adapt instrumentation density as a function of increasing knowledge: a methodology for selecting high priority parameters whose monitoring would be maintained in a larger number of instrumented structures (next section) and a methodology for distributing instrumented structures within the repository (section 4). This approach is only developed here based on reversibility needs, the approach used for selecting the candidate parameters needed to confirm the knowledge base for long term safety assessment is not addressed (but has also been studied by Andra).

3. Process and parameter selection for reversibility needs

3.1 Methodology

The approach used for optimizing the embedded instrumentation density is aimed at identifying monitoring objectives for “witness” structures, where all objectives will be monitored, and for “echelon 2” structures, where only parameters of major interest would be characterized.

The risk analysis of the Failure Modes, Effects and Criticality Analysis (FMECA) methodology has been applied to two waste package removal scenarios, one for a ILW-LL cell package and one for a High Level Waste (HLW) package. It was prepared based on the hypothesis of a level 2 reversibility situation (cell full, radiological safety established but not sealed) given that this level could last for up to 100 years.

By evaluating the factors that could hinder waste package removal, and then characterizing them in terms of (i) probability of occurrence and (ii) seriousness, which estimates the levels of difficulty regarding package removal, the method allows prioritization of the various monitoring requirements. It was then refined by adding a criteria relating to the ability to detect an event before it happens. The overall score then allows identification and prioritization of the monitoring means to be implemented in relation to reversibility.

More precisely, the first step consists of identifying the problems in relation to removal of a package by envisaging the procedure step-by-step and imagining the failures at each step. For each failure mode identified, a score was given in terms of the probability of occurrence (P) and seriousness (S) with regard to the ability to remove. For each criterion, the score was quantified from 0 (most favourable) to 5 (most uncertain). A probability of 0 represents an excluded occurrence given the expected phenomenological analyses, including the taking into account of uncertainties. On the other hand, a probability of 5 is an event expected to occur in all cells. The seriousness is scored 0 if a known and tested palliative measure has been identified that does not require detection of the malfunction and has no impact on the removal progress or on the operational lifetime. A seriousness of 5 means that removal is considered to be impossible.

In the second stage, the feasibility of detection of these failures (before the failure occurs) was also quantified. To do this, Andra refers to the progress in the qualification of the measurement technology. A difficulty of detection (D) of 1 is allocated when the means of detection is developed and hardened, then tested under various conditions including the most extreme. A D value of 5 indicates that no means of detection exists regarding to disposal facility monitoring needs.

The approach can be refined by envisaging two levels of detection: continuous detection (D1) using monitoring devices permanently located in the cell or a periodic detection in preparation for removal (D2), which corresponds to selective (temporally) monitoring by “mobile means” for example, i.e. instruments that can be shared amongst several installations.

Once the scores have been allocated, two products, referred to as criticality indices, were calculated for prioritization. The product P x S characterizes the intrinsic criticality of the failure mode. The product P x D x S characterizes the criticality of the failure mode given its ability to be detected before it happens. These values were then used to prioritize the various failures envisaged in terms of their level importance: “maximum” (shown in red), “significant” (orange), “moderate” (yellow) and “low” (white). This importance could then be described in the form of a grid. The highest scores indicate failure modes for which, in the solution currently presented as a reference, progress in the definition of a counter-measure should be made a priority. The comparison between the P x S and P x S x D classifications shows the usefulness of early detection. It helps to evaluate the importance of the associated monitoring objective.

3.2 Parameters for HLW cell considering reversibility

Table 1 shows the list of parameters that will be completely monitored in witness cells.

Table 1: List of parameters to be monitored and observed for evaluation of reversibility conditions in HLW cells

Monitoring requirements	Parameters of influence
Mechanical integrity of metallic liner	Thermo/hydraulic/mechanical loading by clay rock (depending on the thermicity of the package) Corrosion condition (external and internal) and the extent of corrosion products Deformation of the gallery with respect to the liner
Handling clearance: Residual vacuum level	Accumulation of corrosion products Presence of foreign bodies (pad fragments)

Monitoring requirements	Parameters of influence
Characterization of the atmosphere in the case of return with respect to explosion risk Characterization of the atmosphere in the case of return: Presence or not of liquid water	Speed of corrosion Hydraulic conditions; nature of liner joints
Integrity of gripping surfaces (e.g. pads, handling neck)	Speed of corrosion Mechanical loads during installation and disposal
Integrity of waste containers	Conditions favourable to low corrosion speeds: Absence of water and/or oxygen

Table 2 shows the results of the prioritization analysis, performed based on the hypothesis of Andra 2009 design, both for the architecture and the monitoring system. It only includes the most critical failures (maximum to moderate importance) that have an impact on the monitoring system. Thus, for example, the metallic liner becoming oval was envisaged but the criticality of this failure proves to be low.

Table 2: Prioritization of monitoring objectives based on the results of a risk analysis performed on the recoverability of HLW packages.

Failure factor	**P x S**	Monitoring method envisaged	**PxDxS**	
			D1	**D2**
Presence of water in the cell	16	Sampling lines	64	64
Presence of H_2 in the cell	16	Sampling lines	32	32
Accumulation of corrosion products	12	Sacrificial cell	48	48
Blocking of the hatch be a foreign body (pad fragment or corrosion products)	10	Sacrificial cell	50	50
Loss of means of environment monitoring (taps)	8	Maintenance of sampling lines	40	40
Presence of H_2 in the head of the cell	10	Sampling lines	20	20
Deformation of the gallery with respect to the insert – potential misalignment of the cover bracket on the insert (monitoring reference)	10	Submerged extensometers	10	10

The most important monitoring requirements are (i) monitoring of liquid water, (ii) characterization and management of hydrogen, (iii) detection of corrosion products, (iv) the capability of characterizing the packages after their extraction from the cell (condition of pads and corrosion products) and (v) mechanical monitoring of the gallery and its position with respect to the liner.

The monitoring system allows the importance to four envisaged failures to be reduced, two whose importance is “significant” and two “moderate”. We envisage that only these parameters will be measured in the “echelon 2” disposal cells. However, certain redundancies will be allowed in the instrumentation to ensure measurement quality.

On the other hand, a few processes identified as being of major importance but their importance could not be reduced, since monitoring technology are not yet commercially-available. For instance, results showed that sacrificial cells were mandatory for corrosion process monitoring, and maintenance, visual inspection, sampling are therefore planned in such structures. In parallel, Andra is carrying out an intensive R&D programme aimed at developing and supplying sensing devices for identified important parameters.

3.4 Example of a highly instrumented structure: HLW “witness” cells

Several instrumentation possibilities are being examined in designing the monitoring system for ‘witness” HLW cells: (i) equipping the cell liner with monitoring devices, (ii) monitoring the behaviour of the rock by means of nearby boreholes or (iii) moving the monitoring to the sealing plate. The design of the overall monitoring system would then look like the schematic illustrated below. Instrumented HLW cells would take advantage of all these technical possibilities. This type of disposal cell, containing such an intensive monitoring approach would need to be distributed at different strategic locations in the repository section dedicated to this type waste.

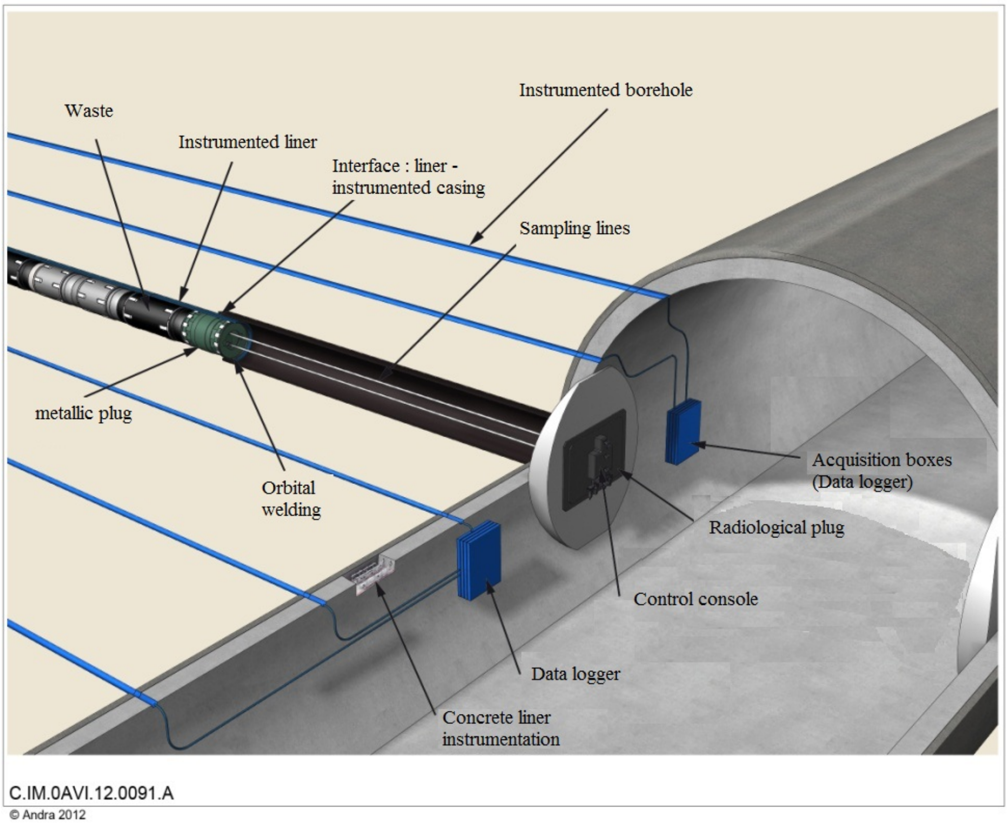

Figure 2: Monitoring system in a highly instrumented HLW cell (echelon 1 or witness structure).

4. Distribution of instrumented structures within the repository: the example of implementation of witness cells inside a module to characterize thermal processes

The operating period is characterized by a succession of relatively short periods of activity (construction, loading, closure) separated by waiting phases of variable durations cadenced by the decision milestones included in the pre-closure management of the disposal process, the latter being governed in accordance with the reversibility in the French concept. The chaining together of these various phases initiates various processes such as physical evolution (simultaneous or sequential, independent or coupled) with their corresponding, and quite differing, characteristic times.

The particular needs can thus be evaluated based on prior knowledge of expected evolutions for a given design and concept for construction and operations, e.g. duration of progressive construction and waste emplacement and ventilation duration and characteristics. This is illustrated below for the example of a design for the HLW disposal unit considered for the French disposal concept in 2009. While the latter is subject to evolution, the lessons learnt as regards the monitoring strategy remain valid.

On the scale of the HLW disposal unit, the monitoring strategy must meet the following needs:

- Checking the interaction between the disposal cells and the access galleries, linked in particular to the gradual loading of the module (see Figure 3, left) and its consequences on interactions (in particular thermo-aeraulic ones) with the access galleries, linked to the ventilation flow (see Figure 4)
- Checking the effects of waiting time between the construction of a cell and its loading (between 1 and 10 years) on changes in processes H, M and H-M from one cell to another.
- Checking the peripheral effect linked to the presence or not of neighbouring cells (cells side-by-side or end-to-end, see Figure 3).

Given these three main objectives, the monitoring strategy anticipates integration of an initial module constructed from witness cells distributed respectively (i) in the core of the module and at its edge, (ii) along the length of the access gallery (in an air intake and an air return) and (iii) along the module (first cells loaded compared to last cells loaded). With some witness cells able to meet both objectives, a pooling of resources made it possible to restrict the number of witness cells to nine (out of approximately 200 in the case of the Andra 2009 architecture), within the initial waste disposal module. This is not a definitive figure and will be amended over time as containers arrive, and adapted to the disposal and operational design choices.

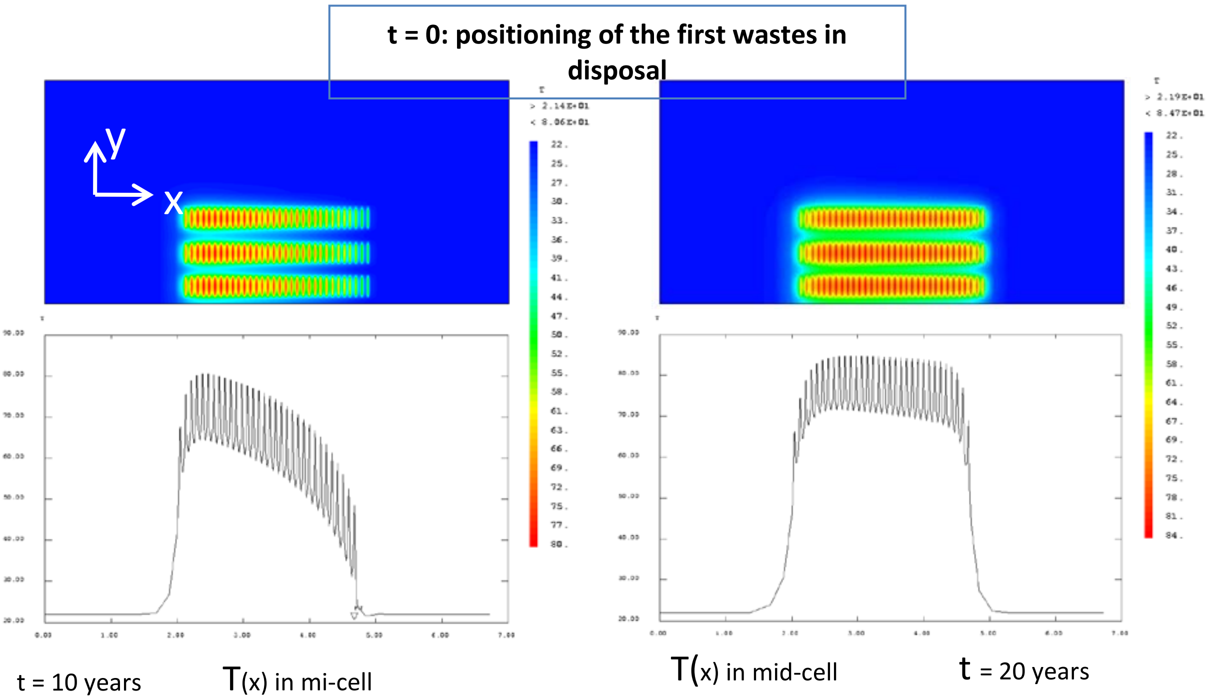

Figure 3: Thermal simulation on the scale of a module taking into account (left) the possible influence of the filling scenario, here a module filled over 10 years from the bottom to the edge and (right) edge effects (here seen 10 years after the end of filling of the same module). Simulations were performed under the hypothesis of HLW characterized by moderate production of heat.

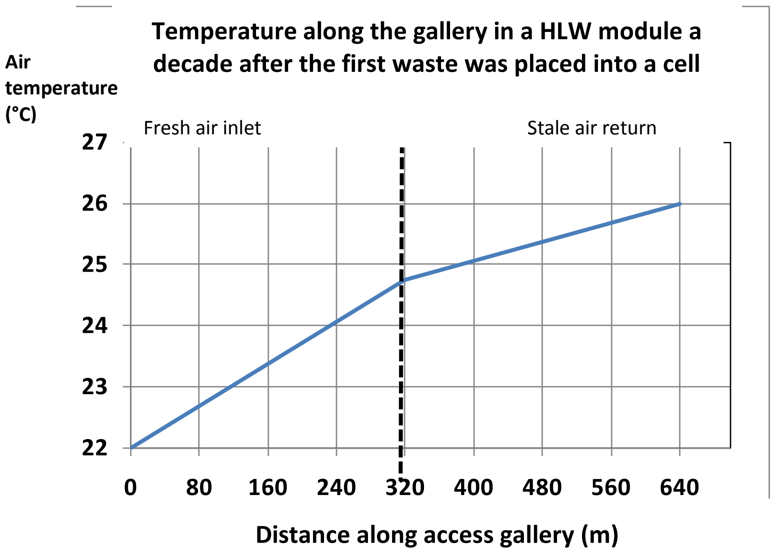

Figure 4: Thermal simulation taking into account interactions between the thermal effect due to the containers and the ventilation in a HLW module (assuming wastes with moderate production of heat)

Cell instrumentation would be supplemented by monitoring in the galleries. For example, an optical fibre providing distributed temperature measurements would contribute to monitor gallery ventilation, and the expected 4°C temperature increase along the access gallery (depending on ventilation direction). Concrete liner monitoring is also planned.

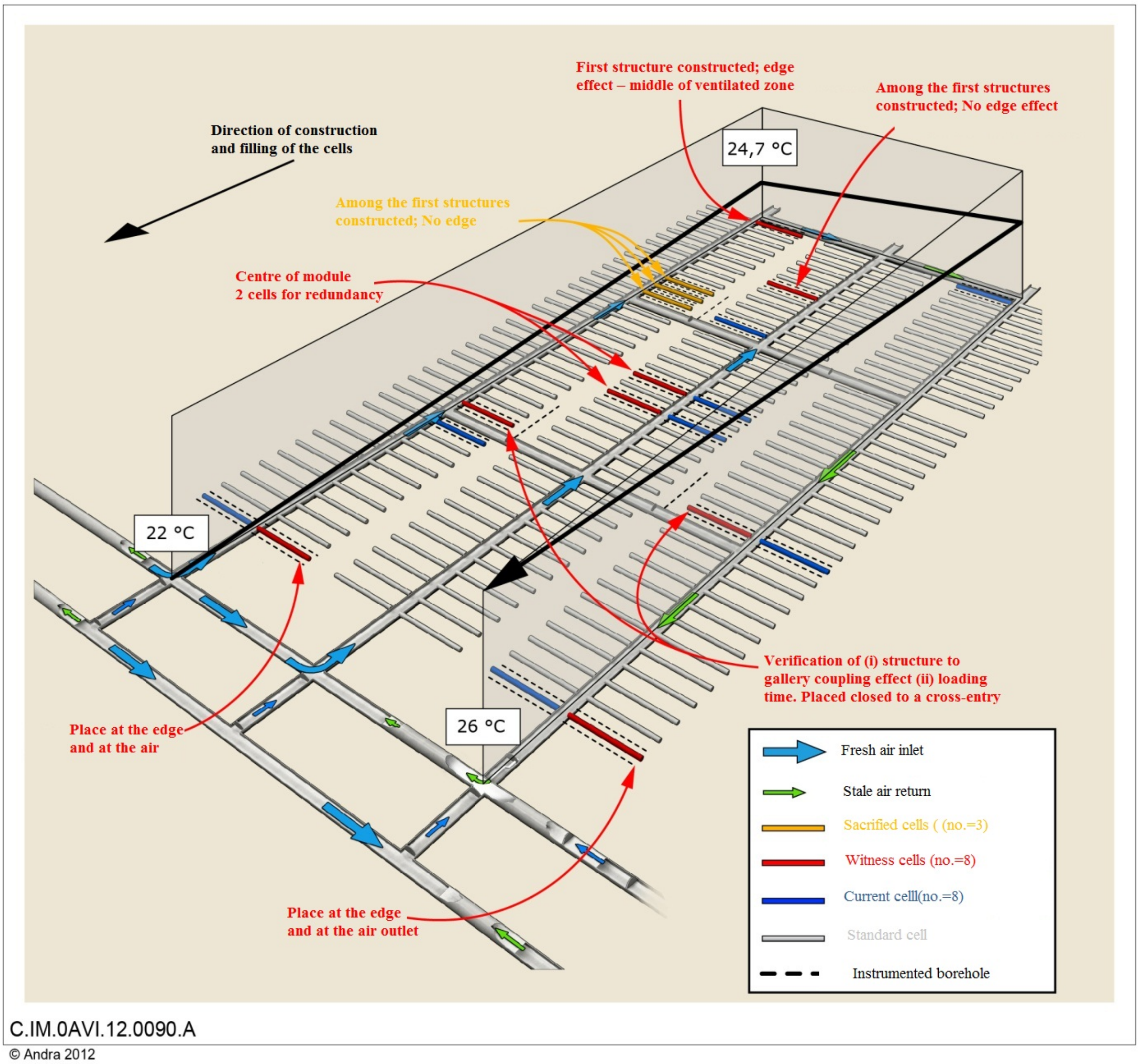

Figure 5: Example of the distribution of the instrumentation in an HLW module.

5. Sensing devices: selection and on-going R&D

Given the potentially harsh conditions which will exist in an underground repository (e.g. radiation levels, temperature, water pressure, pH… in an HLW disposal cell) and certain less common specifications for monitoring technology, in particular durability and non-disturbance of barrier performance, we know that many of the off-the-shelf monitoring technologies will rapidly fail to provide reliable measurements.

This is why Andra has implemented a qualification procedure for commercially-available monitoring technologies, and carries out R&D when no sensor seems to be available.

5.1 Sensor qualification procedure

Andra's qualification process entails testing and qualifying the complete measurement chain, by progressive steps. The overall process is inspired from the qualification guide for non-destructive methods[2]. The global test sequence includes four stages.

- Stage one consists of acquiring in-depth knowledge of the sensing technology, engineering solutions, and practical implementation constraints. It aims at selecting the technologies best suited to the specific requirements of monitoring geological repositories for long-lived nuclear wastes. When commercially-available sensing chain performance does not fulfill requirements, Andra initiates research programs.
- Stage two consists of carrying out laboratory tests, under fully supervised and/or controlled environmental conditions, to qualify the sensitive component and assess the complete measurement chain performance. Sensors are tested in air, and embedded in the host material of interest.
- Stage three consists of outdoor tests in order to evaluated field implementation influence. At this stage, the sensing chain is protected from hazardous conditions, extreme temperature or gamma rays. Unexpected influence parameters might thus be revealed.
- The fourth stage involves hardening in view of the application environmental conditions. In the envisioned French geological repository, temperatures would range from 25°C to 90°C, gamma radiation rates reach Gy/h, total dose 10^7Gy and hydrogen release is also expected (up to 100% hydrogen content in the atmosphere.

Presently, T-H-M sensors are finishing the qualification process while C-R- sensors are still at the upstream stage. Two examples are provided below.

5.2 Specific tests and large-scale experiments in the underground research laboratory

The Andra monitoring system will rely on platinum probes (T), vibrating wire extensometers (VWS- M), strain and temperature distributed optical fibre sensors based on Raman and Brillouin scatterings (T, M)), water content sensors based on Time Domain Reflectometry probes (H), interstitial pressure cells based on VWS (M), long-based-field-extensometer (M).

These sensors have been tested separately under various conditions (the three qualification stages). They have recently been implemented in the Andra underground laboratory, as detailed in R. Farhoud abstract (this meeting) and illustrated in Figure 6.

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[2] Qualification guide FD CEN/TR 14748 "Non-destructive testing – Methodology for qualification of non-destructive tests" 2005

Figure 6: Pictures of the Andra URL (left) when extensometer and optical fiber sensors (right) were installed inside a borehole.

5.3 Research example: corrosion process monitoring

Complementary approaches are under development in order to monitor metal corrosion rates. The first technique makes use of corrosion monitoring specimens which must be (i) produced from the same materials as the target component and (ii) installed on the sacrificial structure in such a way as to simulate realistic behaviour of the investigated structural component surface. At the present time, a series of corrosion specimens is planned to be placed in sacrificial cells, and to be periodically withdrawn for physical (mass evaluation) inspection.

Figure 7: corrosion specimen support with samples developed in Andra URL in the MCO experiment.

Figure 8: Wavemaker Pipe Testing Equipment is used in a wide variety of industrial environments and applications.

For all the other components, the use of non-destructive and non-intrusive technique is promising. The Guided Waves Ultrasonic Technique provides an attractive solution to this problem because they can be excited at the cell entrance and will propagate many metres along the liner therefore allowing screening corrosion detection. The technique is now applied for pipeline monitoring. Andra is leading development on such method to provide measurements on cells.

6. Conclusion

Examples have been given for the design of a monitoring system in a deep geological radwaste repository in a clayrock formation. They will be adapted to structure design evolutions and increasing knowledge (acquired in URL for instance).

Several important features have driven the design:

Monitoring system design is based on expected underground repository evolution, both short and long term. This is mandatory in order for the monitoring system to be efficient: positioning sensors where variations will occur and to make sure that the instrumentation will be able to resist aggressive environmental conditions for decades. For the latter, qualification procedures are developed based on known environmental conditions.

We illustrated why it is mandatory to design a monitoring system which takes into account a variety of scales, both temporal (long term versus operational scale) as well as spatial (focus on disposal cells then on disposal units).

We also illustrated the limits of monitoring technology and propose some solutions to bypass them, with the concept of “sacrificial cells” which is very similar with the “pilot facility” of other underground repository concepts. In addition, recommendations developed within this Case study provide arguments in favour of distributing instrumented structures over the entire repository, to ensure that representative information is provided for performance confirmation. The overall strategy proposes to decrease instrumentation density with increasing knowledge and assurance gained from available performance confirmation.

Monitoring of the Planned Repository for Spent Nuclear Fuel in Sweden

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Summary

In March 2011 SKB (The Swedish Nuclear Fuel and Management Company) submitted license applications according to the Act on Nuclear Activities and the Environmental Code for a final repository for spent nuclear fuel at Forsmark, and a licensing review is currently being undertaken by Swedish authorities. The repository will be constructed according to the KBS-3 method. The application is, among other things, based on comprehensive site investigations of the candidate area at Forsmark in the municipality of Östhammar, Sweden.

As an essential part of these investigations a monitoring programme, covering both geoscientific and ecological parameters, was initiated. A primary objective of this programme is to establish the baseline by defining a reference against which the changes caused by repository development can be recognised and distinguished from natural and man-made temporal and spatial variations in the repository environment. Monitoring the impact of repository construction will be an integral part of the detailed investigation programme [2] that will be implemented once the underground excavation activities commence. The objective of the monitoring will be to study how repository construction and operation affects the geosphere and the biosphere. These observations will also provide data for the updating and verification of the hydrogeological and hydrogeochemical models, as well as for meeting the needs of the environmental control programme and control of repository construction.

In Sweden there are no legal requirements for monitoring the repository after closure, and monitoring is planned to continue as long as the repository is inoperation, i.e. until all canisters with nuclear waste has been emplaced and closure of the repository facility is commenced. At closure the monitoring systems will be successively decommissioned. However, at that time it must be considered to what extent the closure process itself needs to be monitored.

1. Introduction

In March 2011 SKB submitted license applications according to the Act on Nuclear Activities and the Environmental Code for a final repository for spent nuclear fuel at Forsmark. A comprehensive licensing review is currently being undertaken by the Swedish Radiation Safety Authority and the Environmental Court. Construction of the repository cannot begin until the necessary licenses have been granted which is expected to occur four to five years into the future.

The repository will be constructed according to the KBS-3 method, i.e. where copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay (Figure 1) and deposited at approximately 500 m depth in saturated metamorphic rock with granitic composition. In each deposition tunnel, which is about 300 m long, there is space for about 30 canister deposition holes. After completed buffer installation and canister emplacements, the deposition tunnel is backfilled with bentonite blocks and sealed with a concrete plug. When a deposition tunnel is plugged, the groundwater seeping into the tunnel will gradually saturate the bentonite. There will be no further control of the evolution of the buffer and backfill. The stepwise construction and deposition of the nuclear waste contained, in approximately 6,000 copper canisters, is illustrated in Figure 2.

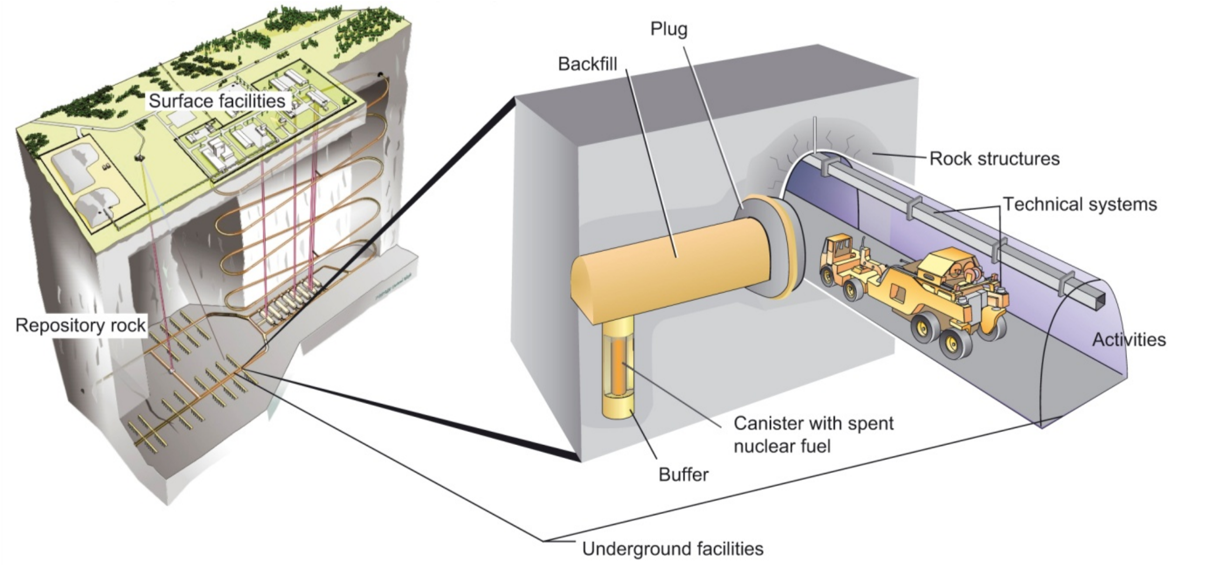

Figure 1: The KBS-3 concept (right), and a general three dimensional overview of three major underground functional areas of the final repository, (Access area, Central area and Deposition area)

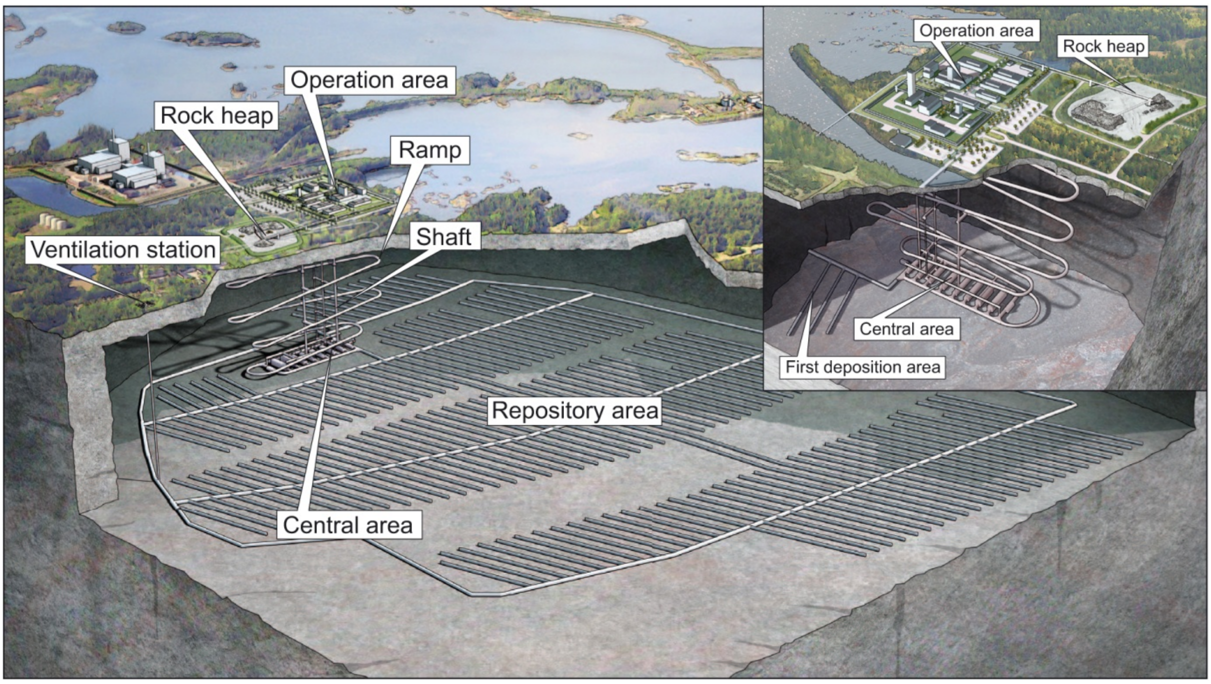

Figure 2: General layout showing the location of the underground layout for the repository for spent nuclear fuel and the surface facilities. The footprint area of the underground facility is c. 4 km^2.

The purpose of the KBS-3 repository is to isolate the nuclear waste from man and the environment by containing the waste for very long times. The license applications include a wide ranging documentation to support that a KBS-3 repository at Forsmark will meet requirements in laws and regulations, including a full evaluation of long term safety [1]. Among other things this application is based on comprehensive investigations of the candidate site Forsmark in the municipality of Östhammar in Sweden [2]. As an integral part of these investigations a monitoring programme, covering both geoscientific and ecological parameters and states, was included.

2. Monitoring at different stages of the repository development

2.1 Monitoring for the baseline description

Many of the investigated site parameters, like meteorological parameters and groundwater levels, show a pattern of more or less pronounced temporal variation. Such variations are for example seasonal fluctuations in temperature and precipitation. Climate change may cause long-term changes or trends in meteorological parameters, which secondarily may be reflected as time-dependent changes also of other monitored parameters, primarily those within the hydrological, hydrogeological and hydrogeochemical disciplines. Furthermore, human activities like investigations and underground excavations themselves may give rise to changes or variations in values of some parameters.

As set out in the overall SKB strategy for monitoring [3] and further detailed in the programme for detailed investigations [4], the purpose of establishing the baseline conditions during the site investigations performed from the ground surface is to define a reference against which the changes caused by the construction of the repository can be recognised, quantified and distinguished from natural and man-made temporal and spatial variations in the repository environment.

The description of the baseline conditions is essentially identical to the site descriptive model of the Forsmark site [2] and is based on the data obtained from the site characterisation programme. However, part of this characterisation concerns properties that vary with time. Therefore, a monitoring programme covering both geoscientific and ecological parameters was initiated during the site investigations, see Section 2.4 of the Site description Forsmark [2]. With a few changes and updates, this programme has continued after the completion of the surface-based site investigations at Forsmark and will also continue once underground excavation work starts.

Given the fact that the system for groundwater monitoring at Forsmark was established during the period 2002–2007, the period of undisturbed monitoring data will cover many years before the start of construction of the final repository. As regards meteorological parameters, groundwater levels/pressures, groundwater flow and the chemical composition of the groundwater as well as the status of some ecological parameters, this means that natural (unaffected) variations will be recorded for many years. The bulk of resulting data represents the baseline, i.e. an extensive body of comparison material, enabling identification of changes related to the impact of the facility, once construction works are initiated.

2.2 Monitoring the impact of repository construction

Monitoring the impact of repository construction will be an integral part of the detailed investigation programme [2] that will be implemented once the underground excavation activities commence. The objective of the monitoring will be to study how repository construction and operation affects the geosphere and the biosphere. These observations will also provide data for the updating and verification of the hydrogeological and hydrogeochemical models, which are in turn based on the geological models.

The monitoring during construction and operation of the repository is planned to build on the existing monitoring programme [5] as the starting point, and to elaborate the monitoring activities further based on that. However, before implementation of the detailed investigations, the adequacy of the existing monitoring programme will be assessed and revised if needed. Particular focus will be on the fact that the programme is intended to operate over a very long time while still being adequate for its main purpose of capturing the impacts from construction and operation on the environment, but also possible natural long-term changes of geoscientific and ecological parameters. The main change of the monitoring programme after start of the construction works is that the monitoring will be extended to a number of new parameters and objects, mainly in the underground facility.

At the start of construction, monitoring will already have been in progress for some time. The monitoring programme that will be implemented is largely a continuation of the programme that started during the site investigation and is still in operation. In addition, monitoring will be extended to a number of new parameters and objects, mainly in the underground facility.

Monitoring includes a broad spectrum of investigations with the common denominator that the time-dependent variation of the observed parameter is of primary interest. One principal purpose is to identify whether and how the facility impacts the parameter in question. 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.

Groundwater monitoring (mainly groundwater levels/pressures, flows and chemistry) comprises a large part of the monitoring programme. Seismic monitoring is another vital type of monitoring, already ongoing at Forsmark, but planned to be supplemented with a local high-sensitive seismic network. Monitoring is foreseen to be a continuous activity during construction of the final repository and as long as the repository is in operation.

As construction and operation proceeds, there will be a need to regularly reassess the selection of monitoring parameters, monitoring objects and measurement frequencies. The monitoring must also meet the needs of the environmental control programme and control of repository construction. Just as important, as adding monitoring parameters and objects as needed, is removing of monitoring objects when they are no longer warranted.

2.3 Monitoring after waste emplacement

Repository closure is a stepwise process from consecutively closing a deposition tunnel to closing one or several deposition areas, after which the entire repository is closed. Monitoring is planned to continue until all canisters with nuclear waste have been emplaced and closure of the repository facility is commenced. At closure the monitoring systems will be decommissioned successively.

A fundamental requirement on the final repository is that it should fulfil its safety function without surveillance (further description in Section 3). Consequently, monitoring of the engineered barrier system, i.e. canister, buffer and backfill, is not intended for finally disposed waste because emplacement of instrumentation and the necessary sensor cabling is likely to impair the safety functions of the engineered barriers.

In Sweden there are no legal requirements for monitoring the repository after closure. When planning closure, consideration must be given to what extent the closure process itself needs to be monitored. The extent of the post-closure monitoring programme will essentially be determined by decisions made at, or shortly before, closure and it is appropriate that any decisions on post-closure monitoring are made by the decision-maker at the time of the final closure of the repository.

However, if monitoring after closure is considered, the applicable regulations by SSM should be considered (SSMFS 2008:21 8§). "The impact on safety of such measures that are adopted to facilitate the monitoring or retrieval of disposed nuclear material or nuclear waste from the repository, or to make access to the repository difficult, shall be analysed and reported to the authority". Furthermore, the recommendation to this paragraph states: "The safety report for the facility, in accordance with 9 § should show that these measures either have a minor or negligible impact on repository safety, or that the measures result in an improvement of safety, compared with the situation that would arise if the measures were not adopted." Since there are currently no plans for post-closure monitoring, and since such monitoring would not be needed to ensure safety, SR-Site gives no consideration to monitoring after closure, and it is also assumed that such monitoring, was it to be performed, would not have any detrimental impact on long-term safety.

3. Confirming the initial state

The analysis of post-closure safety is based on ensuring the quality of barriers and other structures where this can be controlled and monitored, i.e. throughout the course of manufacture and disposal. Repository evolution after deposition is assessed by the tools developed for post closure safety assessment. Ensuring quality control and verification of the actual measures taken during construction and operation are input conditions in the safety analysis.

In order to ensure that the engineered barriers are designed and constructed such that they enhance long term safety, design premises have been developed [6]. Design premises typically concern specification on what mechanical loads the barriers must be able to withstand, restrictions on the composition of barrier materials, or acceptance criteria for the various underground excavations.

The design application of these requirements are described in a number of Production reports covering the spent fuel, the canister, the buffer, the tunnel backfill, the repository closure and the underground openings [6]. Each report gives an account of:

- *i)* the design premises to be fulfilled
- *ii)* the reference design selected to achieve the requirements
- *iii)* verifying analyses that the reference design does fulfil the design premises
- *iv)* the production and control procedures selected to achieve the reference design
- *v)* verifying analyses that these procedures do achieve the reference design
- *vi)* the achieved initial state, which is the key input to the safety assessment

A control programme will be developed prior to excavation, with the objective of ensuring that the design premises and other requirements on the construction work and on the operations are fulfilled. The control programme with its documentation and quality control is the basis for assessing whether the construction and operational work conform to the stated design premises and requirements on efficiency and quality. The objectives and contents of the control programme will evolve and be adjusted in response to experience gained.

4. Discussion and conclusions

During construction and operation, the final repository will affect the site's soil, bedrock and environment in different ways. Monitoring of changes contributes to continued, systematic and more detailed site characterisation, which in turn serves as a basis for detailed adaptation to the properties of the bedrock, for updated safety assessments and for determination of environmental impact. In order for the monitoring results to be used in this way, monitoring must have been done for a sufficiently long time before the start of construction of the repository in order to obtain a baseline for a number of parameters expected to be affected by the repository. Monitoring is planned to continue as long as the repository is in operation. The content and scope of the monitoring programme will vary in time and space as new deposition areas are constructed, at the same time as deposition is under way in other parts, and deposition tunnels have already been backfilled and closed in yet other parts of the repository.

To ensure that the repository barriers meet the design premises related to safety is a key element in the operation of the repository. It should be noted that compliance with requirements that connect to the safety is not only a question of the non-destructive testing to measure barrier properties at a given time. An equally important component of a quality programme is to ensure that the production, handling and installation of the engineered barriers as well as rock excavation and choice of deposition positions take place within the allowable process window. This quality-management and -control may need to be validated by destructive testing on a sample of manufactured barriers. However, given the longevity of the repository evolutionary processes, the additional understanding, which could be achieved through a post closure monitoring programme, implemented to follow the evolution of the barriers over time, is actually quite limited.

References

[1] SKB TR-11-01. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project, Svensk Kärnbränslehantering AB.

[2] SKB TR-08-05. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. Svensk Kärnbränslehantering AB.

[3] SKB R-04-13. Bäckblom G, Almén K-E, 2004. Monitoring during the stepwise implementation of the Swedish deep repository for spent fuel. Svensk Kärnbränslehantering AB.

[4] SKB R-11-14. Framework programme for detailed characterisation in connection with construction and operation of a final repository for spent nuclear fuel, Svensk Kärnbränslehantering AB.

[5] SKB R-07-34. Forsmark site investigation. Programme for long-term observations of geosphere and biosphere after completed site investigations. Svensk Kärnbränslehantering AB.

[6] SKB TR-10-12. Design and production of the KBS-3 repository, Svensk Kärnbränslehantering AB.

Development of the UK's Geological Disposal Facility Monitoring Programme

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Summary
This paper provides a summary of the approach taken in developing the UK monitoring programme for a geological disposal facility for radioactive waste. Work to address monitoring of geological disposal commenced around the start of the century with the main focus on attempting to identify what was required from a monitoring programme with later work focused on how that programme could be developed and what techniques could be applied to a monitoring programme. The early development of monitoring plans has been followed by a number of co-operative programmes with other national radioactive disposal agencies and their specialist contractors, much of this work being conducted within EC projects. The latest of these projects, the EC MoDeRn Project, provides a platform for the project partners to develop an approach to monitoring which will help guide future monitoring programmes; to better understand and develop the state-of-the-art; and to provide a basis for discussing monitoring with stakeholders.

The UK programme for geological disposal is still in the early stages of a programme of voluntarism before specific site(s) and related host geologies can be identified. The lack of a specific site or geology limits the capacity to develop plans for monitoring that are specific and detailed; however, early consultation with stakeholders identified the importance of a coherent and transparent monitoring programme as a basis for developing confidence in and providing oversight of a disposal programme.

Many stakeholders have discussed monitoring in conjunction with retrievability and prior to defining a monitoring strategy a number of workshops, focused on monitoring and retrievability, were held (2000 – 2002) with key stakeholders (public representatives, industry and regulators). The aim of the workshops was to better understand key concerns and expectations related to monitoring and retrievability. These engagements identified a number of concerns related to monitoring which relate to:

- Technical issues linked to capable and reliable monitoring systems and the capacity to address slow evolution;
- A clear strategy, particularly for dealing with anomalous data; and
- An independent basis for assessing monitoring data.

A number of technical studies were carried out in the UK to provide better understanding of the available options and applicable technology for monitoring during phased disposal, including the potential for monitoring after closure. These studies and co-operative studies with other national agencies including the EC Thematic Network on Monitoring (EUR 21025 EN, 2004) have helped to identify the key principles of a

monitoring programme and those areas where development of monitoring techniques have the potential to enhance monitoring capabilities. These issues were discussed in a number of international workshops which lead to the establishment of the EC MoDeRn project.

1. Introduction

This paper provides a summary of the approach taken in developing a monitoring programme for geological disposal in the UK. Monitoring was recognised by all stakeholders as an important consideration in developing geological disposal design and has often been linked with the potential for retrievability of wastes. This paper provides some detail to the approach taken in the UK to address monitoring activities; this has been addressed in the following stages:

1. Understanding stakeholder requirements from monitoring;
2. A better understanding and development of state-of-the-art monitoring techniques;
3. Providing a basis and framework for discussing and developing monitoring programmes with stakeholders.

It summarises the steps taken in developing these three specific stages and discusses the wider value of consultation and collaborative work programmes to help bring more definition to monitoring programmes. It highlights some of the challenges in monitoring for geological disposal and describes the basis of the EC MoDeRn project (http://www.modern-fp7.eu).

2. UK programme for geological disposal

In October 2006, the UK Government and the devolved administrations[3] accepted recommendations from the Committee on Radioactive Waste Management (CoRWM, 2006) that geological disposal, preceded by safe and secure interim storage, was the best available approach for the long-term management of higher activity radioactive wastes. A framework for managing higher activity radioactive waste in the long-term through geological disposal was set out in a Government White Paper published in June 2008 (Defra 2008), known as the Managing Radioactive Waste Safely (MRWS) White Paper. This included an approach to identifying and siting a geological disposal facility (GDF) based on voluntarism and partnership with local communities.

The White Paper specified that the Nuclear Decommissioning Authority (NDA) would be the implementing organisation for the geological disposal facility. Within the NDA, the Radioactive Waste Management Directorate (RWMD) is responsible for delivering the geological disposal programme. RWMD, which took over the role previously held by UK Nirex Ltd (Nirex), is the implementing organisation and is independently regulated by the Office of Nuclear Regulation (ONR) of the Health and Safety Executive (HSE) and the environment agencies.

The MRWS White Paper includes within the framework, NDA's technical approach for developing a geological disposal facility, including the use of a staged implementation approach and ongoing research and development to support delivery.

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[3] The Scottish Executive was not a sponsor of the 2007 MRWS consultation on the framework for geological disposal of higher activity radioactive waste. It continues to support long-term interim storage and an ongoing programme of research and development.

The UK programme for geological disposal is still in the early stages of a programme of voluntarism before specific site(s) and related host geologies can be identified. The lack of a specific site or geology has to date, restricted the development of specific, detailed monitoring plans. However, early consultation with stakeholders identified the importance of a coherent and transparent monitoring programme as a basis for developing confidence in and providing oversight of a disposal programme.

3. Research on monitoring

An international workshop on monitoring, organised by Nirex was held in Oxford, England in September 1999 (Nirex, 1999). This workshop reported on some state-of-the-art monitoring techniques, such as the use of optical fibres that were being applied in some disposal mock-ups in underground research facilities. Most implementers had also identified the basic principles for monitoring and at that time the International Atomic Energy Agency (IAEA) had just commenced drafting a technical document on the approach to monitoring (IAEA, 2001). The relevance and capabilities of monitoring systems to monitor the safety, effectiveness and environmental protection were recognised and many established monitoring techniques were already being applied effectively in nuclear and mining operations and civil construction. However, most parties recognised the wider challenges of monitoring geological disposal and the need for development and definition of monitoring programmes. To achieve this would require a better understanding of what would be required from a monitoring programme for geological disposal and of what techniques could be applied to meet those requirements. At that time in the UK, discussions on monitoring was inextricably linked with consideration of retrievability and while most parties recognised the need and value of monitoring as a principle, specific requirements were not defined.

3.1 UK Stakeholder consultation

Prior to embarking on defining a strategy for monitoring, UK Nirex Limited held two workshops with the aim of understanding stakeholder concerns and requirements related to monitoring and retrievability. The first workshop was held in December 2000, and was with a cross-section of key stakeholders[4] from outside of the UK nuclear industry (UK CEED and CSEC, 2000). The second workshop, held in February 2001, was with representatives from the nuclear industry or companies that are (or have been) involved in work for the nuclear industry (UK CEED and Sextant Consulting, 2001).

Responses to the comments received at the two workshops were recorded and published (Nirex 2001a). The comments regarding monitoring included the following issues:

- **Technical Issues**: Many technical issues were raised including concerns that:
- There could be a time-lag between a problem with the geological disposal facility and the problem being detected.
- Instrumentation could fail - there needed to be development of equipment that will last for the periods required in the monitoring programme, and this equipment needed to be tested in demonstration facilities.
- A monitoring programme should be evaluated against a predictable short-term expected evolution.

[4] The participants included stakeholders with limited technical knowledge of geological disposal, as well as participants with extensive knowledge of the subject.

- A monitoring programme should cover several different spatial scales (expressed by workshop participants as relating to waste, rock and environment).
- A monitoring programme should be able to distinguish between natural and facility-induced processes, to ensure that decision-making was based on performance of the geological disposal facility.
- The details of a monitoring programme should be specific to the design of the geological disposal facility.
- **Strategy**: Workshop participants felt that a strategy should be developed that included the response to anomalous data, and that technical monitoring should be undertaken in parallel with monitoring of general issues, such as societal stability. Participants suggested that Nirex develop a “decision-making/action matrix” to deal with the possibility of recording anomalous data.
- **Independence**: Many comments highlighted the need for a monitoring programme to consider publication and independent assessment of monitoring data.

The participants of both workshops were keen to continue the discussions in another workshop that brought together both groups. Therefore, Nirex organised the Third Monitoring and Retrievability Workshop in February 2002 in Manchester (see Figure 7-1). This workshop also reviewed the Nirex Forward Programme (Nirex, 2001b). Nirex provided feedback to participants on the work done so far in order to obtain their views on how the work should be developed further. The results of the workshop provided more information about the views of various stakeholders on the subjects of monitoring and retrievability and the sorts of issues that they felt needed to be addressed in these areas (UK CEED, 2002). Several of the comments on monitoring are presented below, some of which overlap with the comments made from the earlier workshops (UK CEED, 2000 and 2001):

- The question was asked as to whether monitoring should be carried out for societal reasons; these would include: the stability of society; public acceptance of an issue; and who monitors the monitors.
- The public perception of monitoring and retrievability is two-sided. On the one hand, monitoring is carried out to show the waste is safe, but on the other hand the need for monitoring can imply that the waste is not safe.
- Stakeholders need to trust those who supply them with monitoring information. Monitoring itself needs to be very broad and should include: the environment; waste integrity, safety issues and geotechnical and hydrological aspects of the process.
- There is a need to monitor those parameters which the public feel are important and inspect these at regular intervals. The package behaviour should also be watched continuously to confirm that nothing dramatic was occurring.
- Once a site is determined, continuous monitoring will help to reassure the local community of its safety.
- It should be made clear what would be monitored and over what periods, and what would happen if the results were unexpected.
- Future work should link monitoring to decision points and show how to build in the assessment of the monitoring results to decision making.
- The issue of monitoring and retrievability allows the community some control as opposed to technical issues which they may not fully understand or have control over.

The feedback received in the Third Monitoring and Retrievability Workshop provided helpful input into the development of Nirex work programme for monitoring and retrievability. Nirex addressed all the issues raised by participants at the workshop (Nirex, 2004a).

In 2001 and 2002, Nirex funded research into public concerns and perceived hazards for geological disposal in the UK (The Future Foundation, 2002; Nirex, 2001a; 2004a, 2004b). Public opinions were gathered by holding a series of focus group meetings. Many of the opinions gathered are relevant to development of a monitoring programme for a geological disposal facility in the UK. During the focus group meetings, participants expressed considerable unease about the post-closure phase of geological disposal. Some participants were disturbed by the idea that there would ever be an end to the human management of radioactive waste. They argued that monitoring should continue for as long as the waste exists.

3.2 Technical studies

The feedback received from the stakeholder consultation confirmed that monitoring was considered a very important factor in providing a basis for stakeholders to gain information on the performance of a disposal facility. Developing a capable and transparent approach to monitoring with independent scrutiny could contribute to stakeholder confidence in the disposal design. However, it was also recognised that the parameters of interest for such monitoring differed from those routinely applied in the associated industries. It was also important to understand what could capably be monitored to address monitoring post-closure.

From the outset there was recognition that experiences across nuclear, civil engineering and mining and other industrial operations has resulted in mature and proven systems for routinely monitoring for environmental, safety and assurance purposes. Without neglecting the need or value in utilising (and developing) these existing techniques where appropriate to maintain equivalent operations, it was, however, recognised that there are aspects of monitoring for geological disposal which have different requirements from these industries and that this raises new challenges. These challenges include:

- The need to ensure that the barrier system designed to achieve safety is not compromised by monitoring, coupled with the requirement that the safety of disposal is not reliant on monitoring;
- The capacity in many cases to provide real value from monitoring processes where the evolution is over considerable timescales thus changes of any significance may not occur over realistic timescales for monitoring;
- The potential for monitoring remotely or non-intrusively recognising the challenges to retaining sensitivity of monitoring systems.
- The durability of monitoring systems located remotely within a harsh environment (heat, radiation etc.) and the challenges to both understanding anomalies and rectifying problems when these occur.

A study [SAM (2002)] was commissioned by Nirex to examine the potential requirements for monitoring and to identify options available for such monitoring, associated with the phased disposal of radioactive wastes. This report was the first step in the development of an overall strategy for monitoring within a phased disposal concept and recognised that further work would be required to develop a fuller understanding of monitoring requirements.

Additional studies (Galson/Golder, 2004 and Galson 2005) were carried out for Nirex to consider the extent to which a repository may be monitored during the post-closure institutional control phase and how a post closure monitoring programme might be progressed. These reports identified techniques which might be employed in the various stages of repository development including after closure. It also recognised the need for a monitoring programme to be defined across the stages of development from baselining the natural conditions of the site through construction, operations and closure. All studies recognised the importance of monitoring programmes including engagement with regulators, the public and other stakeholders in the development and progression of a monitoring programme. They also recognised the need for transparency in monitoring as a basis for developing confidence and trust in monitoring information.

The potential to utilise non-intrusive monitoring techniques was recognised as a means of meeting the particular needs of remotely monitoring geological disposal. This was a particularly important factor in providing methods for monitoring without affecting the passive safety of intact repository barriers. Non-intrusive, remote monitoring avoids the problems associated with the failure of monitoring sensors located within the engineered barrier system which isolates the wastes. A programme addressing non-intrusive monitoring, lead by Nirex/NDA was initiated within a large-scale EC demonstration project ESDRED (http://www.esdred.info). This programme assessed a range of non-intrusive monitoring techniques, including wireless technology before deciding to use cross-hole seismic tomography to monitor a disposal cell mock-up (Nagra HG-A experiment) developed by Nagra in Opalinus clay at Mont Terri underground research laboratory (URL) in Switzerland. This technical programme, managed by the Swiss Federal Institute of Technology in Zurich (ETHZ), included a PhD study. NDA, Nagra (Switzerland), Andra (France), Solexperts (Switzerland) and ETHZ also partnered in a further collaborative project entitled 'Testing and Evaluation of Monitoring Systems' (TEM) in granite at the Grimsel Test Site (GTS) in Switzerland. This project utilised a mock-up of a disposal barrier developed under the ESDRED and the project gave a unique opportunity to monitor the saturation behind a low pH shotcrete plug using three different monitoring systems (seismic tomography, wireless transmission and conventional wired systems). ETHZ have now completed 2 PhD (Manukyan 2011, Marelli 2012) studies addressing the development of seismic tomography at the 2 Swiss URLs, copies of which can be found on the MoDeRn website (http://www.modern-fp7.eu). These studies have helped in understanding how seismic tomography techniques can be applied to support non-intrusive monitoring of geological disposal. The experiences of using both seismic tomography and wireless sensor networks at URLs are discussed in more detail in papers to be presented at this conference (Maurer et al, 2013) and (García-Siñeriz et al, 2013).

These technical testing and demonstration programmes utilising mock-ups of disposal cells assist the implementer in both developing state-of-the-art monitoring technologies and in understanding the capabilities and limitations of these techniques. The value of progressing these studies at this stage is that they assist the implementer, regulators and other stakeholders in understanding what can be achieved in monitoring and assist in providing a basis for dialogue on monitoring programmes, which can help in ensuring that monitoring requirements are suitably accounted for when developing designs. As designs for geological disposal develop it will be necessary to continue to develop and refine monitoring systems and analysis techniques. The approach of initial trialling in disposal mock-ups helps the implementer to test and understand the capability of the specific technique; to advance the capabilities and to understand the performance of both individual barriers and composite barrier designs prior to applying these in a repository system. The research, development and demonstration at mock-up facilities also provide an improved basis for stakeholder understanding of what techniques might be employed; what information would be obtained and how that might inform a monitoring programme. Developing these at an early stage provides a platform for consultation on the approach to monitoring.

3.3 Framework for developing monitoring programmes

One of the key drivers for monitoring is to provide assurance that a design is conforming to expectations. In some situations, monitoring is used as a basis for taking action, for example many structures are regularly monitored as a basis for early notification of deterioration which could ultimately result in some form of failure. One of the key challenges of monitoring for geological disposal has been the identification of a clear process for progressing monitoring programmes. For this reason many implementers have grappled with the challenge of defining a monitoring programme for geological disposal.

Concurrent with the work programme on monitoring techniques, work has progressed in defining requirements and providing guidance for monitoring programmes for geological disposal. This has included the following:

- Regulation and guidance
- EC Thematic network on monitoring
- Collaborative workshops with international partners
- EC MoDeRn project

The flowchart below (Figure 1) presents a pictorial summary of the development of the approach to monitoring from a UK perspective and explains how work has progressed to develop a framework for monitoring. It also highlights some of the discussions and sharing of thinking on monitoring with international partners and other stakeholders. The recognised value of sharing effort, knowledge and experience by working collaboratively to: address a framework for monitoring; to gain a better understanding of the state of the art for monitoring; and to advance that state of the art by research, development and demonstration, has lead to the development of the EC MoDeRn project, which is being presented at this conference.

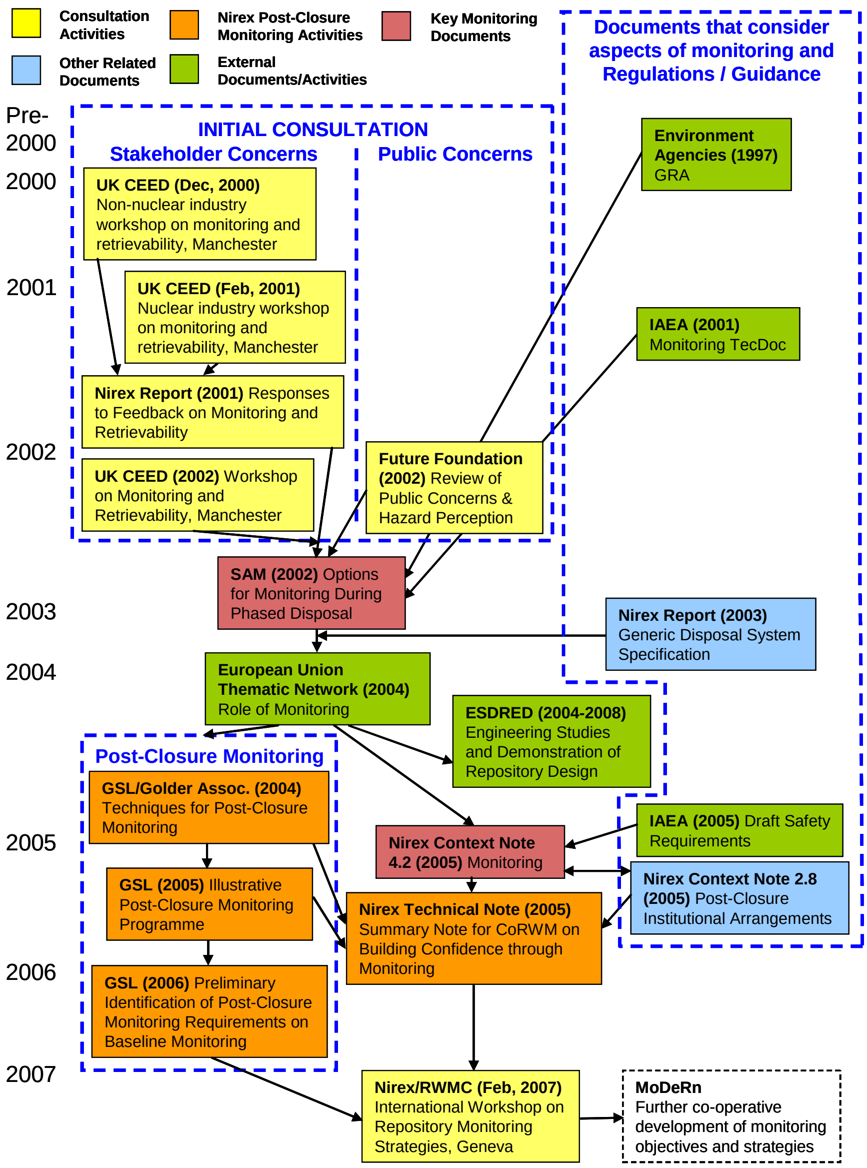

Figure 1: Flowchart illustrating key monitoring activities undertaken in the UK; their relationship to each other and to key regulatory/guidance documents

Regulation and guidance

In the UK, regulation of geological disposal is the responsibility of the Health and Safety Executive (HSE) and the environment agencies. The HSE regulates nuclear and radiological safety of nuclear installations through its Office for Nuclear Regulation (ONR). The Environment Agency (EA) is responsible for the enforcement of environmental protection regulation in England and Wales. Equivalent bodies are the Scottish Environment Protection Agency (SEPA) in Scotland and the Northern Ireland Environment Agency (NIEA) in Northern Ireland.

The principals under which the NII regulates nuclear facilities are outlined in its Safety Assessment Principles (SAPs) (NII, 2006).

The environment agencies have responsibility for granting authorisation for the disposal of radioactive waste (and for authorising radioactive discharges), and for enforcing legislation for controlling the creation and disposal of radioactive waste set out in the Radioactive Substances Act 1993 (RSA 93).
The EA and NIEA published guidance on the requirements for authorisation (Defra, 2009). The guidance set out requirements for monitoring geological disposal:

Requirement R14: Monitoring (from Defra, 2009)
"*In support of the environmental safety case, the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by construction, operation and closure of the facility.*

- *The developer/operator should establish a reasoned approach to a programme for monitoring the site and facility. This monitoring will provide data during the period of authorisation to ensure that the facility is operating within the parameters set out in the environmental safety case. However, the monitoring must not itself compromise the environmental safety of the facility.*
- *In order to provide a baseline for monitoring at later stages, the developer/operator will need to carry out monitoring during the investigation and pre-construction stages. The same measurements may form part of the site investigation programme (see Requirement R11 above). They should include measurements of pre-existing radioactivity in appropriate media, together with geological, physical and chemical parameters which are relevant to environmental safety and which might change as a result of construction and waste emplacement (for example groundwater properties such as pressures, flows and chemical composition).*
- *During the period of authorisation, radiological monitoring and assessment will be needed to provide evidence of compliance with authorised discharge limits and assurance of radiological protection of members of the public. In addition, during the construction stage and the period of authorisation, the developer/operator will need to monitor non-radiological parameters to confirm understanding of the effects that construction, operation and closure of the facility have on the characteristics of the site. In particular, the developer/operator will need to demonstrate that the changes in, and evolution of, the parameters monitored are consistent with the environmental safety case.*
- *We shall need to be satisfied that the developer/operator has carried out appropriate investigation and monitoring during the construction stage and period of authorisation to establish: the characteristics of the site; the behaviour of the disposal system; and the extent of disturbance caused by intrusive site investigation procedures and by construction, operation and closure of the facility.*
- *The monitoring programme will also need clearly to set out the levels of specific contaminants that will trigger action. It should include an action plan to deal with possible contamination from the facility and an approach to confirming any apparently positive results to avoid inappropriate action being taken in the event of a false positive observation.*
- *In accordance with Principle 4, i.e. that unreasonable reliance shall not be placed on human action to protect people and the environment, assurance of environmental safety must not depend on monitoring or surveillance after the declared end of the period of authorisation. Subsequent monitoring that the developer/operator may wish*

to include is not ruled out, provided it does not produce an unacceptable effect on the environmental safety case."

This guidance (aside from general expectations on an operation of this nature) clearly places a requirement on the implementer to monitor without compromising the environment safety case or without reliance upon monitoring as a basis for sustaining safety.

IAEA Monitoring Guidance

The IAEA Monitoring TecDoc (IAEA, 2001) set out five key purposes for monitoring which included:

- Informing decisions
- Understanding system behaviour
- Informing society at large to give confidence to advance to the next stage
- Accumulate an environmental database; and
- Meet nuclear safeguards requirements

The TecDoc also concluded that:
"*It is widely accepted that the long-term safety of geological disposal should not rely on a continued capability to monitor a repository after it has been sealed and closed. Although future generations may wish to monitor, it would be presumptuous to speculate how and why they might do this. However, there are several more immediate applications of monitoring information obtained from the outset of a development programme which the repository designers and operators can, and should, be required to consider.*"

EC Thematic Network on Monitoring

In considering how to approach monitoring for geological disposal an EC Thematic Network (EUR 21025 EN, 2004), was established to:

- Improve both the understanding of the role of and the options for monitoring within a phased approach to the deep geological disposal of radioactive waste; and
- Identify how monitoring can contribute to decision-making, operational and post-closure safety and confidence in our understanding of the repository development.

The Thematic Network (TN) was coordinated by Nirex, and brought together expertise from 12 different organisations from 10 countries. All the participants agreed on the importance of monitoring in relation to establishing baseline conditions, maintaining operational safety, and compliance (including safeguards), and in support of model confirmation regarding post-closure safety. The work within the Thematic Network built upon the earlier guidance provided by IAEA (IAEA, 2001) which identified the key purposes for monitoring geological disposal. The TN considered the role of monitoring in a phased approach to geological disposal of radioactive waste by clarifying the role of monitoring and the options for monitoring.

The TN identified many of the key principles that could be applied to monitoring, while recognising that there were recognisable reasons why monitoring schemes would differ for different countries and concepts. It also advised that the extent of monitoring should be limited to that which could provide useful results, but recognised the sensitivity of such limitations. It also cautioned against raising expectations on what monitoring could be achieved over the long timescales for geological disposal.

Geneva workshop

Following on from the completion of the EC Thematic Network and further analysis of what is required to develop a monitoring programme, Nirex and RWMC (Japan) combined to organise a workshop, attended by representatives from 13 organisations from 7 countries, in Geneva, Switzerland in 2007. The objective of the Geneva Workshop was to define the strategic basis for the development of effective repository monitoring programmes such that these would provide:

- A basis for consultation with stakeholders seeking greater confidence in the safe implementation of geological disposal.
- A process for progressive confidence building in the capability to monitor repository systems.
- Identification of areas where deeper knowledge and/or improved techniques may be required, thereby suggesting future research, demonstration and development priorities.

The key conclusions from the workshop (E.J Harvey & M.J. White, 2008) specific to future development needs were:

"*National and international programmes should:*

- *Develop monitoring strategies and objectives to contribute to the decision making process. This should be done well before embarking on any operations. Technical objectives should be carefully defined so that they are practicable, in order to avoid the potential for perception by stakeholders that decision makers are not adhering to what is perceived as an agreed process.*
- *Develop an understanding of how monitoring may contribute to the long-term safety case for a repository.*
- *Develop monitoring strategies to accompany repository design concepts.*
- *Develop a shared vision on how to respond to unexpected and/or contradictory data.*
- *Develop data management strategies for monitoring data collected from a variety of sources and locations over extensive time frames.*"

At the end of the Geneva workshop, the attendees agreed that there would be benefits in co-operative research and development between waste management organisations to clarify some of the strategic and technical requirements on research and development of monitoring in geological repositories. With this in mind, the attendees agreed that future collaboration could be undertaken through the European Commission (EC) Euratom Framework Programme and that a proposal to the EC should be developed. This resulted in the development of the EC MoDeRn project, which is being discussed in more detail at this conference.

EC MoDeRn Project

The EC MoDeRn project commenced in May 2008 and has 18 partners from 12 countries. The EC MoDeRn project has developed a framework which is aimed as structured guidance to the implementer in developing a monitoring programme including addressing anomalous results and developing case studies for monitoring in different host environments. The aim is to provide a basis for discussion and consultation with regulators, the public and other stakeholders.

The MoDeRn project has conducted research into state-of-the-art monitoring applicable to geological disposal, as well as conducting state-of-the-art research, development and demonstration of monitoring techniques which have advanced the capabilities for monitoring geological disposal. The MoDeRn project has also included a range of engagements with expert and public stakeholders and the MoDeRn project team includes social scientist professionals who have provided an important input, analysis and advice on applying and communicating information on monitoring. The work conducted under MoDeRn will benefit the UK and other national programmes in developing and consulting on their monitoring programmes, particularly as all interested parties have stressed the importance of monitoring.

4. Conclusions

This paper has summarised the UK programme for development of monitoring of geological disposal over the past decade. The consultation, research, development and demonstration conducted under this programme has helped NDA RWMD as implementing organisation to:

- Better understand the importance of monitoring to all stakeholders and through wider discussions to better understand some areas of public concern, particularly in the need for a transparent programme with the capacity for independent assessment of monitoring data.
- Appreciate that techniques to address routine construction and operational monitoring largely exist and have been well developed to the needs of geological disposal. Have a better understanding of state-of-the-art monitoring techniques applicable to monitoring geological disposal. However, as basis for assurance that disposal designs perform as required, there is a need to continue to address means of monitoring these designs with particular reference to the use of non-intrusive techniques where these are feasible.
- Consider monitoring needs as an integral component of disposal designs as they develop.
- Utilise the framework for monitoring arising from the MoDeRn project as a basis for consultation on and development of monitoring programmes.

Monitoring will continue to be an important consideration in the UK programme. There will be future opportunities for development and enhancement of specific monitoring techniques to support the forward programme. It is important that the effort applied to monitoring programmes provides value while meeting stakeholder needs and expectations. The development and use of a framework for monitoring should help both as a basis for consultation but also to assure a coherent and transparent approach.

References

[1] CoRWM (2006) Committee on Radioactive Waste Management, “Managing our Radioactive Waste Safely- CoRWM’s Recommendations to Government”, July 2006. CoRWM Document 700. Available at www.corwm.org.uk

[2] Defra (2008). Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal, A White Paper (Cmnd 7386) by Defra, BERR and the devolved administrations for Wales and Northern Ireland.

[3] Environment Agency and Northern Ireland Environment Agency (2009). Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation, February 2009.

[4] EUR 21025 EN (2004) Thematic network on the role of monitoring in a phased approach to geological disposal of radioactive waste

[5] E.J. Harvey and M.J. White, Monitoring of Geological Repositories: Summary Note of an RWMC / Nirex Workshop Geneva, 2007

[6] GSL and Golder Associates (UK) Ltd (2004). Techniques for Post Closure Monitoring Summary Report, 0358-2 Version 1.1.

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

[8] NII (2006). Safety Assessment Principles for Nuclear Facilities. 2006 Edition, Revision 1.

[9] Nirex (1999) – 4th International Workshop on Design and Construction of Final Repositories – Monitoring, Oxford, 1999.

[10] Nirex (2001a) Nirex Report N/33 – Generic Repository Studies – Responses to Feedback on Monitoring and Retrievability, July 2001

[11] Nirex (2004a). Responses to Feedback Received at Follow-up Workshop on Monitoring and Retrievability. Nirex Report N/112.

[12] Nirex (2004b) Nirex Report N/11 – The Foundation Report on the Nirex Involvement Programme and Social Science Research, March 2004

[13] The Future Foundation (2002). Identifying Public Concerns and Perceived Hazards for the Phased Disposal Concept, A report to Nirex.

[14] UK CEED and CSEC (2000). Workshop on the Monitoring and Retrievability of Radioactive Waste, A report for Nirex.

[15] UK CEED and Sextant Consulting (2001). Industry Workshop on the Monitoring and Retrievability of Radioactive Waste.

[16] UK CEED (2002). Workshop on the Monitoring and Retrievability of Radioactive Waste. A Report for Nirex prepared by The UK Centre for Economic and Environmental Development (UK CEED) in association with ForthRoad Limited and The Centre for the Study of Environmental Change (CSEC) in Lancaster University.

C.3 Session S3: Theme 2: Monitoring – The wider perspective: Regulatory and stakeholder viewpoints

Different Views on Monitoring and the Governance of Repository Development and Staged Closure

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Summary

Repository monitoring is now widely seen as a necessary part of programmes for the geological disposal of radioactive waste. However, we find competing perspectives on how to specify the significance of monitoring. Among technical experts monitoring is viewed firstly as a matter of "performance confirmation", a tool for validating the safety case underlying repository construction. A second view we find among lay stakeholders is that of monitoring as enabling the "critical assessment" of safety, an instrument for detecting uncertainties and emergent problems in a repository. After presenting these differing perspectives on monitoring in connection to the questions of "whether", "why", "what", "where" and "for how long" to monitor we discuss monitoring in light of Alvin Weinberg's identification of "tireless vigilance" as a combined technical and moral principle of nuclear safety. We suggest that questions about "how much monitoring constitutes sufficient vigilance" and "how should it be organised" are of a societal nature and as such need to be broadly discussed and debated. We can also expect significantly different resolutions to these issues to inform the design and development of repository programmes in different contexts.

1. Introduction

Geological disposal of higher activity radioactive waste presents many technical and societal challenges, not least because of the timescales involved. Research on geological disposal has been carried out in different countries for about half-a-century but it is only in the past decade or so that monitoring has become a specific focus of political, policy and research & development activity. Monitoring can refer to a range of different activities and arrangements, which raises the questions of what is meant by monitoring and what is its purpose?

In this paper, drawing on original research conducted as part of an international research project and involving the analysis of key documents, expert interviews and stakeholder workshops, we explore the views of professional experts in the field of radioactive waste management and of community stakeholders on the nature and role of monitoring in geological disposal.[5] We find that monitoring has different meanings for different people, and that expectations of monitoring differ between groups in society, and even between individuals belonging to the same group or organisation. We point to a tension between two

[5] A full description of the project and copies of published reports can be found at: http://www.modern-fp7.eu/home/.

perspectives on how to assess monitoring. The first we find among technical experts, who tend to view monitoring in terms of "performance confirmation"; that is, as a tool for validating the repository design concept and its construction. The second view we find among lay stakeholders, many of whom see monitoring in terms of the 'critical assessment' of safety; that is, as a form of surveillance that acknowledges uncertainties and can detect unanticipated problems in a repository. We first outline the different views on monitoring that we have identified, structured as a series of questions about "whether", "why", "what", "how/where" and "for how long" to monitor. We conclude by considering the role of monitoring in the governance of geological disposal and in particular in relation to the exercise of societal vigilance.

2. Empirical data

The findings summarised here are based on several data sources: an analysis of strategic and technical documents on repository monitoring; interviews with 18 specialists in European radioactive waste management organisations; observation of technical workshops on repository monitoring; workshops involving volunteers from communities which host existing nuclear facilities who have had varying degrees of engagement with radioactive waste management projects in Belgium, Sweden and the United Kingdom; and a visit to two underground research laboratories (URLs) in Switzerland with a subset of these volunteers. Where possible, interviews and group discussions were recorded and fully transcribed to facilitate thematic content analysis. Interpretation of the results was supported by reference to relevant research literature from the field of social studies of science and technology.

The research methods employed generated qualitative data the analysis of which cannot be claimed to provide a representative categorisation of different opinions regarding monitoring in relation to geological disposal, either at a national or a European level, but which provide insight into the understandings, concerns, reasoning and preferences of experts and affected citizens.

3. To monitor or not to monitor

One thing on which all of our respondents agreed was that monitoring should be an integral part of repository development and design.[6] Two reports are referred to by waste management experts as being decisive in the way their community looks at monitoring today. The first of these is an International Atomic Energy Agency (IAEA) Technical Document on monitoring of geological repositories for high level radioactive waste (IAEA 2001). In this report we find the first explicit definition of monitoring for geological disposal. The second is the report of a European Thematic Network (ETN) on the role of monitoring in a phased approach to the geological disposal of radioactive waste (EC 2004). The structural integration of monitoring activities into the geological disposal process is therefore a relatively recent development. This has been marked at the international level by the inclusion of safety requirements relating to repository monitoring strategies in an IAEA Safety Standards document (IAEA 2006). This document states that safety should be ensured 'by passive means inherent in the characteristics of the site and the facility and those of the waste

[6] There are nevertheless evident national differences in the attention given to monitoring by radioactive waste management organisations and regulators, a point to which we return further on in this paper. This is often associated with different disposal concepts: in France, for example, where reversibility has become a policy requirement, monitoring has been the focus of research and development, whereas in Sweden, where the proposed concept does not envisage retrievability of wastes, monitoring is not viewed as the same challenge.

packages' (IAEA 2006, p. 4), and should not depend upon monitoring and active management. As we shall see, however, the IAEA envisages a contributory role for monitoring that supports progress to the goal of passive safety.

Why monitor? Both the IAEA and the ETN reports give multiple reasons for monitoring a geological repository. The main reasons can be summarised as being that monitoring can: (a) enhance understanding of the behaviour of the repository system and its environment, (b) offer confirmation of the disposal concept, and thus (c) provide information on the repository system for purposes of decision making now and in the future, thereby supporting a stepwise implementation of geological disposal. The role of monitoring in performance confirmation is also explicitly pointed out in the IAEA's Safety Standards document, which refers to its role in confirming the conditions for both operational and post-closure safety, thereby supplying an evidential basis for decision-making leading to the stepwise implementation of geological disposal (IAEA 2006). In addition, it is explicitly assumed that monitoring can support 'public confidence' (IAEA 2001; EC 2004) or social or public 'acceptability' and 'acceptance' (e.g. IAEA 2006, p. 2, 30)[7]. The role of monitoring in providing assurance was explicitly mentioned by all of the technical specialists interviewed as one of the main drivers for monitoring, with distinctions being drawn between three different ways in which this is done:

- monitoring as a tool of performance assessment and quality assurance for the designer, modeller, implementer – supplying means for the verification of both the repository system and the modelling behind it;
- monitoring as a tool for demonstrating that the repository programme has successfully incorporated specific societal expectations by being compliant with regulatory requirements, thereby providing assurance to regulators (as intermediaries between implementers and the public), particularly in relation to requirements for operational safety and environmental impact assessment;
- monitoring as a tool for building public confidence both by responding to and even pre-empting potentially changing public demands for transparency and oversight of repository development and staged closure.

The role of monitoring for public confidence building was echoed in the workshop activities with local stakeholders in Belgium, Sweden and the United Kingdom (UK). The Belgian group, for example, came to the conclusion that confidence building and 'keeping guard' over the safety of the facility were the main reasons for monitoring.[8] The UK group also identified stakeholder confidence in the safety of the repository as one of three reasons to monitor, the other two reasons being verification of compliance with prevailing regulations or standards, and 'quality control' to support continuous refinement or improvement.[9] Informing both the Belgian view on 'keeping guard' and UK views on verification of continued safety is a notion of maintaining a watch over the repository, something to which we return below. Both local and national stakeholder representatives in Sweden discussed the importance of the timing and placing of monitoring activities, such as the question of whether monitoring programmes carried out in underground laboratories or pilot facilities (referred to by the implementer as 'dress rehearsal' laboratories) during repository development can reduce the need for monitoring of the 'real' repository during implementation?[10] In both Sweden and

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[7] In this last document, the role of monitoring for social or public 'acceptability' is particularly linked to the question of post-closure safety.

[8] MoDeRn Exploratory Engagement Exercise – Belgian Workshop 1 – Mol – 15 December 2011.

[9] MoDeRn Exploratory Engagement Exercise – UK Workshop 1 – Birmingham – 19 April 2012.

[10] MoDeRn Exploratory Engagement Exercise – Swedish Workshop – Östhammar – 16 March 2012.

Belgium, the argument was made by participants that monitoring is needed 'to know what happens in reality'. Confidence building through compliance monitoring and quality control thus seems to be the key reason for monitoring put forward by implementers, regulators and citizens confronted with a geological repository programme. However, some subtle but significant differences can be detected between the viewpoints of these different actors.
An important difference in the positions taken by regulators and implementers and their monitoring experts on the one hand, and (potentially) affected citizens on the other hand, is the emphasis put by the former on performance 'confirmation', while the latter comes in from the angle of quality control and 'checking' expected behaviour. This difference in view is particularly evident where the question of long-term safety is concerned.

During an 'expert stakeholder workshop' with implementers and regulators[11], it was stressed on several occasions that the focus should be on performance confirmation, and not on checking performance (see Harvey, White 2011). Because these actors rely heavily on the safety case as 'the principal method for demonstrating confidence in the safety of the disposal system', they consider that checks on whether or not the system provides adequate safety come from the development of the repository design, and from the site selection and site characterisation activities. Obtaining a licence for constructing and operating a repository, they argued, is proof of a high degree of confidence in the safe performance of a repository, and hence 'there would not be reliance on monitoring as a basis for ensuring safety' (recorded in Harvey, White 2011, p.18, emphasis added). If monitoring is dedicated to helping stake out a path to inherently safe waste packages, facilities and sites then it must be dedicated to progressively reducing the need to repeatedly 'check-up' on safety. It must be dedicated to verifying the needlessness of continuing to look.

However, drawing on research on risk and trust (e.g. Luhmann 1979, Zucker 1986, Shapiro 1987, Wildavsky and Dake 1990, Giddens 1991, Simmons and Wynne 1993, Irwin 2008) and on an analysis of published accounts of the relationship between stakeholders and monitoring activities focussed on the field of radioactive waste management, it seems clear that in many situations, stakeholders expect a more critical assessment of safety. For that reason, they do not only require operator and expert assurance of safety, but also the additional assurance of (independent) monitoring for any evidence of exposure to harmful releases. They may not expect the monitoring activity in itself to contribute to the safety of the repository, but do expect it to assess, or check that safety is ensured. This distinction between "checking" and "confirming" may therefore seem to be largely a question of semantics. As we argue below, however, there is more to it than that.

The only "lay" participant in the 'expert stakeholder workshop' referred to above observed that the focus on confirmation, rather than on checking, of expected behaviour came across as 'rather arrogant, since the system might not perform as expected'. He furthermore pointed out that 'implementers should not assume that monitoring will only confirm their expectations' (cited in Harvey, White 2011, p. 18). Similar arguments were made by participants in the Belgian, Swedish and UK workshops with community stakeholders. In the Swedish discussions, the idea that the performance of, for example, waste packages could be confirmed through experimental monitoring in an underground research facility, distant from the actual repository site, was questioned[12]. When discussing this point with the Belgian group, the use of the term 'performance confirmation' in a presentation by a waste

[11] MoDeRn 'Expert Stakeholder Workshop' – Oxford – 4-5 May 2011.

[12] MoDeRn Exploratory Engagement Exercise – Swedish Workshop – Östhammar – 16 March 2012.

management organisation representative was questioned, as participants considered it inappropriate to take as a starting point the assumption that no problems can occur in future. They pointed out that in the case of geological disposal one will never be able to reach full certainty that all will go well in future before starting implementation[13]. Monitoring was thus considered a necessary action to remain 'on guard', but was only seen as effective if accompanied by a proper 'response plan' or what UK stakeholders referred to as a 'Plan B' should anything unexpected be detected[14]. This raised the concern that designing monitoring programmes for performance confirmation is likely to lead to implementers prioritizing different measures to those which might be most appropriate for registering more unlikely and unexpected events.

4. What, where and how to monitor?

The IAEA and ETN documents identify a number of different types of monitoring: monitoring related to occupational health and safety during the operational phase; monitoring the surrounding environment for environmental protection; monitoring repository processes for a variety of technical reasons and to support staged decision making; and Safeguards monitoring to prevent nuclear proliferation (EC 2004; IAEA 2001; IAEA 2006). From an implementer's perspective, monitoring the behaviour of the repository system at close range, so within the repository itself, for the purpose of verifying design elements supporting the long term safety of the facility is considered especially advantageous during the phase of construction and operation, when changes in the design remain possible. It does, however, present two important challenges.

The first challenge is whether or not there are processes that can be measured in the relatively short period before closure which would conclusively validate the accuracy of predictions of (very) long term system behaviour. Today, discussion continues about what exactly should be measured, and which parameters are important. However, the general position taken by the technical specialists interviewed was that it will be possible to identify measurable parameters that would enable them to validate (and if need be calibrate or adjust) the models on which they build their safety cases, but that for both technical and financial reasons the parameters selected are likely to be few in number.

The second is how to organise such monitoring without comprising fundamental safety barriers. This is seen as particularly problematic after closure of the facility (see below), but already plays a part during the stages before closure. Hence the focus on investigating options for non-intrusive monitoring techniques, such as wireless sensor networks and wireless through-the-earth data transmission, fibre-optic technologies and geophysical techniques, monitoring of groundwater and chemistry, geotechnical monitoring, or air-based and satellite-based monitoring. But although some of these techniques look promising and are likely to be of relevance for repository monitoring, several of them (e.g. wireless data transmission, fibre-optics and geophysics) still require quite some further research to adapt them to the specific repository monitoring requirements (White et al 2010).

Based on the impressions of lay-stakeholder concerns expressed by the experts that we interviewed, it seems that there is a widely held perception in the expert community that public and stakeholder expectations are likely to focus on environmental monitoring in order

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[13] MoDeRn Exploratory Engagement Exercise – Belgian Workshop 2 – Mol – February 2nd 2012.

[14] MoDeRn Exploratory Engagement Exercise – Belgian Workshop 1 – Mol – December 15th 2011 and UK Workshop 1 – 19th April 2012.

to protect against human health impacts. A review of literature on citizen and stakeholder engagement with monitoring, within the nuclear sector and in other contexts, seems to corroborate this perception, as most of the activities reported did involve some sort of environmental monitoring. In several cases this monitoring was commissioned or conducted by local institutional stakeholders, particularly local governments, including some examples that integrate this with monitoring of the socioeconomic environment (e.g. Conway et al 2009). Dissatisfaction with or distrust of institutions has also led members of some communities to demand or even initiate participatory environmental monitoring, which involves local citizens in data collection (e.g. Vari, Ferencz 2007; NEA 2009). In the field of radioactive waste and other nuclear industry facilities, there is considerable evidence of stakeholder and citizen involvement in facility monitoring activities (e.g. NEA 2003, 2010). This demonstrates the desire of citizens and communities in many different contexts for active engagement with facility monitoring programmes.

From our own engagement exercises, we learned that local citizens were less concerned about the "what" and "where" questions in terms of which parameters or at which exact location to monitor. What they did insist upon, was that a monitoring programme for geological disposal should be as comprehensive as possible (including but not restricted to monitoring of the socioeconomic environment), and should have a broad scope, including both near-field and far field-monitoring. Both the Belgian and UK groups acknowledged the potential tension between potentially intrusive near-field monitoring and the integrity of barriers and seals that is required for passive safety. It was also considered to be important, most notably by the Belgian group, to continue searching for alternative parameters or techniques for processes that would be difficult to monitor with current technology, and to consider laboratory simulations as alternatives to near-field monitoring (e.g. in a post-closure situation)[15].

5. How long to monitor?

On the question of how long to monitor, the views of technical specialists and concerned citizens again tended to differ. Post-closure monitoring is something that was considered by technical experts to be unnecessary, as they did not expect anything to be detected once a situation of passive safety had been ensured by properly closing a facility. For them, monitoring is an activity dedicated to advancing and facilitating repository closure and confirming that the conditions outlined in the regulatory safety case have been achieved. Near-field monitoring in particular was said by many of them to be unrealistic and even potentially counterproductive insofar as the techniques used could contribute in any way to compromising barrier integrity. Nevertheless, many experts interviewed thought that there could be value in post-closure monitoring if it were needed to reassure other actors such as local communities, a position that was also expressed in technical opinion documents (e.g. IAEA 2006). It was furthermore noted by our respondents that although there may be little evidence of statutory requirements for post-closure monitoring for reasons of radiological protection, it seemed likely that they would be introduced in some countries in the future in response to societal demands.

Evidence from the Belgian, Swedish and UK workshops confirmed that constructively engaged citizens do have expectations and concerns regarding post-closure monitoring, and are not likely to accept the issue being ignored. What was less clear is the type of monitoring (near-field, far-field or the surface environment) they would be expecting in the post-closure

[15] Conclusion drawn by the participants during the final workshop in Belgium (MoDeRn Exploratory Engagement Exercise – Belgian Workshop 4 – Mol – May 24th 2012).

period. In the Swedish workshop it was pointed out that even if post-closure monitoring is considered desirable, the technological innovation required to enable such monitoring is hardly likely to take place without the purposeful allocation of funds to related research and development.[16] Community stakeholders were therefore concerned about post-closure safety but, unlike the technical experts, tended to see continued monitoring of some sort as being necessary not merely to confirm that the evolution of the repository system conforms to technical expectations but to ensure that it continues to do so and is not affected by unanticipated events or evolutions, a concern to which we return in our final section.

6. The role of monitoring in the (risk) governance of geological repositories

For several decades now, one of the key principles informing the management and regulation of nuclear safety has been that of constant surveillance. This is firstly a political and moral principle which informs the practical design and development of nuclear activities: this principle is therefore an expression of what societies interpret nuclear safety to mean. Monitoring programmes focused on different types of nuclear activity are therefore ways of putting the moral principle of tireless vigilance into technical practice. This is particularly the case for nuclear installations such as power plants, fuel production or reprocessing plants, and storage facilities, as pointed out by nuclear scientist Alvin Weinberg, when he referred to the unusual degree of vigilance which of necessity had to be exercised over all programmes of nuclear power generation during the entire course of their development in order to guarantee safety (Weinberg 1972). Deep geological repositories, incorporating the technical - and moral - principle of passive safety, can be understood as a way of trying to renegotiate the need for unremitting vigilance by delegating responsibility for safety to an engineered geological disposal system. The question then is how should the gradual transition from active human vigilance to passive safety without human intervention be organised?[17] Weinberg believed that effective geological disposal reduced the need for vigilance to a minimum, in line with current expert thinking that all that will be needed of society to ensure safety is surveillance to avoid intentional or unintentional human intrusion into the repository system. However, our exploratory engagement with community stakeholders from three European countries suggests that more is expected by many citizens.

These are, as Weinberg reminds us, societal questions that cannot be answered from a technical-expert perspective alone (Weinberg 1972). Society will therefore have to decide what kind of human vigilance is needed and for how long it should continue. Nevertheless, for society to relinquish direct control of the wastes will require confidence in the repository system and trust in those responsible for designing, implementing, overseeing and regulating it. It may therefore be easier for national and local decision-makers – and the communities that they represent - to commit to taking successive steps in repository siting, development, licensing, construction and operation if the contingent nature of their trust and commitment[18] at each and every stage is acknowledged and the opportunity to re-evaluate or even veto plans is upheld.

In addition to providing confirmation of the models upon which the safety case is based, therefore, there is another way in which monitoring can support public confidence. This is by

[16] MoDeRn Exploratory Engagement Exercise – Swedish Workshop – Östhammar – 16 March 2012.

[17] This is excepting, of course, any external safeguards monitoring, most likely involving remote sensing technology, against human access in order to prevent the proliferation of nuclear materials.

[18] On the provisional nature of social trust see, for example, Lewis and Weigert 1985; Giddens 1991; Jones and George 1998; Walls et al. 2004.

helping to demonstrate that the implementer of a disposal programme is aware that there are always systemic uncertainties involved and that it is necessary to take a precautionary approach[19], although this potential role of monitoring was not emphasised explicitly in our workshops. Such open acknowledgement of uncertainty is not without its risks, of course, in that it may appear to bring into question the premise of passive safety as the technological solution to the socio-technical problem of guaranteeing unflagging vigilance over long-lived high-level radioactive waste. By introducing the notion of retrievability or reversibility into law, however, countries such as Switzerland and France are already moving towards an adapted socio-technical solution, one still directed towards achieving passive safety, but which recognises that this end point may be further away than initially planned, subject to a longer chain of socio-technical decision-making, and may not be final.20 Such evolutions remind us that we may inevitably pass the burden of decision about final closure to subsequent generations. Acknowledging this requires that we think more specifically about the type of information, knowledge and skills that need to be passed on to future generations, and the role that monitoring might play in meeting the needs of future operators, regulators, decision-makers and affected citizens.

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References

[1] *Barthe, Y.* 2009: Les qualités politiques des technologies. Irréversibilité et réversibilité dans la gestion des déchets nucléaires. In : Tracés. Revue de Sciences humaines 16 : p. 119-137

[2] *Conway, S.; Aguero, J.; Navis, I.L.* 2009: The Clark County Monitoring System – An Early Warning Indicator System for Clark County, Nevada. In: Sirgy, M.J. (ed.): Community Quality-of-Life Indicators: Best Cases III. New York and Berlin

[3] *EC*, 2004: Final report of the Thematic Network on the role of monitoring in a phased approach to geological disposal of radioactive waste (EUR 21025 EN). Brussels

[4] *Giddens, A.*, 1991: Modernity and Self-Identity. Stanford, California

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[19] On uncertainty, precaution and the governance of technology see, for example, Stirling 2006.

[20] For a discussion of the adoption of the principle of reversibility in French radioactive waste policy, see Barthe 2009.

[5] *Giddens, A.*, 1994: Risk, trust, reflexivity. In: Beck, U.; Giddens, A.; Lash S. (eds.): Reflexive Modernization: Politics, Tradition and Aesthetics in the Modern Social Order. Cambridge

[6] *Harvey, L.; White, M.*, 2011: MoDeRn Expert Stakeholders Workshop Report. Deliverable D5.3.1 of the MoDeRn project – Euratom – FP7 (232598). http://www.modern-fp7.eu/fileadmin/modern/docs/Deliverables/MoDeRn_D5.3.1_Expert_Stakeholders_Workshop_Report.pdf

[7] *IAEA*, 2001: Monitoring of geological repositories for high level radioactive waste (IAEA-TECDOC-1208). Vienna

[8] *IAEA*, 2006: Geological Disposal of Radioactive Waste, Safety Requirements. (IAEA Safety Standards Series No.WS-R-4. Vienna

[9] *Irwin, A.*, 2008: Risk, Science and Public Communication: third-order thinking about scientific culture, In: Bucchi, M.; Trench, B. (eds.) Handbook of Public Communication of Science and Technology. London & New York

[10] *Jones, G. R.; George, J.M.*, 1998: The Experience and Evolution of Trust: Implications for Cooperation and Teamwork. In: The Academy of Management Review 23/3 (1998), p. 531-546

[11] *Lewis, J. D.; Weigert, A.*, 1985: Trust as a Social Reality. In: Social Forces, 63/4 (1985), p. 967–985

[12] *Luhmann, N.*, 1979: Trust: a mechanism for the reduction of social complexity. In: Luhmann, N. (ed.): Trust and Power. New York

[13] *MoDeRn*, 2011: National Monitoring Contexts - Summary Report. Euratom – FP7 (232598). http://www.modern-fp7.eu/fileadmin/modern/docs/Reports/MoDeRn_MonitoringContext_SummaryReport.pdf

[14] *NEA*, 2003: Public Confidence in the Management of Radioactive Waste: The Canadian Context, Workshop Proceedings Ottawa, Canada 14-18 October 2002. OECD-Nuclear Energy Agency. Paris

[15] *NEA*, 2009: Regional Development and Community Support for Radioactive Waste Management, Synthesis of the FSC National Workshop and Community Visit, Tengelic and Bátaapáti, Hungary, 14-17 November 2006. OECD-NEA No 6258. OECD-Nuclear Energy Agency. Paris

[16] *NEA*, 2010: Radioactive Waste Repositories and Host Regions: Envisaging the Future Together, Synthesis of the FSC National Workshop and Community Visit, Bar-le-Duc, France 7-9 April 2009. OECD-NEA No 6925. OECD-Nuclear Energy Agency. Paris

[17] *Shapiro, S.P.*, 1987: The Social Control of Impersonal Trust. In: American Journal of Sociology (1987) 93/3, p. 623-658

[18] *Simmons, P.; Wynne, B.*, 1993: 'Responsible Care: trust, credibility and environmental management'. In: Schot, J.; Fischer, K. (eds.): Environmental Strategies for Industry: International Perspectives on Research Needs and Policy Implications. Washington

[19] *Stirling, A.* 2006: Uncertainty, precaution and sustainability: towards more reflective governance of technology. In: Voss, J.P.; Bauknecht, D.; Kemp, R. (eds.): Reflexive Governance for Sustainable Development. Cheltenham

[20] *Vári, A,; Ferencz, Z.,* 2007 : Radioactive waste management in Hungary: changing approaches and conflicts, *Journal of Environmental Assessment Policy and Management*, 9/2 (2004): p. 185–209

[21] *Walls, J.; Pidgeon, N.; Weyman, A.; Horlick-Jones, T.*, 2004: Critical trust: understanding lay perceptions of health and safety risk regulation. In: Health, Risk & Society 6/2 (2004), p. 133 - 150

[22] *Weinberg, A.*, 1972: Social Institutions and Nuclear Energy. In: Science 177/4043 (1972), p. 27-34

[23] *White, M.; Morris, J.; Harvey, L.*, 2010 : Monitoring Technologies Workshop Report (7-8 June 2010 – Troyes , France). Deliverable 2.2.1. of the MoDeRn project – Euratom – FP7 (232598). http://www.modern-fp7.eu/fileadmin/modern/docs/Deliverables/MoDeRn_D2.2.1_Troyes_Monitoring_Technologies_Workshop.pdf

[24] *Wildavsky, A.; Dake, K.,* 1990: Theories of Risk Perception: Who Fears What and Why? In: Daedalus (1990) 119/4, p. 41-60

[25] *Zucker, L.G.*, 1986: Production of Trust: Institutional Sources of Economic Structure, 1840-1920. In: Research in Organizational Behaviour 8 (1986), p. 53-111

Monitoring For Geological Disposal – A Stakeholders Viewpoint

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Summary
This paper/presentation is an attempt to describe the scope and objectives of monitoring in different stages of siting, design, preparation, operation and follow up of a geological repository for high-level long-lived radioactive/nuclear waste.
In all stages, monitoring should assist in building confidence of all the stakeholders, including not only high level skilled specialists of authorities and regulatory bodies but also concerned political authorities and non-technical stakeholders, e.g. the population of the region around the repository. This is extra important if a repository has to be built and used in a (densely) populated region. In the later stages, monitoring shall guarantee early warning and if necessary eventually indicate the need for remediation.
Confidence in the planned repository has to be created early in the design and preparation and maintained during the whole lifetime of the repository, also after closing. This means that monitoring has to begin early in the stage of design/preparation, and the results of this monitoring have to be communicated efficiently to all stakeholders, appropriate to their needs and wishes. The monitoring techniques and objectives will evolve in time as the repository will evolve from a potential location, through the preparation of the installation, the use and finally the closure of the installation.
As our normal engineered equipment and barriers have a limited lifetime, measured in decades, maximum in centuries, and the required timescale for a repository of this type is much longer, approaching eternity, it could be wise to also consider, in addition to the well-known classic barriers and techniques, the properties of naturally occurring materials known to be stable during the geological timescale.

1. Introduction

This paper does not represent the viewpoint of the Stora or Mona partnership but of individual members, volunteering in the Stora partnership from the community of Dessel, Belgium. It is based on their experience in Stora with monitoring for the cAt-project (disposal of the Belgian low-level and short-lived waste) and on the participation in the Modern project. The Belgian local partnerships Mona and Stora were invited to participate in the Modern Workshops. Several volunteers of both partnerships participated and exchanged their views on different aspects of monitoring.

2. Scope

This presentation tries to highlight the view of (local) stakeholders on the different monitoring activities that have to be considered in the frame of the siting, design, preparation, construction, operation and closure of a geological repository for high-level long-lived radioactive and nuclear waste.

3. Objectives

Confidence building in the system, and maintaining it, is one of the main objectives of monitoring through all stages of the setting up, operation and follow up of the repository. In the later stages, operation and follow-up, monitoring should be able to provide early warning if something unexpected happens and to initiate remediation, if appropriate.

In the early stages of preparing a repository for high-level long-lived waste, monitoring should be established in order to verify that the behaviour of site geology and conditioned waste is as predicted/foreseen. This is essential for the building of confidence in the whole system.

During construction of the repository, monitoring shall also ensure that safety and security of workers, population and environment is maintained and guaranteed, in order to further support and maintain the confidence of all stakeholders, including the local population.

After closure, monitoring should be able to guarantee that safety and security of population (also at distance) and environment is maintained, also for the future. If measurements should detect an evolution that indicates potential risk for people or environment, necessary corrective actions, including resettlement of population if necessary, shall be taken in due time if appropriate. Renewing, maintaining and extension of confidence will be necessary as there will be an evolution in stakeholders in the future centuries.

4. Confidence Building

Confidence building and maintenance is vital from the early stages of siting and design of the repository in order to avoid NIMBY reactions and actions, and therefore it has to be initiated very early in the process. A very important mechanism to achieve this can be the monitoring in the successive stages, and the appropriate communication of the results of this monitoring to all the different stakeholders. This communication has to be adapted to the specific needs of the different stakeholders. Involvement of ALL stakeholders including also the residents of the region where the repository will be built (”local stakeholders”), for instance through an organized partnership, can be an important step in building confidence. There can be a lot of important know-how present among these stakeholders that can be used e.g. in the framing of a certain level of co-design (e.g. civil construction, corrosion and ageing effects in other installations, …).

The information transmitted to the technically responsible authorities will be very technical and the justification of conclusions will be on a very specialized level, whereas the communication to the politically responsible people and the locals living in the vicinity of the repository has to be such that it can be understood also by people who are not technical specialists. Although the content and the form of the information, shared with the different stakeholders will not be identical, there should not be any contradiction between them.

5. Design and preparation

Man-made barriers, even using modern, highly technological techniques and materials, will have a limited guaranteed lifetime measured mainly in decades or, exceptionally, centuries. In the case of a repository for long-lived high-level radioactive and nuclear waste, safety and security has to be maintained and guaranteed over thousands of years. Other than for a repository of short-lived low-level waste, we cannot rely exclusively on manmade barriers. These barriers should be complemented with natural barriers that, through archeological and geological investigations, have been demonstrated to be stable for the required period, taking into account foreseeable short, medium and long term evolutions (climate changes!?) .

In the early stages of preparation of a repository (site investigation and preparation, conditioning of the waste) monitoring of the behaviour of the geological environment and of the conditioned waste can be started up. Evaluation/comparison of these monitoring results with the predicted long term properties and evolution should be performed. If substantial discrepancies or malfunctions appear, corrective actions have to be taken and preventive actions established (proper management principles) in order to minimize consequences in the near and further future. This should be communicated and explained in due time to the respective stakeholders in an adequate fashion.

If monitoring is based on measurements of e.g. physical or chemical properties, it should be decided as far as is reasonable what actions will be undertaken if the results of this measurements are different from what is normally expected. If through monitoring, a situation appears that is not predicted or an evolution appears completely different from what was expected, a reevaluation of this situation will be mandatory. The new situation has to be discussed and evaluated with all stakeholders, including politicians and inhabitants of the region and the consequences of this situation have to be communicated clearly to them.

6. Construction and Operation

In addition to the monitoring established in the previous phases, supplementary monitoring has to be implemented in order to guarantee safety and security of workers, population and environment during construction and operations of the repository. Immediately prior to loading the conditioned waste receptacles in the repository, a detailed investigation should be undertaken in order to guarantee, so far as is realistic, the proper behaviour of the material in the past and in the future. Probably, there will be a time lapse of several decades between the start of the siting and design of such a repository and the start of placing the waste in the repository. It should be a waste of resources if monitoring equipment, deemed to be necessary only several decades further in the future, is installed too early, as we can expect a substantial progress in techniques and know-how. Nevertheless it should be feasible, with the knowledge and techniques available at that moment, to build and operate the equipment, deemed necessary at that time and to take the necessary corrective and preventive measures if monitoring conclusions require it. There should be sufficient flexibility in the system to respond to unexpected, unfavorable events that occur. Retrievability and possible reversibility could be a requirement during this phase of the process.

Confidence building and maintenance will remain an important issue, as the complete process of siting, design, building and using the repository will extend over several (6-10) decades, and therefore also over several (3-4) generations. Adapted techniques should be developed and implemented to overcome this difficulty. This phenomenon is much more important for a geological repository for high-level long-lived waste than it is for low-level short-lived waste, where the whole process can be finished in a few decades – one or two generations.

7. After Closure

The monitoring systems in place after the closure of the repository have to be able to detect and alert in due time any event that could pose a potential threat to the environment in order to allow authorities to take appropriate countermeasures. At this time, it is not reasonable to define criteria and limits that will be acceptable and valid for the future generations, but it is important, and should be part of the design of the whole process, that we could build, operate and implement such a monitoring system taking into account the present know-how, capabilities and actually accepted criteria and limits.

An important issue is to keep in memory for the future generations what is in the repository, what are the risks, the expected evolution of them in time etc. It should be avoided to place or use in the repository materials that could have a high value for future generations in order not to provoke attempts of retrieval and re-use of such materials (similar to the actual urban mining).

8. Conclusions

If appropriate monitoring techniques are implemented in an early stage of the process, a lot of useful information can be collected in the decades prior to definitive steps, in order to correct the parts of the system that do not behave appropriately.

This process of monitoring, evaluation of results, establishing corrective/preventive actions, adequately informing and communicating with all stakeholders, can be an important basis to build the necessary confidence of all stakeholders in the decision making.

Another cornerstone for building and sustaining confidence with the local stakeholders, over several generations, could be the establishment of a partnership with them that could eventually result in a level of co-design of (parts of) the repository.

References

This paper is based upon:

- the experience we gathered during the STOLA-STORA and MONA partnerships related to the design and preparation of a repository for low/medium-level short-lived radioactive waste.
- The discussions during the MoDeRn Be workshops (UA coordination, partnerships Mona and Stora).

Environmental Monitoring of the WIPP-A Deep Geological Repository for Transuranic Waste

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Summary

The Waste Isolation Pilot Plant also known as WIPP is a transuranic (TRU) waste repository operated by the U.S. Department of Energy (DOE). The repository is emplacing defense-related TRU wastes in the Salado Formation, a bedded salt formation. Emplacement takes place at approximately 655 m (2150 ft.) below the surface of the Earth. Located near Carlsbad, New Mexico, an area with fewer than 30,000 people, the WIPP facility is the world's first underground repository licensed to accept TRU waste, with activity concentrations of alpha-emitting isotopes >3700 Bq/m^3 (>100 nCi/g) and half-life >20 years. The upper waste acceptance criteria are <0.85 TBq/liter (<23 Ci/liter) of total activity and <10 Sv/hr dose rate on contact with unshielded waste containers. The repository, which opened in March 1999, will eventually contain the equivalent of ~176,000 m^3 of TRU waste. Many factors contribute to the success of this project; an important one being environmental monitoring in the vicinity of the WIPP, both before and after WIPP began receiving nuclear waste.

The monitoring is being conducted by an independent agency, the Carlsbad Environmental Monitoring and Research Center (CEMRC), which is associated with the New Mexico State University system. CEMRC is funded by DOE through a grant process that respects its independence. During the operational phase of WIPP, the primary focus is on airborne radioactive particulate, however other pathways are also monitored. The collected pre-operational baseline data of various anthropogenic radionuclides present in the WIPP environment either from global fallout as a result of nuclear weapons testing or Chernobyl type accidents are essential for the proper evaluation of the WIPP's integrity. These data can be compared against disposal phase data to assess the radiological and ecological impacts, if any, of radiation on workers, and on the general public that lives and works near WIPP. The program has capabilities to detect radionuclides rapidly in case of accidental releases from the repository or the site during operations.

Under the CEMRC monitoring program, air, drinking-water, surface water, soil, sediments, vegetation and the local population around the WIPP facility, as well as air entering and exiting the WIPP underground, are regularly analyzed. This paper will present an evaluation of more than ten years of environmental monitoring data that inform the public that there is no evidence of increases in radiological contaminants in the region that could be attributed to releases from the WIPP. CEMRC's independence and its extensive monitoring program and constant public engagement provide a model for nuclear waste repositories elsewhere in the world.

1. Introduction

The Waste Isolation Pilot Plant is an underground nuclear waste repository located in the remote Chihuahuan desert of southeastern New Mexico near Carlsbad. The facility is designed to dispose of transuranic (TRU) wastes that were generated from research and production of nuclear weapons at various DOE sites. The WIPP facilities consist of above ground buildings and underground mined areas. The underground part of the WIPP is located 665 meters (2,150 feet) below the surface and is divided in two main areas. The northern part is a research area and is open to the scientific community, while the much larger southern part is the Waste Disposal Area. As shown in Fig. 1, the WIPP repository has eight panels, each consisting of seven waste disposal rooms approximately 300 feet (91 meters) long and 33 feet (10 meters) wide. Seven of the planned panels have been excavated and the first five have been closed and sealed from ventilation air. Waste disposal is in progress in the sixth panel. Usually three panels are in operation with one already filled with waste and being closed (closure mode), the second panel already excavated with waste disposal in progress (waste disposal mode), and the third panel being mined (mining mode). Panel 5 is in closure mode, Panel 6 is in waste disposal mode and Panel 7 in mining mode at this time.

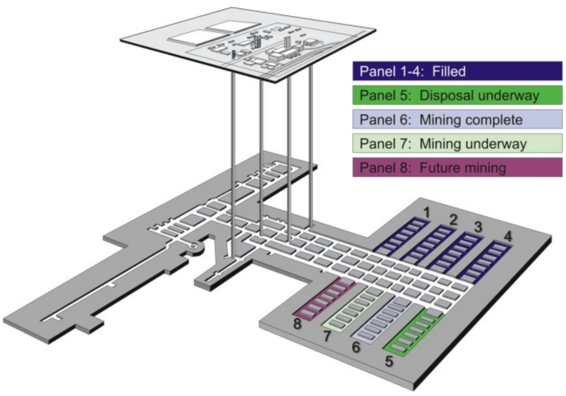

Figure 1. Layout of WIPP

Two types of TRU wastes are currently stored in the WIPP repository: (1) mixed transuranic waste (MTRU), meaning there are also hazardous waste components present, and (2) non-mixed waste that contains only radioactive elements, mostly plutonium. The TRU waste is subdivided into contact-handled (CH) and remote-handled (RH) waste on the basis of the dose equivalent rate at the surface of the waste container. If the dose is < 200 mrem/h (2 mSv/h) the waste is categorized as CH-TRU waste; otherwise, the categorization is RH-TRU waste. The WIPP became operational in March 26, 1999 for the disposal of TRU waste, and the WIPP first received mixed waste shipments on September 9, 2000. The WIPP mission is to dispose of 176, 000 m^3 (6.2 million cubic feet) of contact-handled waste and 7,080 m^3 (250, 000 cubic feet) of remote-handled waste which is equivalent to about 800,000 55-gallon drums. The radionuclides of greatest concern in the WIPP are $^{239+240}Pu$ and ^{241}Am, which account for more than 99% of the total radioactivity in the disposed inventory. In this context, the variation in concentrations of these two radionuclides in the WIPP environment is important, not only because they are the main component of the WIPP wastes, but also because of their global background activity.

The radiological environment near the WIPP site includes natural radioactivity, global fallout from nuclear weapons test and potentially, a local source of anthropogenic radioactive contamination remaining from Project Gnome. In 1961, the surface area of the Gnome site was contaminated with fission radionuclides when an underground test of a 3.3-kiloton ^{239}Pu device vented radioactive materials to the surface [1]. The site was decontaminated in 1968-1969 and again in 1978 . However, despite these clean-up efforts, an elevated level of ^{137}Cs and plutonium has been detected in some of the surface soil samples collected at the Gnome site [2]. These contaminated soils are of practical concern because they are a potential source of wind-blown contamination for environmental samples being collected to monitor release of radionuclides from the WIPP. So awareness of this potential source is necessary to maintain the integrity of the WIPP monitoring program.

In this paper the current trend of the radionuclides, specifically Pu and Am, are evaluated in the vicinity of the WIPP. The data reported were generated by an independent oversight organization, the Carlsbad Environmental Monitoring & Research Center (CEMRC). Results from this program are accessible to the public and are used here in evaluating the long-term history of these radionuclides to assess the impact of WIPP (if any) on the local environment, and to let the public know what effect WIPP operations have on their environment. This type of information is important for assessing the impact of WIPP on the local environment, but also provides an independent basis for the public to use in judging their willingness to initially accept and then continue to support such projects.

2. Methodology

Public surveys of the region around Carlsbad showed that the main public concern for contamination was first air, second drinking water, and soil and other environmental media a distant third. Based on an evaluation of various release events, it has been established that the atmospheric pathway is the most credible exposure pathway to the public from the WIPP, because that is the pathway by which radioactive or chemical contaminants released from the site would likely be most rapidly and widely dispersed throughout the environment.

Sample location and pretreatment

WIPP exhaust air: The major potential effluent stream at the WIPP facility is exhaust air from the underground repository. For monitoring of the WIPP exhaust air, Fixed Air Samplers (FAS) collect particulates from the effluent air stream on a Versapore filter at a collection site known as Station A. The effluent studies at Station A are a major component of CEMRC’s WIPP Environmental Monitoring (WIPP-EM) program. The airflow through the FAS is approximately 170 liters per minute. Samples are typically collected daily except for weekends. Weekend samples run from Friday to Monday so the coverage is continuous. Air filters from station A are counted for gross alpha/beta activities for 1200 minutes using a low-background Gas Proportional Counter (Protean MPC 9604) and then filter samples are composited on a monthly basis. The monthly composites are analyzed first for the gamma radionuclides and then spiked with appropriate tracers and routinely analyzed for ^{238}Pu, $^{239+240}$Pu, ^{241}Am, and $^{235, 234, 238}$U.

Ambient air: Ambient aerosols are collected using high volume samplers (flow rate ~1.13 m^3 min^{-1}) from three monitoring stations: (1) OnSite, which is about 0.1 km northwest (down prevailing wind) of the WIPP exhaust shaft, (2) Near Field, about 1 km northwest of the facility; and (3) Cactus Flats, about 19 km southeast (up prevailing wind) of the WIPP site. These sites were selected based on an analysis of the most probable scenario for radioactivity release if there was an accidental release during the operation of the WIPP. The aerosol samples were collected on 20x25 cm A/E™ glass fiber filters (Pall German Laboratory, Ann

Arbor, MI) taken over a period of 3 to 6 weeks depending on the levels of particulate matter that accumulate on the filters. For radiochemical analyses, filters are ashed in a muffle furnace at 500°C for 6 hours and then each filter is digested with strong acid mixtures and subsequently the actinides are separated as a group by co-precipitation with $Fe(OH)_3$.

Drinking water samples are collected from the major drinking water supplies used by communities in the WIPP region. The sources include the community water supplies of Carlsbad, Loving, Otis, Hobbs, and the water supply for the WIPP site (Double Eagle).

Soil samples were collected at two sampling sites, including the Near Field air sampling site, which includes the set of sampling locations within the WIPP site boundary. The second site is the Cactus Flats site approximately 19 km southeast of the WIPP facility. At both sites a grid was established with sixteen undisturbed soil sampling locations. At each sampling spot, soil was collected to a depth of approximately 2-cm. Individual sampling sites were selected on the basis of relatively flat topography, minimum surface erosion and minimum surface disturbance by human or livestock activity.

In addition to the environment, the people working at WIPP as well as the people who live and work close to the facility in Eddy and Lea counties are at risk of potential exposure from any releases of contaminants at WIPP. The Internal Dosimetry (ID) and Whole Body Monitoring of citizens living within a 100-mile radius of WIPP was established as part of the WIPP-EM program to obtain baselines concerning aspects of human health and citizen concerns, which change with time.

All the analyses of the WIPP environmental samples are performed according to methods detailed in CEMRC standard operating procedures. In short, gamma analysis was conducted using a high purity (HPGe) detector, while alpha emitting isotopes of Pu and Am were measured for at least 5 days on alpha spectrometers (Oxford Oasis System, Oxford Instruments Inc.) with 72 vacuum chambers (PIPS detector with 22% efficiency, 20 keV Full Width-Half Maximum (FWHM), and 450 mm^2 active areas) after radiochemical separation/purification and micro-coprecipitation. In order to ensure the high quality of analytical results, blank, duplicate, and spiked samples were analyzed periodically according to an internal quality assurance program. Periodic checks of the background and the efficiency were performed for the measurement systems. Periodic checks of performance with an appropriate calibrated standard solution are made as part of the QA/QC program, which also included participation in the national MAPEP (DOE Mixed-Analyte Performance Evaluation Program) and NIST-NRIP (NIST-Radiochemistry Inter-comparison Program) performance evaluation programs.

3. Results

The daily gross alpha and beta activity concentrations in the WIPP exhaust air samples measured using a low-background Gas Proportional Counter are shown in Fig. 2. The gross alpha and beta activity in air filters prior to arrival of TRU waste at WIPP were used as a baseline concentration. The baseline concentrations of gross alpha and gross beta activities were $1.49x10^{-3}$ Bq/m^3 and $4.90x10^{-3}$ Bq/m^3, respectively. Average concentrations of $^{239+240}Pu$, ^{238}Pu, and ^{241}Am measured in the WIPP exhaust air during the period from 1998 to 2011 are shown in Fig.3. Gamma radionuclides (^{137}Cs and ^{60}Co) were not detected in any of the WIPP exhaust air samples while ^{40}K was detected occasionally. Average air concentrations of actinides in the aerosol samples during the period from 1998 to 2011 are summarized in Table 1 and the time-series of annual $^{239+240}$Pu activity concentrations in aerosol filters collected from On Site, Near Field and Cactus Flats stations in the period from 1998 to end of 2011 are shown in Fig. 4.

The concentrations of radionuclides in regional drinking water samples from 2011 are listed in Table 2. The ^{238}Pu, $^{239+240}$Pu, and ^{241}Am were not detected in any of the drinking water samples since monitoring commenced in 1997. The soil sample analysis data for the gamma radionuclides and actinides show that ^{137}Cs, ^{40}K and $^{239+240}$Pu were detected frequently, ^{241}Am was detected in all but four of the samples, whereas ^{238}Pu was not detected in any of the samples.

4. Discussion

The gross alpha and beta activities in the samples collected prior to the receipt of the first waste shipment represent the pre-disposal background and the bulk of the activity in those samples results from naturally occurring radioactive materials, specifically radon daughters. As shown in Fig.2, both gross alpha and beta activities exhibit clear seasonal variability with peaks occurring in the winter. The two samples with elevated gross beta activity concentrations ca. 0.058 Bq/m^3 observed in early 2001 are because of contamination by material released from an underground fire extinguisher. Follow-up measurements verified that the fire retardant containing ^{40}K was the cause of the elevated results and that WIPP waste had not been released. Overall both alpha and beta activities have remained consistent over the years. The average concentrations of $^{239+240}$Pu and ^{241}Am measured in the WIPP exhaust air samples from 1998 to 2011 are presented in Fig. 3. The concentrations of $^{239+240}$Pu in 2003, 2008, 2009, and 2010, and that of ^{241}Am and ^{238}Pu in 2008 and 2009 are higher than the rest of the years. In all these years, one of the composite samples was observed to have Pu and Am concentrations greater than the minimum detectable concentrations (MDCs). However, these activities were extremely low and well below (approximately 6-7 orders of magnitude) the action level of 37 Bq/m^3 that triggers the Continuous Air Alarms (CAMs) that are distributed throughout the WIPP. The mean ^{238}Pu to $^{239+240}$Pu activity ratio of 0.025±0.004 in these samples are consistent with the source being largely global fallout. The naturally occurring isotopes of U were detected in all monthly WIPP exhaust air composite samples. The average ^{234}U/^{238}U activity ratio of 1.57±0.30 indicates the presence of natural U [3].

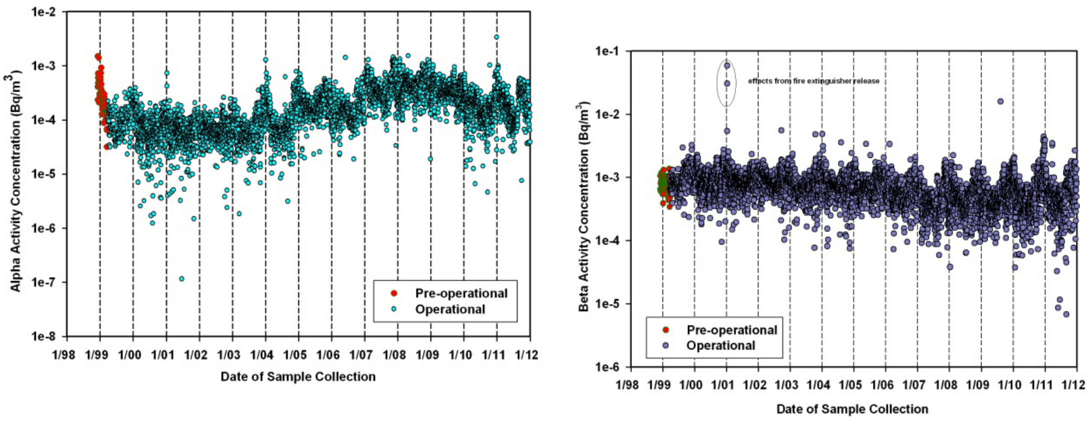

Figure 2. Average activity concentration of $^{239+240}$Pu, ^{238}Pu and ^{241}Am in the WIPP exhaust air

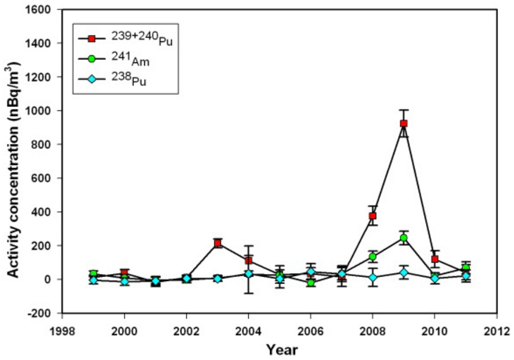

Figure 3. Average activity concentration of $^{239+240}Pu$, ^{238}Pu and ^{241}Am in the WIPP exhaust air samples

Average air concentrations of actinides in the aerosol samples during the period from 1998 to 2010 are summarized in Table 1. The average air concentrations of actinides after WIPP become operational are not statistically different than those measured prior to waste disposal operations. A typical springtime enhanced activity of Pu was also observed in the ambient aerosol samples collected near the WIPP site (Fig 4). Such springtime enhanced activity of radionuclides was also observed in the aerosol samples collected from Monoco [4], Germany [5] and Sodankyla, Finland [6]. The observed seasonality in Pu activity concentration is attributed to the re-suspension of contaminated soil dust plus the local precipitation to some extent. Studies conducted prior to the end of the atmospheric weapons testing showed that Pu activities varied seasonally, being highest in spring and summer because of the springtime enhanced transportation of radioactive aerosols from the stratosphere to troposphere. However, with the cessation of nuclear weapons tests and considering the fact that the residence time of Pu in the atmosphere is on the order of a year, the stratospheric deposition of radionuclides including Pu, is no longer a dominant factor for the Pu concentration in air. Nor did the Chernobyl accident bring significant amounts of Pu to this area. Thus, re-suspension is assumed to be the main source of Pu in the aerosol samples around the WIPP.

Table 1. $^{239+240}Pu$, ^{238}Pu, ^{241}Am activity concentrations (Bq/m^3) and the mass loadings ($\mu g/m^3$) in high-volume aerosol samples around WIPP.

	Statistics	Cactus Flats	Near Field	On Site
Aerosol mass	N	130	132	132
	Average	29.2±14.3	27.13±12.3	37.3±17.0
^{241}Am	N	56	54	60
	Average	$6.3\times10^{-9}\pm5.2\times10^{-9}$	$4.9\times10^{-9}\pm3.9\times10^{-9}$	$1.3\times10^{-7}\pm9.4\times10^{-7}$
^{238}Pu	N	9	2	10
	Average	$6.1\times10^{-9}\pm1.1\times10^{-8}$	$2.4\times10^{-9}\pm2.1\times10^{-9}$	$3.0\times10^{-9}\pm1.5\times10^{-9}$
$^{239+240}Pu$	N	89	100	97
	Average	$1.6\times10^{-8}\pm1.3\times10^{-8}$	$1.39\times10^{-8}\pm9.8\times10^{-9}$	$1.4\times10^{-8}\pm8.8\times10^{-9}$
^{137}Cs	N	3	3	1
	Average	$1.3\times10^{-5}\pm5.2\times10^{-5}$	$1.5\times10^{-5}\pm6.6\times10^{-5}$	$2.1\times10^{-5}\pm6.3\times10^{-5}$

N = number of samples with activities (>MDC).

The activity concentrations of ^{241}Am in the ambient aerosol samples also show the same springtime peaks as those of $^{239+240}$Pu (Fig. 4)). A strong correlation between aerosol ^{241}Am and $^{239+240}$Pu activity concentrations exists (r^2 = 0.75, 0.72, and 0.76 respectively, for On Site, Near Field and Cactus Flats stations) even though neither ^{239}Pu nor ^{240}Pu are immediate progeny of ^{241}Am. Ambient air particulate activity concentrations of $^{239+240}$Pu ranges from 5.5-18.3 nBq/m^3 at OnSite, 4.9-19.4 nBq/m^3 at Near Field, 2.3-20.3 nBq/m^3 at Cactus Flats in broad agreement with previously published data (10 to 100 nBq/m^3) in the continental US [7]. Furthermore, the relative activities of ^{241}Am and $^{239+240}$Pu were similar at all aerosol stations. The mean activity ratios of ^{241}Am/$^{239+240}$Pu (as of Jan 2010) at three aerosol stations were found to be 0.37±0.05 (On Site), 0.37±0.02 (Near Field), and 0.41±0.04 (Cactus Flats) indicating their global fallout origin. However, the measured ^{238}Pu/$^{239+240}$Pu activity ratio (0.069±0.02 to 0.12±0.04) was found to be higher than the global fallout ratio of about 0.03 [8]. At present, we don't have logical explanations for these high ^{238}Pu/$^{239+240}$Pu ratios in aerosol samples collected near the WIPP. However, it can be assumed that source for most of the Pu in the aerosol samples is re-suspension of soil particles which are contaminated from nuclear device tests and regional fallout. Additional studies are needed to obtain a better understanding of the behavior of Pu in the WIPP environment. The high ^{238}Pu/$^{239+240}$Pu ratio as in the present investigation is also reported in aerosol samples taken from

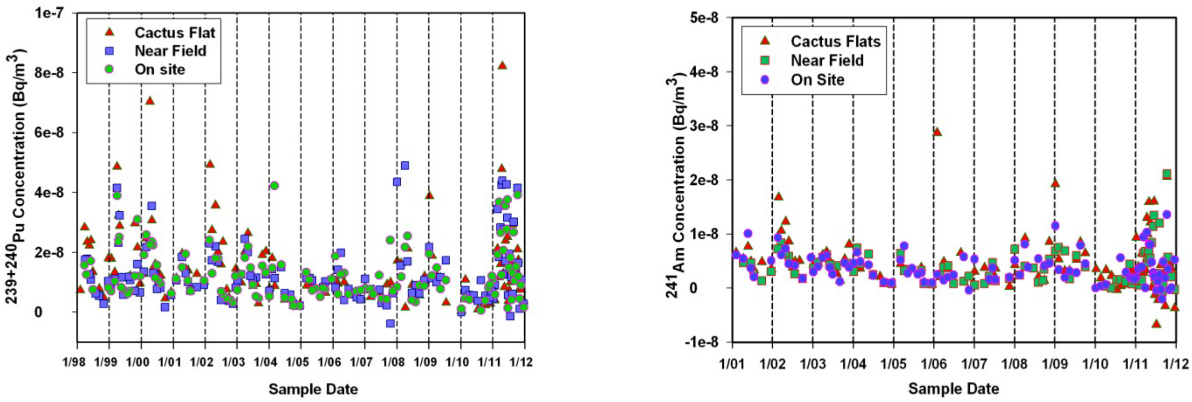

Figure 4. Temporal variations in $^{239+240}$Pu and ^{241}Am concentrations in aerosol samples during 1998 to 2011

Krakow by Mietelski et al [9] while, unusually high ^{238}Pu/$^{239+240}$Pu activity ratios of 0.36 (decay corrected to Jan 2010) and 0.041 (decay corrected to Jan 2010) were found in three quarterly aerosol samples collected from Germany [5]. Similarly, the high ^{238}Pu/$^{239+240}$Pu activity ratio of 0.42 (decay corrected to Jan 2010) was reported in aerosol samples collected from Lublin, Poland in 1999 [10].

As shown in Table 2, the isotopes of Pu, Am and gamma radionuclides were below the detection level in the drinking water samples since monitoring began in 1997. The federal and state action level for gross alpha emitters, which includes isotopes of plutonium and uranium, is 15pCi/L (0.56Bq/L). This is over 10,000 times the MDCs at CEMRC. The naturally occurring isotopes of U were detected in all drinking water samples as is the case for most waters in New Mexico. The low concentration of ^{235}U in water samples is consistent with the lower concentration of ^{235}U in the natural environmental as compared to the concentrations of ^{234}U and ^{238}U. WIPP site groundwater monitoring is not done by CEMRC as the two geologic units that contain some groundwater at the site, i.e., the Culebra Dolomite unit in the Rustler formation and Salado Anhydrite within the salt bed, have a high salt content and are also not sufficiently permeable to serve as sources of drinking water [11].

Table 2. The radionuclide (RN) concentrations (mBq/L) in regional drinking water samples in 2011

RN	Carlsbad	Hobbs	Loving	Otis	Double Eagle
$^{239+240}Pu$	0.00±0.02(0.05)	0.00±0.02(0.04)	0.03±0.03(0.03)	0.03±0.05(0.04)	0.01±0.03(0.05)
^{238}Pu	0.00±0.02(0.05)	0.00±0.02(0.05)	0.01±0.02(0.04)	0.02±0.04(0.05)	-0.01±0.03(0.05)
^{241}Am	0.02±0.03(0.05)	0.00±0.02(0.04)	0.02±0.02(0.05)	0.01±0.03(0.04)	-0.01±0.02(0.05)
^{234}U	28.3±1.4(0.11)	104.0±6.0(0.30)	76.4±2.2(0.10)	154.0±0.83(0.10)	48.0±1.7(0.11)
^{235}U	7.8±1.7(0.70)	2.6±0.5(0.30)	20.4±2.6(0.60)	11.9±0.10(0.30)	1.1±0.20(0.70)
^{238}U	10.9±0.7(0.11)	45.0±2.9(0.30)	25.7±0.9(0.10)	239±0.45(0.60)	18.6±0.8(0.11)
^{137}Cs	8.6±73.2(121)	5.0±73.0(121)	-1.2±73.2(121)	-14.5±36.1(122)	-9.6±73.8(121)
^{40}K	134±716(1190)	12±724(1200)	253±730(1210)	690±367(1150)	201±714(1190)
^{60}Co	7.9±34 (79)	-9.8±35.2(82.5)	-7.8±34.4 (80.2)	-7.8±17 (79.7)	33.0±33.6(75.8)

Values in parantheses are MDC

The activity concentration of ^{137}Cs in the Near Field surface soil ranged from 0.50 to 5.12 Bq/kg, with a mean value of 3.29 Bq/kg. The $^{239+240}$Pu concentrations in the Near Field ranged from 0.02 to 0.24 Bq/kg, with a mean value of 0.01 Bq/kg, while that for ^{241}Am ranged from 0.001 to 0.07 Bq/kg, with a mean value of 0.004 Bq/kg. The concentrations of these nuclides are comparable to historical data recorded in 1997 prior to arrival of TRU wastes in the WIPP Surface soils were not collected from Cactus Flats in 2007 through 2009. However those collected in 1998 to 2006 show activity concentrations of $^{239+240}$Pu ranging from 0.01 to 0.51 Bq/kg, while that of ^{241}Am varied from 0.10 to 0.26 Bq/kg. The ^{137}Cs concentration ranged from 0.69 to 14.83 Bq/kg. The concentration of ^{137}Cs in the surface soil at Cactus Flats is approximately three times higher than that of surface soil at Near Field, while concentrations of $^{239+240}$Pu and ^{241}Am are ca. 2-3 times higher. However, there is no apparent difference between the radionuclides concentration in soil collected before and after WIPP started receiving TRU waste. The mean ratio of ^{137}Cs/$^{239+240}$Pu across all sampling grids around WIPP was found to be 30±5. There was no significant difference between the mean ratios measured for the Cactus Flats (29±4) and Near Field soils (30±7). Correcting these two ratios for decay to July 1, 1999 yields ratios of 33 ±4 and 34 ±4, respectively. Although our ratio is somewhat lower than previously reported data for global fallout (36±4), it falls within the reported uncertainty associated with those ratios. This agreement suggests that the WIPP soils have received their Pu and Cs from world-wide fallout from nuclear weapons testing and are typical “background” soils.

The mean activity ratio of ^{241}Am /$^{239+240}$Pu in WIPP soils was 0.36±0.03 (Near Field) and 0.39±0.04 (Cactus Flats) which is indicative of global fallout origin. However, high ^{238}Pu/$^{239+240}$ Pu activity ratios ranging from 0.06 to 0.19 with a mean value of 0.14±0.05 were measured for the WIPP soils. This ratio is comparable to a mean observed ratio of 0.13±0.03 and 0.16±0.02 reported previously for the Gnome soils. It is interesting to note that the mean activity ratio of ^{238}Pu/$^{239+240}$Pu and ^{241}Am /$^{239+240}$Pu in aerosol samples are similar to those found in soils around the WIPP. Although the particle distributions of the soils and aerosols are quite different and mineral composition likely varies with particle size, the similarity of ^{238}Pu/$^{239+240}$Pu and ^{241}Am/$^{239+240}$Pu activity ratios in the two studies does support a connection between contaminated soil and aerosol. The mean ^{240}Pu/^{239}Pu atom-ratio observed in the WIPP samples (0.175) is consistent with the source being largely global fallout [8] with a minor Gnome soil contribution. Thus it is likely most of the Pu in the WIPP environment comes from atmospheric resuspension of soil particles with Pu deposited from global fallout. The variation in activity ratio as well as concentration is likely because of variations in the resuspension conditions and atmospheric transport and dispersion conditions.

In addition to the environment, people working at WIPP, people who live and work close to the facility in Eddy and Lea counties are at risk of potential exposure for any releases of contaminants that could occur at WIPP. The Internal Dosimetry and Whole Body Monitoring of citizens living within a 100-mile radius of WIPP were established as part of the WIPP-EM program to obtain baselines concerning aspects of human health and the citizen concerns which change with time. The program consists of a lung and whole body count of individuals every two years. The internal dosimetry program conducts analyses and consultations for the study and management of radiation exposure on both citizens with no possibility of occupational dose, and workers at WIPP and other facilities with occupational dose. In the *Lie Down and Be Counted* Program (LDBC), citizens within a 100-mile radius of WIPP, can simply come into CEMRC for a whole body count. Analyses include collection of information on work and residence history, past and current radiation exposure, bioassays to measure the presence of radionuclides within body tissues (*in vivo*) or body fluids and excretions (*in vitro*), and calculation of dose associated with observed uptakes.

As of December 2011, 986 individuals have participated in the LDBC project. At the time the WIPP opened, 366 of these individuals had been measured constituting the pre-operational baseline to which subsequent results are compared. Based on the data obtained thus far, there is no evidence of an increase in the frequency of detection of internally deposited radionuclides for citizens living within the vicinity of WIPP since WIPP began receipt of radioactive waste. As discussed in ref [12] , the criterion, L_C, is used to evaluate whether a result exceeds background and the use of this criterion will result in a statistically inherent 5% false-positive error rate per pair-wise comparison (5% of all measurements will be determined to be positive when there is no activity present in the person).

For the baseline measurements the percentage of results greater than L_C are observed for radionuclides except ^{232}Th via the decay of ^{212}Pb, ^{235}U / ^{226}Ra, ^{60}Co, ^{137}Cs, ^{40}K, ^{54}Mn, and ^{232}Th via the decay of ^{228}Ac. Five of these (^{232}Th via ^{212}Pb, ^{60}Co, ^{40}K, ^{54}Mn (^{228}Ac interference) and ^{232}Th (via ^{228}Ac)) are part of the shield-room background and positive detection is expected at low frequency. ^{40}K is a naturally occurring isotope of an essential biological element, so detection in all individuals is expected. ^{137}Cs and ^{235}U/^{226}Ra are not components of the shielded room background and were observed at frequencies greater than the 95% confidence interval for the false positive error rate.

For the operational monitoring the percentage of results greater than L_C is consistent with baseline, except for ^{60}Co and ^{232}Th (via ^{228}Ac). For these radionuclides, the percentage of results greater than L_C decreased relative to the baseline. This is likely due to the short half-life of ^{60}Co (5.2 years) and the replacement of aluminum (tends to contain Th and U) in some of the detector cryostat components with those manufactured from low radiation background steel. ^{40}K results have been positive for all participants and ranges from 792 to 5558 Bq/person with an overall mean of 2477±23 Bq/person. Such results are expected since K is an essential biological element contained primarily in muscle and a theoretical constant fraction of all naturally occurring K is the radioactive isotope ^{40}K. The mean ^{40}K value (3059±27 Bq/person) for males is significantly greater than that of females (1884±19 Bq/person) because of larger body sizes and greater muscle content of males than females.

Detectable ^{137}Cs is present in 21.4 ± 3% of citizens living in the Carlsbad area and ranges from 4.9 to 132 Bq/person with an overall mean of 12± 0.9 Bq/person. The mean ^{137}Cs body burden for males is 13.6±1.2 Bq/person which is significantly greater than that of females which is 8.6±0.3 Bq/person. The presence of ^{137}Cs is independent of ethnicity, age, and radiation work history, consumption of wild game, nuclear medical treatments and European travel. However, the occurrence of detectable ^{137}Cs is associated with gender where males had higher prevalence of ^{137}Cs relative to females. Furthermore, the presence of ^{137}Cs is associated with smoking. Smokers had a higher prevalence of detectable ^{137}Cs (27.9 %) as compared to non-smokers (23.2%). The association of ^{137}Cs with smoking could be related to the presence of fallout ^{137}Cs in tobacco, decreased pulmonary clearing capability in smokers or other as yet unidentified factors.

The absence of detectable levels of plutonium suggests that there have been no releases from WIPP. As reported in previous CEMRC reports the percentage of results greater than L_C for ^{235}U/^{226}Ra (11 %) are significantly higher than the distribution-free confidence interval for a 5 % random false-positive error rate. These data are not nearly as compelling as those for ^{137}Cs, but the large sample size of the current cohort tends to support the observed pattern. Although ^{235}U and ^{226}Ra cannot be differentiated via gamma spectroscopy, it is likely that the signal is the result of ^{226}Ra because the natural abundance of ^{226}Ra is much greater than that of ^{235}U. Based on the data collected so far, there is no evidence of an increase in the frequency of detection of internally deposited radionuclides for citizens living within the vicinity of the WIPP since the WIPP began receipt of radioactive waste.

5. Conclusion

The Carlsbad Environmental Monitoring & Research Center, located in Carlsbad, New Mexico, is an independent, academic-based environmental monitoring facility developed to monitor the environment around the WIPP for radionuclides and other contaminants of interest to the regional community. The source and level of radionuclides around the WIPP environment prior to arrival of the TRU waste and after it became operational were compared to assess if there is any evidence of an increase in radionuclide activity concentrations in the region that could be attributed to releases from WIPP. After twelve years of continuous operations, there is no evidence of increases in radiological contaminants in the region that could be attributed to releases from WIPP. Radionuclide concentrations in the vicinity of the WIPP are a mixture of global and local fallout. Resuspension of soil particles which are contaminated from nuclear tests continues to be considered the predominant source of radionuclides in the environment surrounding the WIPP area. The success and independence of such a monitoring program provides a basis for public evaluations of their own safety, which has a direct relationship to their initial or continuing acceptance of a nearby nuclear facility.

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References

[1] USAEC (1973). Gnome/Coach site disposal options. U.S. Atomic Energy Commission NVO-131. Las Vegas, NV.

[2] Faller, F. (1994), Residual soil radioactivity at the Gnome Test Site in Eddy County,

NewMexico, Report No. EPA 600/R-94/117, July 1994. Washington, DC, Environmental Protection Agency.

[3] Eisenbud, M., T. Gesell, T (1997) Environmental Radioactivity, Academic Press, San Diego.

[4] S.H. Lee, M.K. Pham, P.P.Povinec, Radionuclide variations in the air over Monaco, J.Radioanal. Nucl. Chem. 254, 445-453 (2002).

[5] D. Arnold, H. Wershofen, Plutonium isotopes in ground-level air in Northern Germany since 1990, J. Radioanal. Nucl. Chem 243, 409-413 (2000).

[6] S. Salminen, J. Paatero, Concentrations of ^{238}Pu, $^{239+240}$Pu and ^{241}Pu in the surface air in Finnish Lapland in 1963, Boreal Environ. Res. 14, 827-836 (2009).

[7] T.B. Kirchner, J.L. Webb, S.B. Webb, R. Arimota, D.A. Schoep, B.D. Stewart, Variability in background levels of surface soil radionuclides in the vicinity of the USDOE waste isolation pilot plant, J. Environ. Radioact. 60, 275-291(2002).

[8] R.W. Perkins, C. W. Thomas. Worldwide Fallout. In: Hanson W. C., ed. Transuranic Elements in the Environment. U.S. Department of Energy: DOE/TIC-22800, 53-82 (1980)

[9] J.W. Mietelski, K. Kozak, B. Was, M. Jasinska, J.O. Krupa, Plutonium isotopes concentration in the ground level air and rain samples from Krakow, Czech. J. Phys. 49, 115-118 (1999).

[10] J.W. Mietelski, K. Kozak, B. Was, M. Jasinska, J.O. Krupa, Plutonium isotopes concentration in the ground level air and rain samples from Krakow, Czech. J. Phys. 49, 115-118 (1999)

[11] Strategic Plan for Groundwater Monitoring at the Waste Isolation Pilot Plant DOE/WIPP-03- 3230

[12] Webb, J. L. Kirchner, T. B (2000), An evaluation of *In vivo* sensitivity via public monitoring, Radiat. Prot. Dosimet**.** 89**,** 183-191.

Locating socio-technical problems: monitoring and demonstrating as political techniques

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Summary

This paper offers a theoretical and sociological analysis of what is often perceived to be merely technical practices: monitoring and demonstrating. The paper takes as a starting point the definition and framing of a problem to be solved (like the safety, location or future of a storage site, for instance). Activities such as monitoring then appear as only one particular activity to address the larger problem of containment, a problem that has a geography of its own. It is both absent and present, both dealt with in laboratories and yet impossible to contain in them, both made tangible in social and spatial settings yet always also intangible, both a concern for experts and an issue that concerns larger publics. The task of the social *and* natural sciences is, then, no other than to try and locate socio-technical problems and to situate monitoring and demonstration as particular moments in an ensemble of political decisions, social values, and technical expertise. In the case of the geological disposal of high level and long lived nuclear waste, the demonstration of safety poses a particular problem: timeframes of several hundred thousand to several millions of years need to be considered. The geological disposal of such waste is thus faced with the difficulty to monitor and demonstrate safety *in situ* and *in actu*. Safety cannot be contained in any single act or place of demonstration but inevitably escapes the spaces of demonstration (such as laboratories, models, equipment, scenarios, etc.). Nonetheless, underground research laboratories play an important role in the processes of monitoring and demonstrating in a number of ways: by being depicted as a site of expertise and trustworthiness, by working on techniques and measures that research safety, by producing results that visualise safety, by being able to materialise the future and by fostering the ‘demonstrability’ of technical devices (that is, to enable them to ‘speak for themselves’).

1. Monitoring is not what it seems

Let me start with a short vignette: this image from the conference flyer, a quite common and easy-to-understand image. The image is that of a person in front of a screen who does what we would call "surveillance" or "monitoring". While, at first sight, this image looks simple, the story I want to tell is that behind this picture there lies a very complex but fascinating world – a world laden with objects, norms, values, uncertainties, difficulties and choices.

Let me do a sort of guided tour of this picture. A bit like an art historian might do in a museum, except that I am sociologists of science and technology and what I am offering is a sociological reading of this picture. And what sociology of science has shown is that there is no such a thing as a neutral, objective and unproblematic technology (see i.e. Winner 1986, Haraway 1989).

Let's start with the person in front of the screen. Who is this person? Or, perhaps better, what is this person? The person is someone who works for a company. You can distinguish a uniform, a helmet, he probably wears a badge, too. In short, this person works for an institution, and is paid by an institution. This is our first important clue: monitoring is something that happens in an organisation; it is a role, a profession, a mission, a responsibility. Monitoring is an activity to supervise: the disposal of radioactive waste, rock formations, but also things like traffic, costumers, travellers, the weather, and so on and so forth. And monitoring is relying on technologies (with their limitations and need for maintenance). Monitoring is an activity that, in some places, is deemed necessary and worthy to be invested with people, money and time.

Why? Because there is a potential "problem": something could potentially go wrong. An attack, a leakage, an earthquake, etc. The problem itself cannot be seen directly in this picture. It is absent. Yet, at any time, it might become present. So the situation is this one: the person we see here on this picture is a person, employed by an institution, that works to make sure that things are under control and problems don't happen, or if they happen, make sure they are recognized and dealt with. Bring things back to normal.

So what is this absent thing, the "problem"? This is one of the most intriguing elements in this picture because it is not there, yet, it is the most important actor in the whole picture. To put it this way: the potential problem is the whole reason why you have got persons looking at screens.

So, we can then ask, what counts as a problem? Who decides that something becomes problematic, risky, out of control, etc.? This is not at all a trivial question, for it is a matter of scientific, legal, or technical expertise.[21] Every problem needs its given set of expertise, for example, policemen watching over surveillance cameras need to be able to spot "tipping points" (Gladwell 2000), that is, when there are signs that a discussion between people might turn into a fight. Another example is biologists or meteorologists who monitor the quality of air or water who need to think about what good indicators are: bacteria, algae, gases, the temperature. *When*, *where* and *what* to measure is crucially important when the natural, social or technical environment is monitored.

Also, related to the issue of when, where and what to measure is that there needs to be some kind of threshold, to define *from what moment on* something counts as a problem. Throughout the history of science we have witnessed many scientific disputes and controversies over what counts as the "right" or "acceptable" threshold, that is, what the limit should be and where to draw the line. Just think about the discussion about the potential effects of a rise of 2°C on the planet, or about what counts as non-toxic levels of exposure to chemicals or radioactivity. The argument, here, is not that defining such thresholds is pointless or futile, or that it does not have any beneficial consequences. Yet, what we can argue is that the definition of standards is always something negotiated and collectively defined, something over which people might not all agree. In short, any norm or standard is both a technical and a social achievement (see Bowker and Star 1999).

This is a key argument in the sociology of science and technology: facts are established, norms are negotiated, standards have to be set… all of which takes time. So, apart from this absence of the key figure – the potential problem – there is another important absence: the history of the problem. The scene, just before this picture, cannot be boiled down to a scene in which there would have been another person saying something like "if you see that x is above y give me a call". The scene before this picture is, in fact, a long sequence of events, a long history: the history of scientific disciplines, of the construction of techniques, of (perhaps controversial) discussions that led to the establishment of norms, of legal and regulatory contexts that require companies like ANDRA to do monitoring, etc.

In fact every thing in this picture has a history: monitors and computer systems have a history, and the monitor in this picture is perhaps a couple of months or years old (so in the near future we might expect better, more reliable and more precise computers and monitors to be developed). The person in this picture has a history: he has probably studied engineering, he has learned through his work, he has learned to distinguish a signal from noise, he has learned how to read machines, how to read pictures.

Let me try to summarise what sociology of science and technology can offer you as a reading of this picture. This picture is not 'easy' and there are a lot of elements that are not visible, but which are crucial to make sense of this picture. The picture is also not only about a purely "technical" activity. It is about institutional choices, education, definitions of problems, learning, regulations, compromises, … Many things are outside the frame of this picture, but

[21] We could add that, in more general terms, nuclear waste, energy and weapons represent what has been called "wicked problems", problems that are persistent, very complex, and difficult to solve (via a conventional linear approach) and that are only ever understood in hindsight, after having been solved (see Roberts 2000, Brunnengräber et al. 2012). Since these kinds of problems usually entail a wide array of different political, social, economic, and technical aspects they often lead to conflict. Future work could thus extend the arguments developed in the present paper by comparing the location of socio-technical problems and the location of their solutions, and explore how conflicts are generated and resolved – and/or how indivisible conflicts are made divisible (see Barthe and Linhardt 2009).

nevertheless fundamental to make it exist: money, electricity, expertise, food, maintenance (computer specialists who repair computers, or doctors who "repair" humans), information, time-schedules, and so on and so forth. Surveillance, Paul Virilio (2006) argued, is nothing without the mastery of its transmission.

What we see, in other words, is what Michel Foucault (1975) describes in his famous work on surveillance. He argues that surveillance is an activity that "makes visible" through "eyes posted everywhere, mobile attentions ever on the alert, a long, hierarchized network". Surveillance works through observation, which, in turn has to be "accumulated in a series of reports and registers (…) by means of a complex documentary organization". Foucault argues that

> "under the surface of images, (…) behind the great abstraction of exchange, there continues the meticulous, concrete training of useful forces; the circuits of communication are the supports of an accumulation and a centralization of knowledge (…) We are much less Greeks than we believe. We are neither in the amphitheatre, nor on the stage, but in the panoptic machine, invested by its effects of power which we bring to ourselves since we are part of its mechanism".

So what we must do, is to look beneath the surface of an image like this – and the image that the person in this picture sees on his screen – and try and uncover the wide array of mechanisms devoted to organizing humans and non-humans; training employees; standardizing and centralising knowledge.

An activity such as monitoring is about the brining together of technology and society, it is an activity that is concerned with control. And control – whether it is about humans, animals, planes, viruses, or waste – is a very human idea. Again, this is not necessarily something to condemn – the world would indeed be a less safe place if dangerous humans, animals, viruses, or radio-nucleotides would freely move around. But, the argument we can make is this one: monitoring is far more than a merely technical activity, it is concerned with organising the relationships with people and their environments, with keeping things in place, with qualifying, distributing and containing them.

This, then, is one of the key arguments I wanted to present through the discussion of this picture of a person in front of a screen. What sociology of science and technology has shown is that science is an inherently political, cultural and social endeavour. There is no "pure" technology or science: technologies reproduce and embody the complex interplay of professional, technical, economic, and political factors (Bijker and Law 1992:3). Technical artefacts have politics (Winner 1986). Consequently, Haraway (1989:13) writes that: "The detached eye of objective science is an ideological fiction, and a powerful one".

2. Demonstrating Safety

We can now build upon this insight to explore the way in which science and technology is not only used in processes of monitoring, but that within these processes we see another crucial activity: demonstration. The safety of nuclear waste disposal is not only *realised*, it is also something *demonstrated*. Not only are there material technologies for making the storage of nuclear waste safe (such as assessing geological barriers, making scenarios, etc.). There are also literary and social techniques to perform, present and show safety as an explicit "case" to a specific audience endowed with the authority to evaluate and validate this case. A safety case not only has to be tested and made, it also has to be circulated and shown for it to be assessed and made reliable.

In the case of nuclear waste, people are faced with a crucial a particular: the long-term safety of a disposal facility cannot be demonstrated in situ. Long-term safety can be modelled, calculated, estimated, schematised, monitored but it cannot be demonstrated like, for instance, a crash-test can be done with a car. So how to *demonstrate* safety in a situation such as this?

The answer is at once simple and paradoxical: without the possibility be demonstrate the long-term safety of a disposal facility (in reality), the only possible strategy is, still, to rely on demonstration. In other words, the answer lies in a particular – and often under-researched - feature of researchers' work: their use of "demos", that is, performances to demonstrate the solidity of a result to a given public. An underground research laboratory, in this sense, is not only a place for monitoring and for doing experiments on safety. It is also, crucially, a place that legitimates safety; that gives scientific authority and produces the social conditions of expertise to make a safety case robust. In the case of nuclear waste and underground disposal facilities, several 'natural analogues' are used as as *demonstrators* of safety, such as different types of fossils preserved over several millennia in geological formations. But also written documents are presented with a similar, almost geological, persuasion: they are used as a 2-dimensional space of inscription that produces safety as something convincing and trustworthy by endowing to nature, to technologies, to scientists and to expertise the capacity to produce safety.

2.1. The concept of demonstration

What does it mean to 'demonstrate'? While demonstration has various significations – ranging from political protests to mathematical proofs, from marketing presentations to scientific demonstrations – I am interested in one particular sense of the term. Demonstration is a social and technical practice through which something (a model, a result, a method, a theory, a device, a place) is shown and presented to an audience. Through this act of demonstration, an idea or an object is assessed and potentially validated or stabilised. Demonstration, then, performs several functions: it does not only show, it also tries to convince, to attribute a value, to show feasibility, to enrol actors. A demonstration is an act that can literally render an idea tangible and that visualises and often also materialises knowledge.

The academic analysis of such processes of demonstration can be traced back to the work of historians of science Steven Shapin and Simon Schaffer (Shapin and Schaffer 1985, Shapin 1988). In his seminal article about the "house of the experiment" in the 17th century, Shapin (1988: 399-400) has distinguished between "trying", "showing" and "discoursing" upon an experiment:

> The trying of an experiment corresponds to research proper, getting the thing to work, possibly attended with uncertainty about what constitutes a working experiment. Showing is the display to others of a working experiment, what is commonly called demonstration. And experimental discourses are the range of expatiatory and interpretative verbal behaviors that either accompany experimental shows or refer to shows or trials done at some other time or place.

The act of showing or demonstrating is crucially important in producing and securing knowledge claims. "The showing of experimental phenomena in public spaces to a relevant public of gentlemen witnesses was an obligatory move in that setting for the construction of reliable knowledge", Shapin (1988: 404) argues.

Discussing more contemporary examples, other authors (Rosental 2007, 2009) have specifically focussed on demonstrations in their work. A contemporary definition of demonstration has been given as follows: "any written or audio-visual development, whose purpose is primarily of a probationary and/or argumentative, or educational order" (Rosental 2009). Demonstration, therefore, can never be reduced to a mere 'technical' activity. Andrew Barry, for instance, has argued that demonstration is at once "a technical, ethical and spatial practice" while also insisting upon the fact that, in comparison to historic demonstration, contemporary *demo* can also be used to show "the possibility of a real object" (Barry 2001: 176, 178).

Demonstration is arguably a key practice of scientists. It is through demonstrations that the legitimacy, the diffusion, and the public validation and witnessing of knowledge claims are sought. Demonstration provides a sense of authority and control of the world: "Mathematicians, calculation specialists and "demonstrators" perform an enormous effort to keep a world which seems ever determined to escape from them within the narrow limits of their models, graphical representations and data" (Arvanitis and Grossetti 2009).

In the case of the geological disposal of nuclear waste, 'safety' has got to be demonstrated. Yet, such demonstrations pose a particular challenge for high level and long lived nuclear waste. They do not only have to address the question of operational safety, and impacts on man and the environment in the here and now. They also have to deal with the question of long-term safety, which in this case means timeframes of several hundred thousand to several millions of years. The geological disposal of nuclear waste is thus faced with the difficulty to demonstrate safety *in situ* and *in actu*. Safety furthermore cannot be 'contained' in any single act or place of demonstration. Demonstrations of safety inevitably escape the spaces of demonstration (such as laboratories, models, equipment, scenarios, etc.). As a consequence, there is a need to find analogues, supports, and equivalences as *demonstrators* of safety.

To demonstrate safety means to try and find the material means which can *do* the demonstration. Safety analyses are one such means through which safety is demonstrated. In their analysis about safety in Sweden, Elam et al. (2010) write: "safety analyses are literally intended to 'speak for themselves' to those with the qualified ability to understand them". In other words, an analysis can come to figure as the material means and the expert promise and method allowing people to state (or not) that safety can be achieved. This also reminds us that a demonstration cannot be reduced to a person discoursing about an issue, but that a demonstration is a combination of discourses, material objects, and the specific sites in which it is carried out. Another way to put this is to say that in demonstrations agency is distributed between humans and non-humans and that, in doing so, things can become 'talkative' (Daston 2004). There are at least two possible ways in which safety is demonstrated to audiences: the showing of an underground research laboratory and of material objects such as containers, used as "technical demonstrators".

2.2. Underground research laboratories as demonstrators of safety

A key means to demonstrate safety is by setting up, experimenting in, and organising communicating about a specific site: the underground research laboratory (URL). Such a laboratory can come to function as such *demonstrator* of safety in a number of ways: by being depicted as a site of expertise and trustworthiness, by working on techniques and measures that research safety, by producing results that visualise safety, and by making predictions and being able to 'materialise' the future. A number of such laboratories have been set up across the world: in Bure (France), the HADES facility (Belgium), the Asse Mine and Gorleben (Germany), the Äspö rock laboratory (Sweden), and the Onkalo facility (Finland) to name but a few.

In France, the underground research laboratory at Bure, whose construction began in 2000, is involved in "trying", "showing" and "discoursing upon" experiments and safety. For ANDRA, the laboratory represents a "unique" tool (ANDRA 2010b), its "most important research tool" (ANDRA 2005: 7).

One way through which ANDRA tries to demonstrate safety is through scientific experiments, the results of which are then published in scientific journals. In such journal articles we might read, for instance, that "the most outstanding result" of the scientific research carried out in the URL "has been the demonstration, through in situ sample measurements, of the representativeness of the confining properties and their transposability at layer scale" (Delay et al. 2010: 20) or that "The coring and core packaging procedure provided samples that (…) can be considered as representative of the in situ material" (Gaucher et al. 2004). Nonetheless, according to the scientists, the transposability of results goes far beyond the immediate vicinity of the laboratory, to a "geographical zone where the properties (…) are similar to those of the site of the laboratory" and this "the zone of transposition extends to around 200 km² to the north and the west of the laboratory" (ANDRA 2005: 13).

Scientific demonstrations like these rely on a diverse set of practices: communicating a scientific result to - and rhetorically trying to convince - a given audience; arguing that the methods and tools used are indeed representative of a whole site (that, in other words, 'scaling up' can be done (see Yaneva 2005)), and, rather implicitly, that scientists and engineers are - with their expertise and methods and in the laboratories they work in - able to analyse, assess and make robust knowledge claims about the nature of rocks.[22]

But demonstration comes in other guises as well. The URL at Bure is also shown to the general public, to students and to pupils, as well as to politicians, journalists, and scientists. ANDRA "invites" people to "discover" its underground laboratory and its scientists who "explain their work and answer to questions of the public" (ANDRA u.d.). To this effect, ANDRA has built a visitor centre with an "identical reconstruction" of the galleries that are at 490 meters below ground, with panels, videos, exhibitions, and an auditorium. ANDRA organises guided tours and "open door" days.

Showing and demonstrating an underground laboratory to a public requires knowledge and objects to be mobile. Scientists, cameras to take pictures of laboratories, measurements, technological equipment, electricity, … all move between the laboratory below ground and the spaces of demonstration above ground.

In order to show an underground laboratory to the public, the laboratory's material and social architecture needs to be rethought and has to deal with an 'extended' object-world. Not only do we encounter some of the objects that scientists and engineers use (such as various kinds of instruments and equipment) but there is also a need to display objects that engage and can 'talk to' the visitor. In effect, in the display of the underground laboratory we encounter at least three kinds of objects: objects that can perform work, objects that display and explain work, and objects that focus attention on the performance and explanation of work (such as

[22] On that latter point ANDRA notes that it has: "mobilisé les meilleurs laboratoires existant au plan français et international dans chaque domaine. La production des résultats a été discutée selon les exigences du monde académique et dans une logique d'excellence. Il en résulte une garantie sur la qualité des travaux" (ANDRA 2005: 34).

posters, panels, information boards, signs, video screens) (see Meyer 2011). Here is how ANDRA depicts its *Espace Technologique*: "The Espace technologique is a place of public information, designed to make concrete the concept of deep reversible storage and show how its operation might look like" (ANDRA 2010a: 14).

In 2009, ANDRA opened an *Espace Technologique* with a dedicated "space of presentation". In this space, visitors are allowed to see *technological demonstrators*. ANDRA explains:

> "Deux types de démonstrateurs ont été construits : des démonstrateurs de conteneurs de stockage de déchets MA-VL et des démonstrateurs dynamiques de manutention des conteneurs de stockage de déchets HA et des combustibles usés. Les démonstrateurs dynamiques permettent par ailleurs d'illustrer la phase initiale de réversibilité, phase qui correspond à la période pendant laquelle les conteneurs de stockage peuvent être retirés du stockage avec des moyens similaires à ceux utilisés pour leur mise en stockage" (ANDRA 2008).

Picture 1: technological demonstrators. Some demonstrators are 'cut open' in order for their interior to be visible and there are panels with texts providing further information. (Source: ANDRA).

Two points can be raised here. First, the construction of these demonstrators, and their presentation and operability is a key matter. For it is the existence of such demonstrators that, in turn, enables people to claim that solutions to store waste safely already exist. They are presented before people's eyes, in a 1 to 1 scale, with their interior to be seen (see picture 1). These demonstrators can and have been built, they work, and more of them can be built – is the implicit message of ANDRA. Second, these demonstrators allow ANDRA to make a certain number of statements. The demonstrators, we are told, have "allowed to validate" certain ideas, and they have "allowed us to study their technical feasibility and to test design alternatives" (ANDRA 2008). They are taken, then, as a material proof of experiments done, a tangible manifestation of principles tested. That an object, like a demonstrator, can indeed "illustrate" a principle such as reversibility clearly indicates the extent to which demonstration is reliant upon 'talkative things', that is, things that stand for and bare the traces of scientific proofs in a visible, tangible and communicable manner.

2.3. From demonstration to demonstrability

The presentation of these technological demonstrators is a combination of social and technical practices. They are, on the one hand, described as technical devices: they stand for scientific expertise; their compositions, dimensions, weights, resistances are calculated and indicated; they are tested in various ways. At the same time, they are also social devices in that they are presented *to people* and narrated as parts of a wider story. They are presented as promissory objects that potentially provide a solution for storing waste and as convincing objects, in that their reality and feasibility should be beyond doubt through their "demonstrability". A worthwhile line of reasoning to pursue is thus to focus on the idea of "demonstrability". A member of staff of ANDRA writes: "Demonstrability is a relative notion and the simplicity of a test is not an end in itself: it is based on the good use of multiple lines of argument (feedback from experiences, qualitative reasoning, use of natural analogues, of technological experiments or demonstrators" (Voinis 2008: 81).

What we can take from this definition are two things. First there are indeed multiple "lines of argumentation" or, as I have shown above, different social, literary, technical and spatial practices to construct arguments. Second, we can broaden our idea of acts/performances of demonstration to include the property of "demonstrability" of technical devices. This "demonstrability" of devices is, I want to argue, a key and powerful resource for those who have stakes at showing safety. For it is a quality that, in a seemingly effortless, direct and evident way, seems to enable technological devices to 'speak for themselves'.

3. Concluding remarks

The storage of waste and the monitoring of it cannot, in itself, bring about an "understanding" or "confidence" or, even worse, "acceptance" of the public and other stakeholders. The monitoring, containment, and measurement of waste is something that needs to be shown, discussed, and opened-up. Monitoring activities need to be demonstrated and witnessed. If the need for social science perspectives and for public engagement is to be more than mere lip service, then the nuclear industry needs to engage wholeheartedly into participatory processes.

In this paper I have provided one possible approach to open up the storage of waste to more democratic and participatory assessments and decision-making. My approach was, above all, to offer a theoretical and sociological reading of what is often perceived to be merely technical practices, such as monitoring and demonstrating (we can extend this list to include practices such as experimentations, risk analysis, cost assessments, and evaluations more generally). In fact – and to turn the argument around - without trust, communication, discourses, norms, rules, institutions, economic choices and calculations, ethics, learning, control, etc. the production of scientific knowledge and technological solutions would simply not exist. The issue is, then, not so much to "include" the public and stakeholders into technological choices, it is rather to reflect about, and select, the particular *moments* and *places* in which they are involved in these choices - choices that are in themselves always social-technical.

This insight is perhaps a way to move beyond the argument that processes like monitoring and demonstrating should be seen as socio-technical processes – an argument that is very familiar within sociology of science and technology. This, because a recognition that technological choices are socio-technical leads to an important and pragmatic question: what to do with this insight? We thus need to move to a more fine-grained appraisal of the precise ways in which the social and the technical come to matter concurrently. To paraphrase some of the workshop titles from the conference, the issue is thus to define *how*, *where*, *when* and *for how long* to involve the public and stakeholders – and thus not to limit these questions to the technical aspects of monitoring alone.

One particular vantage point that can be taken for such an enterprise is to focus on "what poses a problem".[23] The definition and framing of a problem to be solved (the safety, location or future of a storage site, for instance) begins before any monitoring of nuclear waste takes place. Monitoring is but one specific activity to address the problem of containment and nuclear waste management cannot be reduced to a single activity like monitoring. Like in the picture with which I opened the discussion in this paper, the "problem" is the most important actor, and yet it is this problem which is particularly difficult to contain for it has a geography of its own. It is both absent and present, both dealt with in laboratories and yet impossible to contain in them, both made tangible in social and spatial settings yet always also intangible, both a concern for experts and an issue that concerns larger publics. The task of the social *and* natural sciences is, then, no other than to try and locate socio-technical problems and to situate monitoring and demonstration as particular moments in an ensemble of political decisions, social values, and technical expertise.

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References

[1] ANDRA (undated) Laboratoire ANDRA. Visiter, s'informer, comprendre, ANDRA

[2] ANDRA (2005) Dossier 2005. Les recherches de l'Andra sur le stockage *géologique des déchets radioactifs à haute activité et à vie longue. Résultats et perspectives*, ANDRA

[3] ANDRA (2008) Les démonstrateurs technologiques, ANDRA

[4] ANDRA (2010a) VISITEZ LES SITES DE L'ANDRA pour comprendre la gestion des *déchets radioactifs,* ANDRA

[5] ANDRA (2010b) *Le Laboratoire souterrain. Un outil scientifique unique pour concevoir un stockage réversible profond*, ANDRA

[6] Arvanitis, R. and M. Grossetti (2009) 'Counting, demonstrating, formalizing', in *Revue d'anthropologie des connaissances*, Vol. 3, no. 2, p. 177-182

[7] Bal, M. (1994) 'Telling objects: a narrative perspective on collecting'. In Elsner J. and R. Cardinal (eds) *The Cultures of Collecting*, p. 97–115.

[8] Barry, A. (2001) *Political Machines. Governing a Technological Society*, London, New York: The Athlone Press

[23] I am grateful to Yannick Barthe for having clarified this point.

[10] Barthe, Y. and Linhardt, D. (2009) ‘L'expérimentation : un autre agir politique’, *CSI Working Papers Series No. 13*

[11] Bijker, W. and Law, J. (1992a) ‘General Introduction’. In Bijker W. and J. Law (eds) *Shaping technology/building society: studies in sociotechnical change*, Cambridge: MIT Press, p. 1–16

[12] Bowker, G. C. and Star, S. L. (1999) *Sorting things out: classification and its consequences*. Cambridge, London: MIT Press.

[13] Brunnengräber, A., L. Mez, M.R. Di Nucci, M. Schreurs (2012) ‘Nukleare Entsorgung: Ein „wicked“ und höchst konfliktbehaftetes Gesellschaftsproblem’, in *Technikfolgenabschätzung - Theorie und Praxis*, Vol. 21, No. 3, p. 59-65

[14] Daston, L. (ed) (2004) *Things that Talk. Object Lessons from Art and Science*, MIT Press

[15] Delay, J., P.L. Forbes, J. Roman (2008) ‘The Meuse/Haute-Marne Underground Research Laboratory: Seven Years of Scientific Investigations’, in *ANDRA Science & Technology Series n° 334*

[16] Elam, M., L. Soneryd, G. Sundqvist (2010) ‘Demonstrating Safety – Validating New Build: The Enduring Template of Swedish Nuclear Waste Management’, in *Journal of Integrative Environmental Sciences*, Vol. 7, No. 3, p. 197-210

[17] Foucault, M. (1979 [1975]) *Discipline and Punish: The Birth of the Prison*, Harmondsworth: Penguin

[18] Gaucher, E. et al. (2004) ‘ANDRA underground research laboratory: interpretation of the mineralogical and geochemical data acquired in the Callovian-Oxfordian formation by investigative drilling’, in *Physics and Chemistry of The Earth*, Vol. 29, No. 1, p. 55-77

[19] Haraway, D. (1989) Primate Visions: Gender, Race and Nature in the World of Modern Science, London: Routledge

[20] Meyer, M. (2011) ‘Researchers on display: moving the laboratory into the museum’, in *Museum Management and Curatorship*, Vol. 26, No. 3, p. 261-272

[22] Roberts, N.C. (2000) ‘Wicked problems and Network Approaches to Resolution’, in *The International Public Management Review*, Vol. 1, No. 1, p. 1-19

[23] Rosental, C. (2007) *Les capitalistes de la science. Enquête sur les démonstrateurs de la Silicon Valley et de la NASA*, CNRS editions

[24] Rosental, C. (2009) ‘Anthropologie de la démonstration’, in *Revue d'anthropologie des connaissances*, Vol. 3, No. 2, p. 233-252

[25] Shapin, S. (1988) ‘The House of Experiment in Seventeenth Century England’, in *ISIS*, 79, p. 373–404

[26] Shapin, S. and Schaffer, S. (1985) *Leviathan and the air-pump: Hobbes, Boyle, and the experimental life*, Princeton: Princeton University Press

[27] Voinis, S. (2008) ‘Réversibilité et sûreté du stockage’, in *Réversibilité et sciences sociales. Actes de la Journée d’études du 2 octobre 2008*, ANDRA

[28] Virilio, P. (2006) *The information bomb*, Verso

[29] Yaneva, Albena (2005) ‘Scaling Up and Down: Extraction Trials in Architectural Design’, in *Social Studies of Science*, Vol. 35, No. 6, p. 867-894

[30] Winner, L. (1986) *The Whale and the Reactor. A Search for Limits in an Age of High Technology*, Chicago: The University of Chicago Press

Oversight of a Deep Geological Repository and the Role of Monitoring – Some preliminary findings within the RK&M Project of the NEA

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Summary
The OECD/NEA Radioactive Waste Management Committee Project on "Preservation of Records, Knowledge & Memory Across Generations" explores and aims to provide guidance on regulatory, policy, managerial and technical aspects of long-term preservation of RK&M. Within this project questions germane to the issue of monitoring are being investigated. The concept of oversight, as revisited and applied by the NEA Reversibility and Retrievability project and adopted by the International Commission on Radiological Protection, provides a useful framework to view technical monitoring activities and societal engagement as parts of a unified whole. Monitoring serves the purpose of oversight and, as such, is part of the latter.

1. Introduction

The International Commission on Radiological Protection (ICRP) is about to release its new recommendations related to geological disposal of long-lived solid radioactive waste [1]. The ICRP report outlines that, from a radiological viewpoint, the application of the protection system is influenced by the level of oversight or 'watchful care' of the disposal facility that is present (p. 6). The report follows on to indicate that three main levels or types of oversight have to be considered: *direct oversight* when access to the waste is possible, i.e., when disposal galleries are still open; *indirect oversight* when direct access to the waste is no longer possible without re-excavation, i.e., for some parts of the disposal facility or for the full facility after sealing; and *absence of oversight* in case the memory of the disposal facility was lost (see Fig. 1). The guidance also states "The different decisions to be made relating to the evolution of the oversight should be discussed with stakeholders" (p. 18).

The goal of a geological disposal facility is to isolate and contain the waste in order to protect humans and the environment for periods that are comparable with geological time scales. The international position and that of the ICRP is that, once closed, the repository should continue to perform its safety mission in a manner that does not require continued human intervention. Namely, the eventual absence or loss of oversight would not result in a change of the intrinsic protective capability of the disposal facility. It is understood, however, that (a) there is no plan to lose memory of the repository and (b) that forms of oversight will be applied. Oversight may be provided through mechanisms such as monitoring of technical system parameters and active keeping of records and memory [2]. In a similar vein, the Euratom Directive 2011/70 of 19 July 2011, Article 12 (e), implies obligations on EU countries in terms of controls after closure at least for a certain period of time and the keeping of records without time limits, hence, again, forms of continued interest in the fate of facility and oversight.

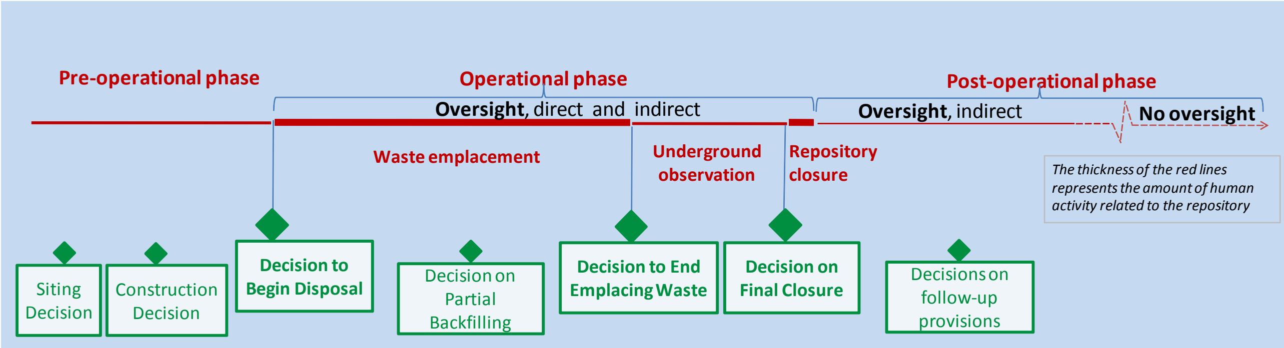

Figure 1: Repository lifecycle phases and examples of associated decisions. The transition between the various forms of oversight is gradual and the actual duration of each time period will vary project by project. (Adapted from the NEA R&R Project [2])

Oversight can be exercised through monitoring of technical parameters and through technical analyses of those data; oversight can also be exercised through monitoring of institutional provisions meant to be protective of the repository, e.g., land withdrawal provisions established by law; oversight can furthermore be exercised in a broader sense through the monitoring of actual implementation of agreements made with the local hosts. Implementers, regulators, policy makers, local communities may be variously engaged in these oversight/monitoring activities. From this point of view it is observed that monitoring serves the purpose of oversight and, as such, is part of oversight. Monitoring can be defined as "to watch and check a situation carefully for a period of time in order to discover something about it" [14].

The preliminary results presented here arise from ongoing work carried out in the framework of the OECD/NEA Radioactive Waste Management Committee Project on "Preservation of Records, Knowledge & Memory across Generations" (RK&M). In particular, two studies are being carried out, one technically oriented and the other societally oriented. The societally-oriented study is based on the analysis of relevant literature on monitoring as well as on the results of a survey on monitoring and preservation of records, knowledge and memory with members of the NEA Forum on Stakeholder Confidence (FSC). The aim is to identify local communities' position on the preservation of knowledge and memory of radioactive waste management facilities. The survey was conducted in July 2012 and was only illustrative and did not aim to be representative. Responses were provided by 17 organisations, including implementers, regulators and scientists from 11 countries. In addition, twelve interviews were conducted with FSC representatives (implementers, regulators and scientists) and local stakeholders and will continue to be conducted in the coming months to complement the views on local communities' demands and confidence in the preservation of RK&M.

2. Oversight and control

Oversight and control are two related terms [6]. Regulatory verification and inspections are forms of both oversight and control. Oversight, however, is always linked to the action and presence of humans; while control can be exercised by the system itself, e.g., through intrinsic, passive safety provisions built in the system. As stated by ICRP [1] and the NEA [2, 6] “oversight is the more general term that refers to society ‘keeping an eye’ on the technical system and the actual implementation of plans and decisions”.

The level or type of oversight, whether or not humans have access to the waste, affects the capability to manage the source and to control exposures. For instance, because oversight assumes a continued “watchful eye”, inadvertent human intrusion into the geological disposal facility is not considered by the ICRP to be a relevant scenario during the period of oversight, direct or indirect [1].

It is important to note that the ICRP requires continuity of oversight as long as practicable, Continuity of oversight suggests that the waste is never “cleared” from regulatory control, which justifies the ICRP’s 0.3 mSv/yr dose constraint for repository performance. (If the waste was “cleared” from regulatory control , the reference dose constraint would be 10 μSv/yr). To this effect, the ICRP makes also the point that a repository has to be considered as functioning nuclear facility at all times, including after closure.

3. Oversight periods and “monitoring”

In the first place, it is the licensee that is responsible for the safety of the nuclear facility for as long as it holds a license for it. Before closure the implementer/licensee is responsible for monitoring the system performance under supervision by the regulator and society at large (local communities, Government, Parliament, etc.).

Responsibilities for “who does what” after closure have not yet been defined. After closure, the regulator’s role will certainly continue but it may become increasingly less prominent. Monitoring of repository system performance parameters, however, is expected to continue for a period of time which, at this stage, is undefined. Studies to this effect are being carried out by radioactive waste management agencies in consultation with other stakeholders, e.g., the MoDeRN project. Specific suggestions and guidelines on monitoring a geological disposal facility are also included in Report of the European Pilot Group [4] and in the GEOSAF draft final report [5].

The Swedish national programme reports the following reasons for technical monitoring during the stepwise implementation of a repository [3]:

- describe the primary baseline conditions of the repository site,
- develop and demonstrate understanding of the repository site and the behaviour of engineered barriers,
- assist in the decision-making process,
- show compliance with international and national guidelines and regulations.

Another national example is provided by the Canadian national programme for used fuel management [22].

There may be, in parallel, measures to monitor that are not strictly technical, or that may be technical but are carried out by other players than the implementer or the technical regulator. Thus, to the extent that oversight is a general term for “watchful care” and refers to society “keeping an eye”, it is important that a programme includes planning for dialogue to periodically renew the basis of understanding among stakeholders. In this sense, “*monitoring plans will be revised periodically in response to technical developments and modifications to* *the repository design and changing societal demands for information*" [19]. Dialogue and its documentation become a means to assure transfer of knowledge, awareness and ultimately, higher confidence in safety.

In the present paper we distinguish between monitoring of repository system performance parameters as it would be performed through technical approaches, and monitoring of other aspects mostly through non-technical, administrative approaches.

3.1 Direct and indirect oversight during the pre-operational and operational phases

3.1.1 Pre-operational phase

Technical expectations and challenges

In the preoperational phase the waste is not yet emplaced in a disposal facility, therefore, preparations are made for its oversight, both direct and indirect oversight. These preparations focus on selecting procedures and technical siting/construction approaches and results, and proper monitoring parameters.

Monitoring of technical parameters starts in the pre-operational phase. At this stage it is important to identify baseline information, to start monitoring from early on, including a set of reference technical and environmental data (site/environment characteristics prior initiating intrusive actions) to later infer which changes may be ascribed to repository development and operation.

Baseline conditions consist of 'undisturbed data' from the site of interest, both surface and subsurface. The relevant monitoring project should commence prior to the start of repository construction, ideally as an element of surface and underground investigations. Selected parameters will need to be checked throughout the whole lifecycle. It would be helpful if their selection were discussed with the most affected stakeholders [9]. For instance, indigenous people may have special living habits that differ from those of other citizens [20].

Societal expectations and challenges

In this phase, local communities may set a number of conditions for continued participation, one of them being monitoring activities. For instance, in its Final Report, the West Cumbria Managing Radioactive Waste Safely Partnership states: "*Research is being carried out to assess the best ways of doing this [monitoring]. However, the research is still in its early stages, so we note that more work would need to be done if the process goes ahead*" [17]. According to the interviews undertaken so far as part of the ongoing study of the NEA, local communities involved in siting or those voicing an interest about the possibility of hosting a geological disposal facility, do express monitoring demands. Namely, general monitoring without further specification, or environmental (e.g. noise, water quality, pollution, etc) and socio-economic monitoring (e.g. benefits packages, property values, economic development, etc). In addition, some local communities suggest that post-closure monitoring should be considered already at the time of siting. A representative from the Osthammar municipality reported in an interview that: "*there is a common feeling in the community that monitoring may be necessary. If something is dangerous, you feel you need to monitor this. […] We need to be prepared as these issues may arise in the future or later in the process*". For this reason, several representatives of local communities from Sweden and the UK have been involved both in the MoDeRn project and in the RK&M project, namely to learn how oversight and monitoring can be prepared. The Nye County in the US, the host county for the Yucca Mountain project before the project was defunded in 2010, proposed a comprehensive programme of environmental monitoring, including monitoring of socioeconomic factors. It would include the establishment of baseline conditions and management of the monitoring and mitigation activities associated with the Yucca Mountain Repository [21]. In a similar vein, indigenous people in Canada have been very explicit about the need to monitor both the environment and the nuclear waste management system. For instance, they recommended setting up a special First Nations/Aboriginal Nuclear Waste Monitoring Agency to be active as long as possible [20].

3.1.2 Operational phase

Technical expectations and challenges

Monitoring of repository system performance parameters during repository operation extends the activities of the pre-disposal phase to include monitoring of changes in the host geological properties (rock stress distribution, hydrological changes, etc.) and of correct emplacement and performance of the engineered barriers system and of safety measures. The monitoring programme also includes operational safety aspects (radioprotection), monitoring of compliance with waste acceptance criteria, and safeguards (if relevant) [7]. The implementer will have to monitor aspects beyond purely radiological ones, as other occupational types of hazards exist, e.g., fire and mining hazards [3, 18].

Newly initiated monitoring projects are dealing typically with engineered barrier system performance, integrity of waste packages, behaviour of disposal facility structures and engineered barriers, disturbances created by the disposal facility (construction, emplacement of waste, and installation of engineered barriers), monitoring of radionuclide and chemical releases and changes to geosphere. Specific role is given to the so called 'compliance monitoring' which, in practical terms, constitutes the review of the work performed using a pre-determined list of parameters and requirements issued or approved by a regulator. Its aim is to attain the required level of operational safety when emplacing the waste and installing the engineered barriers [7].

Facility operation is a period when oversight and monitoring are performed most intensively. The regulator, the operator and other stakeholders apply both direct and indirect measures to assure that disposal process is run according to licensed design, and that workers, the public and the environment are adequately protected. Decisions, assessments, or relevant remediation actions are dependent on the extent and the quality of data generated by the monitoring programme, as well as of other information regarding, e.g., the safety culture of the operator. Figure 1 above shows that some programmes also have a specific underground observation period before closure of the facility.

Most disposal projects consider sequential construction of disposal galleries: then, a part of the underground facility might be under construction, other in the disposal process, and another even sealed and closed. As a result, the disposal facility would be under ***direct and indirect*** oversight at the same time. The consequences for monitoring are evident: while data collection from nearby closed disposal spaces will have to be terminated and system behaviour further noted through remote measuring points only, construction activities may affect results of monitoring of areas being sealed and loaded, specifically regarding hydrology, seismicity and geotechnical parameters. The ongoing NEA technical study observes that potential data fluctuations should be adequately interpreted to distinguish between normal transient behaviour and possible more steady but unwanted effects. These are part of the challenges that should be considered while developing the monitoring plan for the facility when under construction.

Societal expectations and challenges

Societal concerns in the operational phase tend to refer in the first place to environmental monitoring and secondly to monitoring of socio-economic impacts, according to the survey undertaken as part of the ongoing NEA societal study on monitoring.

In the UK, "monitoring and testing performance" are issues of concern to the local authorities, and they can be crucial as the national approach is to seek "suitable" (i.e., not necessarily "best") geology and the repository designed to site circumstances [8]. In Sweden, demands on monitoring and preservation of RK&M have emerged at the local level and will be an issue to be looked at by both SKB and the Swedish Council for Nuclear Waste. In France, the FSC workshop in Bar-le-Duc in 2009 showed that the CLIS were particularly concerned about public health and that epidemiological monitoring is a key issue [9]. Overall, local communities can contribute to monitoring. Partnerships can also enable the local community to undertake some of the monitoring tasks, including monitoring other institutions performance [10, 11].

3.2. Indirect oversight during the post operational phase

Even if safety is assured by the intrinsic, built-in provisions of the design of the disposal facility, it is expected that activities will be undertaken to support continued confidence in the performance of the system. These activities would provide further opportunities for future decision making, including applying corrective measures. This will likely require continuation of monitoring of baseline environmental parameters. Maintaining information archives (to keep memory) will also take place and safeguards controls will continue.

Technical expectations and challenges

The duration of post-closure monitoring will vary nation by nation. For example, as reported in [16], in Switzerland it will continue "… as long as it is thought beneficial to society" and in the USA, for the WIPP facility, the programme will last until "…no more meaningful data are being collected". Other programmes have not yet made explicit the extent and duration of post closure monitoring.

Reasons for post-closure monitoring can be diverse and can be of more than just technical nature (cf. [15, 16]). The ongoing compilation by the NEA (to be finalised in 2013) reports the following:

- **Safeguards** (Belgium, Canada, Germany, Netherlands, Spain, Sweden, Switzerland).
- To understand the **evolution of the near-field** (Netherlands, Sweden).
- To determine the **post-closure evolution** of the geosphere (WIPP, Belgium, Canada, Netherlands, Russia).
- To evaluate the **impacts** of the repository **on the surface** (Canada, Netherlands).

- To confirm **performance assessment** assumptions (WIPP, Yucca Mountain, Canada, Finland, Spain).
- As an **aid to decision-making** - retrieval the waste or ending the institutional control phase (Belgium, France, Japan, Netherlands).
- To gain **public acceptability** and public **confidence** (Belgium, Canada, Germany, Japan, Sweden, Switzerland).
- To meet **legal requirement** (the Netherlands, WIPP, Yucca Mountain, Hungary).

Key parameters considered in the national programmes above include:

- *For safeguards:* Human activity.
- *For evaluating the impact on the environment*: Groundwater pressure and water table elevation; Temperature; Ground elevation; Seismicity, including microseismicity and acoustic emission.
- *For performance assessment*: Groundwater chemistry.
- *For providing information to stakeholders:* Surface environment, including environmental radioactivity.

The geological disposal system will be required to provide for the determined safety levels for a period of at least tens of thousands years; whereas the containment of radionuclides within the engineered disposal system is typically designed for a number of millennia. The parameters identified above would support the view that ***monitoring*** of nuclear substances in the time frame of decades or centuries may not be a technically productive lead. Besides, post-closure monitoring in/nearby the disposal spaces may impair the containment function of the disposal system. Additionally, at the present state of the art, the necessary instrumentation would not have the required durability and longevity, nor would it be possible to reach out and replace failed sensors and measuring devices.

Societal expectations and challenges

From the ongoing NEA survey, requests for monitoring during the post-operational phase are not so clearly articulated by local communities, compared to monitoring during the pre-operational and operational phases. When monitoring is suggested, environmental monitoring is the main concern. Nevertheless, it is clear that there is an emerging role for local communities in local stewardship, which consists, basically, in oversight perpetuity [12]. There is a high debate in France on the contribution of local people to preserve memory; Sweden seems to be still entering this field and discussing which would be the best way to pass knowledge on to future generations. Tools for the local community to maintain memory are country specific and range from land registers and markers, to oral history, regular dissemination and developing the culture of memory in institutions and territories [13].

4. Final reflections

The concept of oversight, as recently adopted by the ICRP and as applied by the NEA Reversibility and Retrievability Project, provides a useful framework to view technical monitoring activities and societal engagement as parts of a unified whole. Oversight is the general term for “watchful care” and “keeping an eye” on the technical system and the actual implementation of plans and decisions. Oversight requires the presence of humans.

The implementation of a disposal project is viewed an incremental process, with different phases, in which there is a gradual transition between various forms of oversight during the pre-operational, operational and post-operational phases. Planning for oversight, both direct and indirect, and therefore also for technical monitoring, should be undertaken since starting the siting procedure, to ensure optimal oversight throughout the repository lifecycle. *"One of the benefits from the early development of design concepts addressing specific monitoring functions is that they provide a basis for identifying the areas where technology development is needed. This would help identify requirements, potential obstacles and alternative solutions to different monitoring tasks."*[22]

Oversight can be exercised through monitoring of technical parameters and through technical analyses of those data; oversight can also be exercised through monitoring institutional provisions meant to be protective of the repository, e.g., land withdrawal provisions established by law; oversight can also be exercised, in a broader sense, through monitoring agreements made with the local hosts. Implementers, regulators, policy makers, local communities may be variously engaged in these oversight/monitoring activities. From this point of view it must be born in mind that monitoring serves the purpose of oversight and is part of the latter. At the same time oversight serves the purpose of preservation of records, knowledge and memory of the facility. In order to find an optimal oversight approach it is important to harmonise social and technical demands from the beginning.

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References

[1] International Commission on Radiological Protection (2011) Radiological Protection in Geological Disposal of Long-Lived Solid Radioactive Waste, Draft Report For Consultation, ICRP ref 4838-8963-9177. July 21, 2011. Available online. Target release date is March 2013.

[2] NEA Radioactive Waste Management Committee (2011) Reversibility and Retrievability (R&R) for the Deep Disposal of High-level Radioactive Waste and Spent Fuel. Final Report of the NEA R&R Project (2007-2011). Available online.

[3] Backblom G., Almen K.E. (2004) Monitoring during the stepwise implementation of the Swedish deep repository for spent fuel, SKB R-04-13, March 2004.

[4] Report on the European Pilot Study on the Regulatory Review of a Safety Case for Geological Disposal of Radioactive Waste. Version for consultation of 26.11.2010 distributed to NEA/IGSC members on 13.07.2011. (Please contact the NEA Secretariat of the IGSC)

[5] International Atomic Energy Agency (2011) GEOSAF. The International Intercomparison and Harmonisation Project on Demonstrating the Safety of Geological Disposal. Available online.

[6] NEA (2012) Glossary of Terms – Draft. NEA Project on Long-term Preservation of Records, Knowledge and Memory (RKM) Across Generations. Available on-line.

[7] International Atomic Energy Agency (2011) Monitoring and Surveillance of Radioactive Waste Disposal Facilities, Draft SAFETY GUIDE DS357.

[8] Knowles, T. & McMorrow, F. (2010) "Reversibility and Retrievability in the Context of "Managing Radioactive Waste Safely" in the United Kingdom". Paper presented at the Reversibility & Retrievability International Conference, Reims, France, 14-17 December 2010. OECD Nuclear Energy Agency.

[9] NEA (2010) Radioactive waste repositories and host regions: Envisaging the future together. Synthesis of the FSC national workshop and community visit Bar-le-Duc, France 7-9 April 2009. OECD Nuclear Energy Agency, Paris.

[10] NEA (2009) Regional Development and Community Support for Radioactive Waste Management. Synthesis of the FSC National Workshop and Community Visit Tengelic and Bátaapáti, Hungary, 14-17 November 2006. OECD, Paris, France.

[11] NEA (2010) Partnering for Long-term Management of Radioactive Waste. Evolution and Current Practice in Thirteen Countries. OECD, Paris, France.

[12] NEA (2012) Reflections on siting approaches for radioactive waste facilities: synthesizing principles based on international learning. Radioactive Waste Management Committee, OECD, Paris, France.

[13] NEA (2008) Tools and Processes for Handling of Transfer of Burdens, Knowledge and Responsibility: Preparing Future Generations and Empowering Local Communities. Proceedings of a Topical Session Issy-les-Moulineaux, France 6-8 June 2007. OECD Nuclear Energy Agency, Paris, France.

[14] Taken from the "Cambridge Dictionaries online" , consulted in January 2013

[15] Torata S., Fukuoka K., Sugiyama T., Yoshimura K., Ohuchi J., Tsuboya T. (2005).: Monitoring of Geological Disposal, Current Status and Technical Possibilities, Technical Report RWMC-TRE-04004

[16] White M.J., Bennett D.G., Crawford M.B., Emsley S. (2004): Techniques for Post-Closure Monitoring, NIREX, UK.

[17] Copeland Borough Council (2012) The Final Report of the West Cumbria Managing Radioactive Waste Safely Partnership. The West Cumbria MRWS Partnership. August.

[18] Streffer C., Gethmann, C.F., Kamp, G., Kröger, W., Rehbinder, E., Renn, O. (2011) Radioactive Waste – Technical and Normative Aspects of its Disposal. Ethics of Science and Technology Assessment, Vol. 38, Springer.

[19] International Atomic Energy Agency (2001) Monitoring of geological repositories for high level waste, IAEA-TECDOC1208.

[20] First Nations Nuclear Fuel Waste Dialogue Working Group (2004), Appendix 7 of Meeting #2 Report, submitted to the Nuclear Waste Management Organization of Canada on November 30, 2004.

[21] Department of Environment (2008), Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-

level radioactive Waste at Yucca Mountain, Nye County, Nevada. Section 9.2.3. Nye County Perspective on Management Actions to Mitigate Potential Adverse Impacts.

[22] Villagran J.E., Development of a Monitoring Program for a Deep Geological Repository for Used Nuclear Fuel, NWMO-TR-2012-18, October 2012

C.4 Session S4: Poster Session

Development of a Monitoring Program for a Deep Geological Repository for Used Nuclear Fuel

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Summary
This paper describes work conducted at the Nuclear Waste Management Organization (NWMO) aimed at developing a repository monitoring program within the framework of Adaptive Phased Management, the approach selected by the Government of Canada for the long-term management of Canada's nuclear fuel waste. The primary functions of the monitoring program are: i) confirming the long-term safety of the repository and, ii) providing information that may be required for future decisions, such as that of closing the repository. This paper outlines the basis and scope for the program and identifies a set of general objectives for the different stages of implementation of the Adaptive Phased Management project. Important components of the work plan include:

- stating a well defined basis for monitoring
- establishing a process for identifying important monitoring parameters
- developing monitoring strategies for potentially suitable host rock formations
- selecting key monitoring parameters based on preliminary repository designs
- developing preliminary monitoring system designs and
- applying the developed processes and strategies to a site-specific repository design

1. Basis for Monitoring

NWMO's repository design concepts are based on placing the used nuclear fuel in long-lived, corrosion resistant containers and placing these containers, surrounded by engineered barriers, inside tunnels excavated in a suitable rock formation. Preliminary repository designs have been developed for two types of geological media: crystalline rock and sedimentary rock. Although it is expected that after the repository operating phase further actions will not be required to ensure the repository safety, it is important to have the means for verifying the repository performance and to provide data that would inform future decisions related to the repository. This can be accomplished by implementing a program that will develop, design, and place in service the required engineered systems to perform specified monitoring functions. The definition of those functions and the development of monitoring systems will take place in parallel with the evolution of repository designs and the associated safety cases. The scope of this study is limited to monitoring activities that would be conducted during the preclosure period, which includes the repository operational phase and an extended monitoring period and will encompass a time of the order of 100 years.

2. Selection of Monitoring Parameters

The safety assessment of a geological repository includes the analysis of a set of repository evolution scenarios. Possible evolution scenarios are identified by considering a comprehensive set of Features, Events and Processes (FEPs) that could affect the repository system over the long-term. Both Normal Evolution and Disruptive-Event scenarios are considered in the safety analyses. A thorough examination of the repository safety case is essential to ensure that a comprehensive set of monitoring parameters is identified. The approach for identification and selection of parameters is based on ranking repository evolution scenarios on the basis of risk and then examining the FEPs associated with those scenarios. The process is schematically shown in Figure 1.

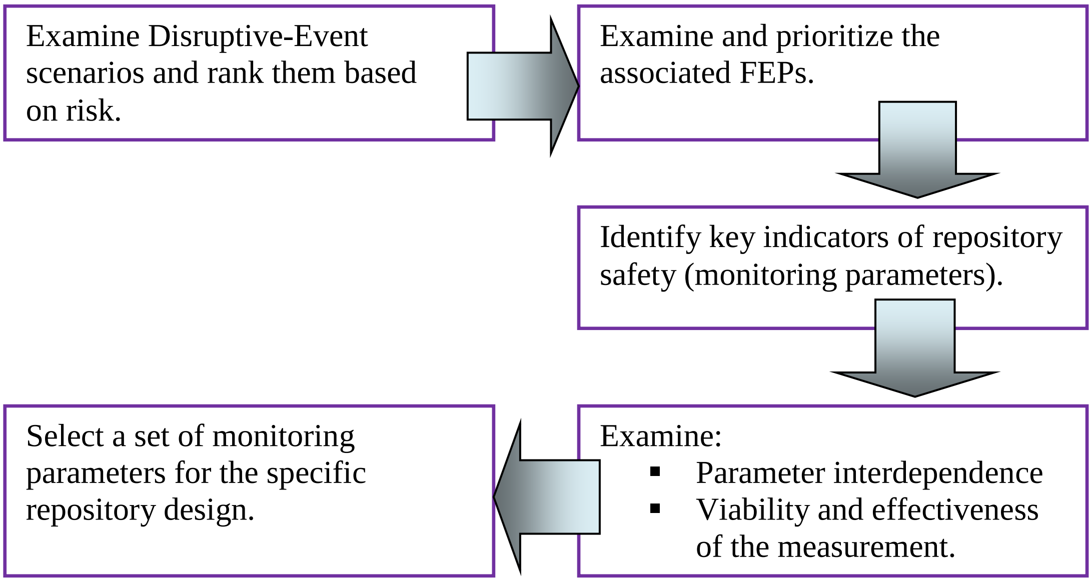

Figure 2: Process for Selection of Monitoring Parameters

These tasks will be followed by review and assessment of applicable technologies and the design and optimization of monitoring systems for the selected set of parameters. To illustrate this process, a repository design concept developed for crystalline rock will be used here. This design concept has been extensively studied in Sweden, Finland and Canada (SNC-Lavalin 2011).

3. Repository Design Concept for Crystalline Rock

The repository design concept used here consists of encapsulating the used nuclear fuel in durable containers and placing the containers in a repository constructed at a depth of approximately 500m in a suitable crystalline rock formation. The used fuel containers (IV-25 design concept) have a capacity of 360 used CANDU fuel bundles and consist of a 25 mm thick copper outer shell that provides a long-lived corrosion barrier and an inner steel inner vessel that provides mechanical strength. The containers length is 3.84 m and the outer diameter 1.25 m. Each container is placed in a vertical borehole drilled in the emplacement tunnel floor. The boreholes are drilled along the tunnel axis, with a center-to-center spacing of 4.2 m. Within these boreholes, the containers are surrounded by compacted bentonite blocks (buffer) that constitute the primary isolation barrier between the container and the rock. The buffer is designed to inhibit groundwater flow, to adsorb many key contaminants and to inhibit the development of bacteria that might produce corrosion agents. The configuration of a container emplacement tunnel is shown in Figure 2.

4. Repository Evolution Scenarios

Although the manufacture, loading and sealing of the used fuel containers include rigorous quality assurance processes, it is possible that a small fraction of the containers placed in the repository could have undetected defects. This is a FEP included in the Normal Evolution Scenario, and assumes a 1/5,000 probability of placing in the repository a container with an undetected through-wall defect. For an inventory of 4.6 million used fuel bundles packaged in about 12,800 containers, this means a maximum of three containers with through-wall defects being placed in the repository.

Analysis of the Normal Evolution Scenario indicated that within the time frame of the assessment the only contaminant releases would originate from the three defective containers, and that if the rest of the repository systems (engineered barriers) perform as per design, the released contaminants would take tens of thousands of years to reach the surface environment and the radiation doses to humans would be well below acceptable limits. There are no other FEPs considered in the Normal Evolution Scenario that would result in unacceptable radiation doses, therefore, Disruptive Event Scenarios that combine defective containers with other FEPs need to be considered.

Container degradation, fuel dissolution rates and contaminant transport rates would all be enhanced by an increased rate in the supply of groundwater to the container surface. Consequently, scenarios where the buffer fails to perform as per design carry an increased risk. Failure of the buffer, whether is caused by a manufacturing defect or by improper installation of buffer blocks, carries a potentially significant risk, thus, buffer integrity is important for ensuring repository safety.

At the time of installation the bentonite blocks will have a specified water content and, initially, the heat from the container will cause the moisture to be redistributed, with the region closest to the container becoming drier. Subsequently, this process will be reversed and the water content of the clay will slowly increase until full saturation of the buffer is achieved, which will ensure protection of the container surface as well as the effective adsorption of many contaminants and a diffusion-dominated transport regime for solute transport. Depending on the permeability of the host rock, the full saturation of the buffer may take from a few decades to several hundred years.

5. Monitoring System Concept for Engineered Barriers

The proposed method for monitoring repository safety performance parameters includes two independent subsystems designed to confirm the expected evolution of the buffer by measuring total pressure. Confirming that the buffer evolves as predicted and attains its target pressure would provide assurance of its effectiveness. Two subsystems (EB System A and EB System B) are proposed to achieve this purpose. They would look at two different samples of the borehole population and monitor the buffer total pressure using two independent measurement methods.

EB System A is intended look at a large sample of the in-floor boreholes in the repository. The sensors for this sub-system consist of three total pressure cells installed in each borehole, as shown in Figure 2. They would be located on the periphery of the buffer, essentially between the buffer and the rock. These pressure cells would not require an external power supply and would be actuated when the buffer total pressure reaches a specified threshold value. The design concept is that of a self-driven pressure sensor capable of generating a signal detectable by a dedicated network of receptors (e.g., geophones) located in the near-field rock. The geophone network could be installed in sub-horizontal, small-diameter boreholes drilled from the cross-cut tunnels into the rock pillars. The time and spatial distribution of the pressure sensor signals would provide a global view of the buffer evolution throughout the repository.

EB System B is intended to measure the rise in pressure the buffer as a function of time in a smaller sample of the borehole population. The intent is for this system to monitor buffer saturation at a number of locations representing the hydrogeological conditions in each repository panel. The sensors installed in each sample borehole would consist of two total-pressure cells mounted on the periphery of the buffer. These sensors would monitor the development of total pressure by providing a periodic signal to a controller unit located inside the emplacement tunnel. This unit would include a power supply and would be capable of wireless transmission of the received signals to a readout unit in the access tunnel.

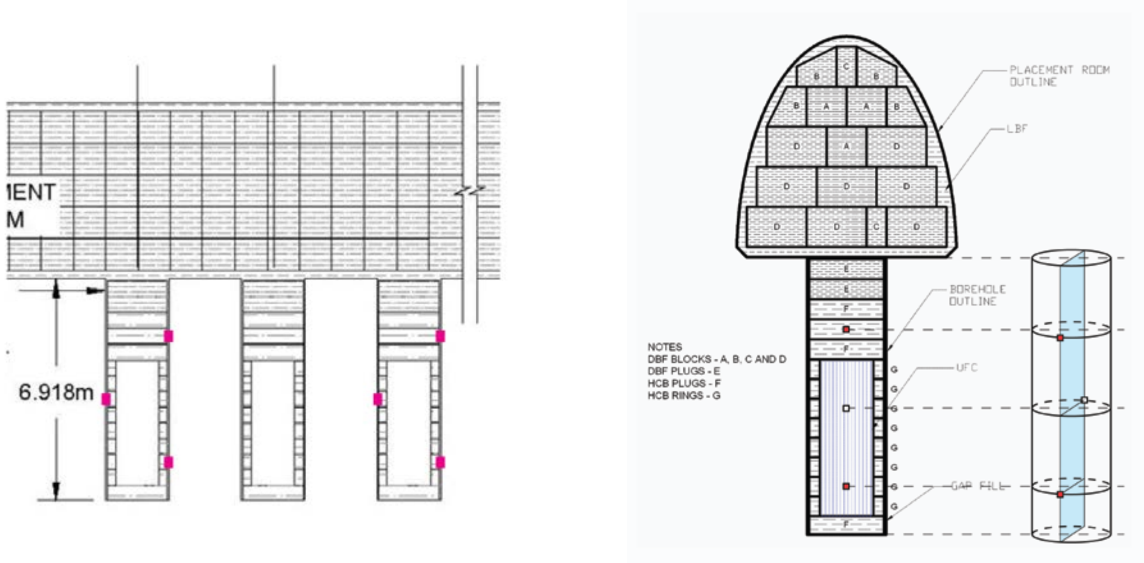

Figure 2: Vertical sections of the container emplacement tunnel showing sensor locations

6. Conclusions

A process for identification and selection of monitoring parameters has been outlined. This process is based on the repository safety case and uses the FEPs associated with selected repository evolution scenarios to identify important parameters. Alternative methods and technologies may play an important role in the selection of the parameters and systems that will be used to confirm repository safety performance. Two independent design concepts for monitoring the evolution of engineered barriers have been suggested.

7. Acknowledgements

This paper describing preliminary development of approaches for monitoring a repository in crystalline rock has benefited from the review of international work conducted in recent years under EU programs, and specifically from the work published by the MoDeRn project (European Commission, 2011).

References

[1] European Commission. 2011. MoDeRn Project Deliverable 3.1.1: Site Plans and Monitoring programmes report. Dated 03/01/11. www.modern-fp7.eu/home. Paris, France.

[2] Garisto, F. and P. Gierszewski. 2011. Used Fuel Repository Conceptual Design and Postclosure Safety in Crystalline Rock - Interim Report. Nuclear Waste Management Organization report NWMO TR-2011-21. Toronto, Canada.

[3] McMurry, J., D.A. Dixon, B.M. Ikeda, S. Stroess-Gascoyne, P. Baumgartner and T. Melnyk. 2003. Evolution of a Canadian deep geologic repository: Base scenario.

Ontario Power Generation Report No. 06819-REP-01200-10092-R00. Toronto, Canada.

[4] NEA. 2005. Nuclear Energy Agency - Radioactive Waste Management Committee. Integration Group for the Safety Case: The Role of Monitoring in a Safety Case. Report NEA/RWMC/IGSC (2005)3. Source: OECD - NEA Website.

[5] SNC-Lavalin Nuclear Inc. 2011. APM Conceptual Design and Cost estimate Update - Deep Geological Repository Design Report - Crystalline Rock Environment. Nuclear Waste Management Organization Report APM-REP-00440-0001. Toronto, Canada.

Interim Storage of Higher Activity Waste Packages – Integrated Approach

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Summary
The period between packaging wastes and emplacing these packages in a geological disposal facility could span several decades. It is therefore important to both control storage conditions and monitor waste packages throughout any period of interim storage, such that the implementer can both protect and understand the condition of the packages to allow them to be safely handled and disposed. A team led by the Nuclear Decommissioning Authority has developed guidance on interim storage of waste packages. This has been developed in line with Government Policies and Committee on Radioactive Waste Management recommendations, and seeks to support NDA strategy to provide for the safe and secure storage of radioactive wastes for a period of at least 100 years. The work programme was designed to include consideration of such areas as package performance, monitoring and inspection, store longevity, store environmental controls and package reworking. This paper describes the scope of the published guidance.

1. Introduction

The design for a geological disposal facility relies upon the integrity of multiple barriers, including those provided by the waste packages. The period between packaging wastes and emplacing these packages in a disposal facility could span several decades. It is therefore important to both control storage conditions and monitor waste packages throughout any period of interim storage, such that the implementer can both protect and understand the condition of the packages to allow them to be safely handled and disposed.

In 2006, the Committee on Radioactive Waste Management (CoRWM) recognising the importance of package conditions in interim storage recommended to UK Government that a robust programme of interim storage must play an integral part in the UK's long-term radioactive waste management strategy [1]. A later review, in 2009, on interim storage arrangements recommended that more needed to be done to demonstrate interim storage is robust to the uncertainties surrounding implementation of the disposal route, and emphasised that a more strategic approach is necessary [2].

The Government, including the Devolved Administrations, accepted this recommendation from CoRWM and noted the proposed formation of an Integrated Project Team (IPT) led by the Nuclear Decommissioning Authority (NDA) [3], designed to address many of the technical issues identified by CoRWM, and by the NDA's own review [4]. Thus the work programme for the IPT was designed to include consideration of areas such as:

- package performance;

- package monitoring and inspection;
- store longevity including facility monitoring and inspection;
- store environmental controls;
- package reworking.

The resulting Guidance, developed in line with UK and Scottish Government Policies and CoRWM recommendations, seeks to support NDA strategy to provide for the safe and secure storage of radioactive wastes for a period of at least 100 years. The Guidance has been published on the NDA website.

2. Scope of the guidance document

The Guidance sets out to support implementation of interim storage arrangements in the UK at site level. The Guidance covers the interim storage of packaged Higher Activity Waste (HAW) across the UK. It should be noted that Scottish HAW Policy [5] refers to the long-term management of HAW in near-surface, near-site facilities.

The strategic aims of the Guidance are to:

- standardise the overall approach to interim storage based on maximising package and store performance, while minimising the need for package reworking;
- promote cross-industry working and establish common approaches for long-term management of waste packages in interim storage;
- inform store planning and design, and monitoring and inspection programmes;
- enhance the recognition by stakeholders of the important relationship between waste packaging, storage, transport and disposal;
- improve the visibility of the wide range of work generated by the IPT to Regulators and other stakeholders.

Robust storage requires a thorough understanding of the overall waste storage system, the processes that may affect its integrity over time, and the interactions and relationship between its components. While it is recognised that the challenge from managing the waste packages and stores differ between and within sites, the Guidance is developed around technical ‘approaches’, practical ‘toolkits’ and defined ‘good practices’, to promote robust package performance and design during interim storage. These are based on a common set of principles that recognise the different context at each store.

3. Package design and performance

The Guidance defines an approach to package design, outlining steps to establish a robust package design including toolkits of existing ‘proven’ container designs, materials and encapsulants, and emerging innovations. It also identifies good practice to establish the long-term performance of new materials, and the importance of maintaining transportability.

Package performance across the waste-management lifecycle is addressed through a ‘goal-setting’ approach, based on nine fundamental safety functions provided by the package. This takes account of evolutionary processes that may affect safety-function performance during storage, and measurable indicators of these processes. The performance of each safety function can then be assessed within three primary performance zones: ‘Ideal’, ‘Tolerable’ and ‘Failing’. A toolkit of computer-based models is identified to assist with this analysis.

A lifetime package care and management approach is identified, which details important steps to preserve the integrity of the package from manufacture of the container through to import of the package into a store. A range of package monitoring and inspection techniques, including new developments, are described as part of a toolkit in this area.

4. Store design and performance

The Guidance includes an approach to store design, including a toolkit of existing designs, consideration of location and robustness to foreseeable hazards, including climate-change effects. Additional factors include the number of packages and their inherent hazards and whether shielding is required. Consideration of the need to build-in inspection and reworking cells for packages, and ease of monitoring, are also highlighted.

Store longevity is examined through the systematic identification of its life-limiting features and design-life components, to meet a target lifetime of at least 100 years. An approach is defined to store environmental control, including controlling:

- temperature and relative humidity;
- moisture;
- salt deposition and other contaminants;
- microbial and animal activity.

Basic ventilation requirements are also described.

An environmental Operational Limits and Conditions (OLCs) approach is defined to support the development of store-specific OLCs for salt deposition, relative humidity and temperature controls. Two different approaches to control relative humidity are outlined either by keeping well below the deliquescence point of any deposited salts, or well above so as to dilute any dissolved salts.

5. Store operation

The Guidance defines an approach to package movements, which identifies important steps during import, storage and export of packages to maintain safe, efficient and effective operations.

Preparation for efficient package export is defined in an approach that outlines steps to improve store operations and system performance. In establishing this approach, it is necessary to balance the need for effective inspection and monitoring, environmental control and package export capability. It is considered good practice to set aside space in stores to accommodate any out-of-specification packages.

An approach to maintaining package safety functions is defined, outlining steps to balance package performance risks with proportionate intervention. Several credible reworking techniques are identified, designed to restore safety functions where necessary.

Approaches are defined to maintain store life-limiting features and extend store lifetimes, including a toolkit of credible repair techniques. Finally, consideration is given to an approach for determining when the environmental conditions in a store may benefit from being changed to protect package and store life-limiting components.

6. Storage system assurance

The Guidance recognises the importance of baselining the waste storage system so that on-going monitoring and inspection results can be properly interpreted. An approach is defined, which includes a toolkit with practicable techniques.

A systematic approach to monitoring and inspecting the storage system is emphasised, with toolkits identified. A statistically-based approach is described for the definition of monitoring and inspection rates to achieve a defined level of confidence over the storage period. This includes selection criteria concerning the practicability of providing reliable and interpretable information.

An approach is defined to establishing strategic archives in stores of materials that could be used to help assure the longevity of the system, including spares of bespoke equipment, samples of life-limiting components and representative inactive waste package simulants.

The optimal deployment of inactive samples and simulants, including dummy packages, is described in a defined approach. Such packages, when planned properly, can provide a low-cost and low-dose supplement to the monitoring and inspection of active packages. The Guidance covers the timing of adding, retaining and discarding samples from an overall co-ordinated programme, and an approved testing regime to extract relevant information.

Finally the Guidance includes analysis of the following associated issues:

- the beneficial role of audits, such as RWMD periodic reviews;
- the fundamental importance of effective knowledge management;
- the need to maintain human resources and skills.

7. Summary and conclusion

The Industry Guidance on Interim Storage of HAW Packages has been developed in line with UK and Scottish Government Policies and CoRWM recommendations. It consists of 26 defined ‘approaches’, 23 practical ‘toolkits’ and 30 examples of ‘good practice’, addressed in sections focusing on Package Design, Store Design, Store Operations and System Assurance.

The monitoring of performance and of the evolution of waste packages, store environmental conditions and store fabric play a crucial role in the Guidance. Full details are provided in the published Guidance, available from the NDA website.

References

[1] Committee on Radioactive Waste Management, Managing our Radioactive Waste Safely. CoRWMs Recommendation to Government, CoRWM Doc 700, July 2006.

[2] Committee on Radioactive Waste Management, Interim Storage of Higher Activity Wastes and the Management of Spent Fuels, Plutonium and Uranium, CoRWM Doc 2500, March 2009.

[3] UK Government and Devolved Administration, Response to the Committee on Radioactive Waste Management (CoRWM) Report on ‘Interim Storage of Higher

Activity Wastes and the Management of Spent Fuels, Plutonium and Uranium, July 2009.

[4] Nuclear Decommissioning Authority, UK Radioactive Higher Activity Waste Storage Review, Issue 1, March 2009.

[5] Scottish Government, Scotland's Higher Activity Radioactive Waste Policy 2011, January 2011.

Hydrogeological Monitoring at Äspö HRL – Motivation and Case Study

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Summary
An overview is presented of the hydrogeological monitoring at Äspö HRL, its motivations and utilisation. The underground research facility of 3.6km length to a depth of 450m, is situated in granitic rock. A staged monitoring approach is adopted where the purpose have shifted focus, from supporting the hydrogeological characterisation and hydrostructural modelling during site selection process through environmental impact assessment (EIA) to support of the in-situ experiments undertaken. Monitoring is made of tunnel inflows, groundwater level and pressure, stream flow and electrical conductivity and of meteorological variables. Boreholes are instrumented with up to ten pressure sections where water samples may be taken. Examples of utilisation of monitoring data is given for a tunnel construction project for tunnel layout and grouting decisions and for hydrogeological processes understanding exemplified by skin zone effect, groundwater recharge and groundwater discharge.

1. Introduction

SKB have studied the feasibility for underground disposal of nuclear waste from Swedish power plants for more than 25 years. Towards this end the Äspö Hard Rock Laboratory (Äspö HRL) was completed 1994 with the purpose to conduct research, development and demonstrate solutions. This is an underground research facility in granitic rock of about 3.6km length reaching a depth of 450m below ground. Hydrogeological monitoring has been performed since its inception during which its purpose have shifted focus somewhat. The Monitoring at Äspö HRL evolved from supporting the hydrogeological characterisation and modelling in the site selection process through environmental impact assessment (EIA) of tunnel drainage and groundwater level to support of the different experiments undertaken. The EIA monitoring was furthermore a stipulation by the Water Rights Board [1].

2. Methodology

Water level and groundwater pressure constitute the bulk of the data collection where we at present record from about 400 locations mostly from the tunnel. For longterm monitoring boreholes are instrumented with up to ten pressure sections where water samples may be taken or tracers injected/circulated. The tunnel drainage is monitored through V-notch weirs at 29 locations of which water salinity is also measured at 22 stations. Hydrological monitoring of flow and salinity is performed in three streams and a meteorological station is recording wind, radiation, precipitation, pressure and humidity. Surface hydrological and soil aquifers monitoring were initiated during the site investigation in Oskarshamn [2]. Some of these monitoring station were in due time incorporated to the Äspö HRL monitoring system.

Data collection is predominantely on-line, channelled to a central database from which data is immediately accessible for plotting and file export. Quality assessment of data is performed at different levels and frequencies;

- on-line alarm system records malfunctioning equipment,
- weekly to check of data for reasonability and anomalous behaviour ,
- every four months including a) description of problems and their remediations and b) explanation of cause/effect of anomalous pressure or flow
- in connection with the annual monitoring report

3. Results

The staged approach to monitoring at Äspö HRL is summarised in Figure 3-1. Monitoring initiated as part of the pre-investigation for the site selection process. Upon completed characterisation boreholes were retained for long term monitoring in support of establishing a baseline. The construction of the laboratory was conditioned by the regulatory Water Rights Courts to monitor groundwater levels and total tunnel discharge. The monitoring system was also utilised for characterisation during construction and to develop site descriptive models.

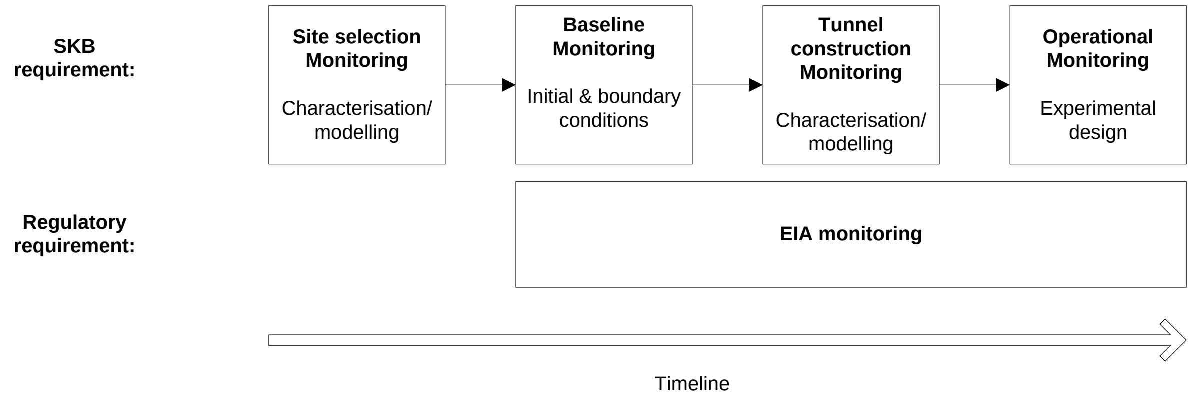

Figure 3-1: The staged approach to monitoring at Äspö HRL.

During its operational phase the laboratory houses a number of different research experiments which are conducted simultaneously at different locations throughout the tunnelsystem. The monitoring system is critical for these several experiments for various reasons. In conjuction with the site descriptive model it provides:

- means to select an appropriate experimental site
- initial and boundary conditions for the experiment
- direct data to experiments
- means to minimize hydraulic disturbances between experiments

Monitoring example 1: Tunnel Expansion Project

The *Tunnel Expansion Project* can serve as an example of the application and usefulness of the staged monitoring approach. The project shall construct new experimental drifts at 400m depth with strict conditions of high groundwater pressure upon completion. Among other things the identification of potentially suitable sites was based on groundwater pressure data from the monitoring system .A promising rock volume was identified at which a comprehensive site characterisation program was implemented. A key component of this characterisation was the monitoring system which yielded a baseline of groundwater pressure as well as hydraulic response matrixes in support of the site descriptive modelling. This allowed us to construct a first hydraulic connectivity model based on pre-construction data. During construction the monitoring continued to support the gradual development of hydraulic connectivity model being further enhanced by utilising drilling rig data (MWD) for correlation to hydraulic responses in the monitoring system.

Prior to tunnel construction a programme was established for the continuous control of groundwater pressure during construction. This was tied to strict remedial action steps for grouting decisions.

The monitoring system also showed the hydraulic influence from the investigation volume to sites with ongoing experiments thereby avoiding disturbing the experiments. Such data on reciprocal hydraulic influence is critical for the laboratory at large where some experiments require undisturbed boundary conditions.

A couple of examples relating to *process understanding* are also brought forward. Such understanding forms part of any modelling exercise.

Monitoring example 2: Skin zone effect

One issue often encountered in groundwater flow modelling of tunnel system is the positive skin zone effect. The effect is introduced as a mean to calibrate the model and is usually a purely numerical adjustment. There is of course sound physical reasoning which motivates such an effect but seldom any field measurements to support it. A simple utilisation of the monitoring system is to measure groundwater head profiles toward the tunnel (Figure 3-1).

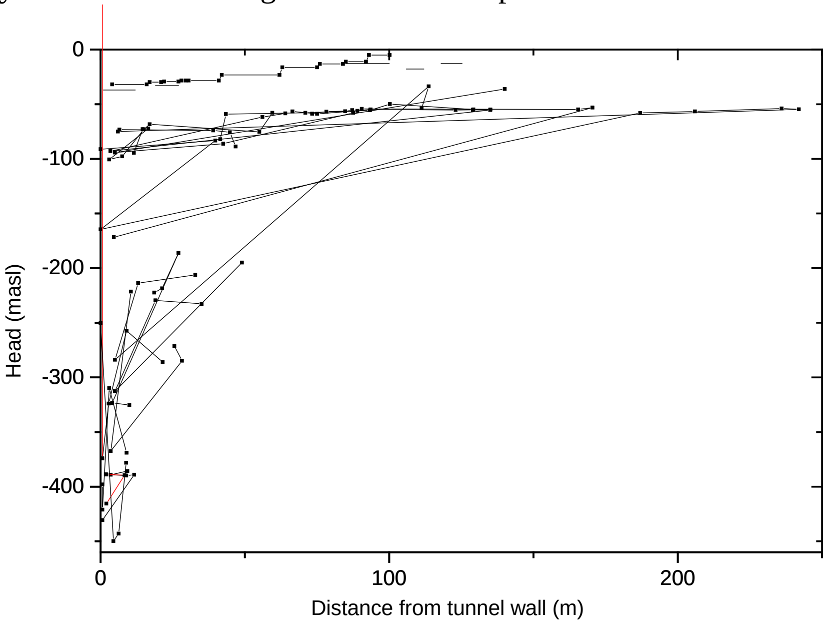

Figure 3-1: Groundwater head profile perpendicular to the tunnel wall at Äspö HRL in many cases showing a large drop in head at the tunnel wall proximity. This may be taken to support the existence of a skin zone. The shape of the graph is of course dependent on the number and length of monitoring sections and none of these monitoring measurements were tailored for skin zone studies.

Monitoring example 3: Groundwater recharge and discharge

The second example of process-understanding is with regard to groundwater recharge and discharge. Meteorological monitoring data is utilised for correlation with monitored water levels. A clear coupling between precipitation event and amount with groundwater levels (Figure 3-4 left) is evident. For this aquifer system the monitoring data gives physical and quantitative evidence of the direct recharge taking place down to the shallow rock aquifer (64m depth) but not deeper, even for a precipitation event of 50mm/d. During summer there is a clear decline in groundwater level during daytime while it stabilises or even slightly increases during night time. This is correlated to the potential evaporation calculated from the meteorological monitoring data. The decline in level is interpreted as groundwater discharge taking place thus being the major contributor to the declining groundwater level (Figure 3-4 right).

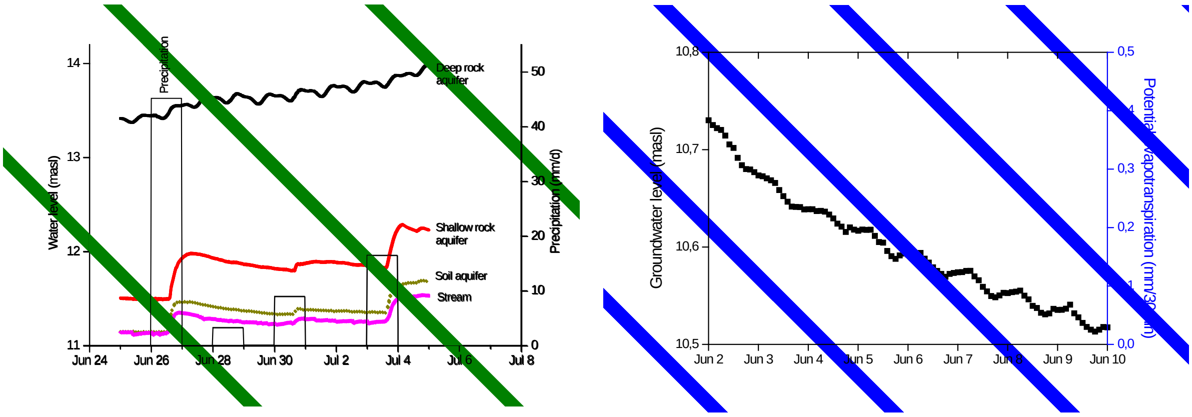

Figure 3-4: Monitoring of water levels and precipitation showing well correlated groundwater recharge events in the shallow aquifer system but not in the deeper system (left graph). Groundwater discharge manifested as declining groundwater level due to evapotranspiration process (right graph).

References

[1] Växjö Tingsrätt Vattendomstolen, 1989. DVA42/1990, VA S/1989.

[2] SKB 2008. Oskarshamn site investigation. Programme for long-term observations of geosphere and biosphere after completed site investigation. SKB R-07-59, Swedish Nuclear Fuel and Waste Management Co.

Groundwater Monitoring In Forsmark

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Summary
Groundwater monitoring (monitoring of groundwater levels, groundwater flow and groundwater chemistry) in Forsmark is performed in cored boreholes and percussion drilled boreholes in crystalline bedrock, as well as in groundwater wells in Quaternary deposits. The cored and percussion boreholes are sectioned with one metre long rubber packers which straddle different fractures and fracture zones penetrated by the borehole. The system allows monitoring of groundwater levels in separate fractures, groundwater sampling for chemical analyses and measurements of the natural groundwater flow in isolated borehole sections. It allows quick response and/or remediation action to any measured event. The measurement data are transferred to SKB´s HMS-system and stored in a database for further analyses.

1. Introduction

During the period 2002-2007, geoscientific and ecological site investigations were performed in Forsmark, northern Uppland, Sweden, with the purpose to localize and characterize a suitable site for a final repository for spent nuclear fuel. Hundreds of investigations were conducted during this period, and besides that a monitoring array was established with the purpose to enable frequent and repeated long-term measurements and observations (here denoted monitoring) of a number of geoscientific and ecological parameters and states. The monitoring activities were planned to continue also after 2007.

In 2009, SKB selected Forsmark as the site for building a final repository for spent nuclear fuel, and in March 2011 an application under the Environmental Code and the Nuclear Activities Act was submitted to the Swedish Government. At the moment, plans are to start construction in 2019, and meanwhile the monitoring to establish necessary base lines continues, in order to establish reliable descriptions of natural undisturbed conditions in the bedrock and at the surface. The subject for this article is groundwater monitoring at the Forsmark site.

2. Methodology

2.1 General

The groundwater levels and flow conditions are, together with the hydrochemical composition of the groundwater, fundamental factors when assessing the long-term safety of a final repository for nuclear waste. The hydrochemical characteristics of the groundwater at the Forsmark site is complex, and groundwater samples from different depths in boreholes situated at different parts of the site indicate that the groundwater is a mixture of groundwater types of at least four different origins. The distribution of a particular groundwater mix is dependent on the groundwater flow conditions, which in turn are governed by structural-geological, hydrogeological, meteorological and hydrological factors.

Groundwater monitoring at Forsmark is performed in cored and percussion drilled boreholes in crystalline bedrock, as well as in groundwater wells in Quaternary deposits located both in- and outside the tectonic lens at Forsmark in which the repository will be placed (Fig. 2-1). Groundwater level monitoring in Quaternary deposits is carried out in open wells, whereas monitoring in deep boreholes in hard bedrock is normally performed in packed-off sections in order to enable the study of groundwater conditions in isolated fractures and fracture zones.

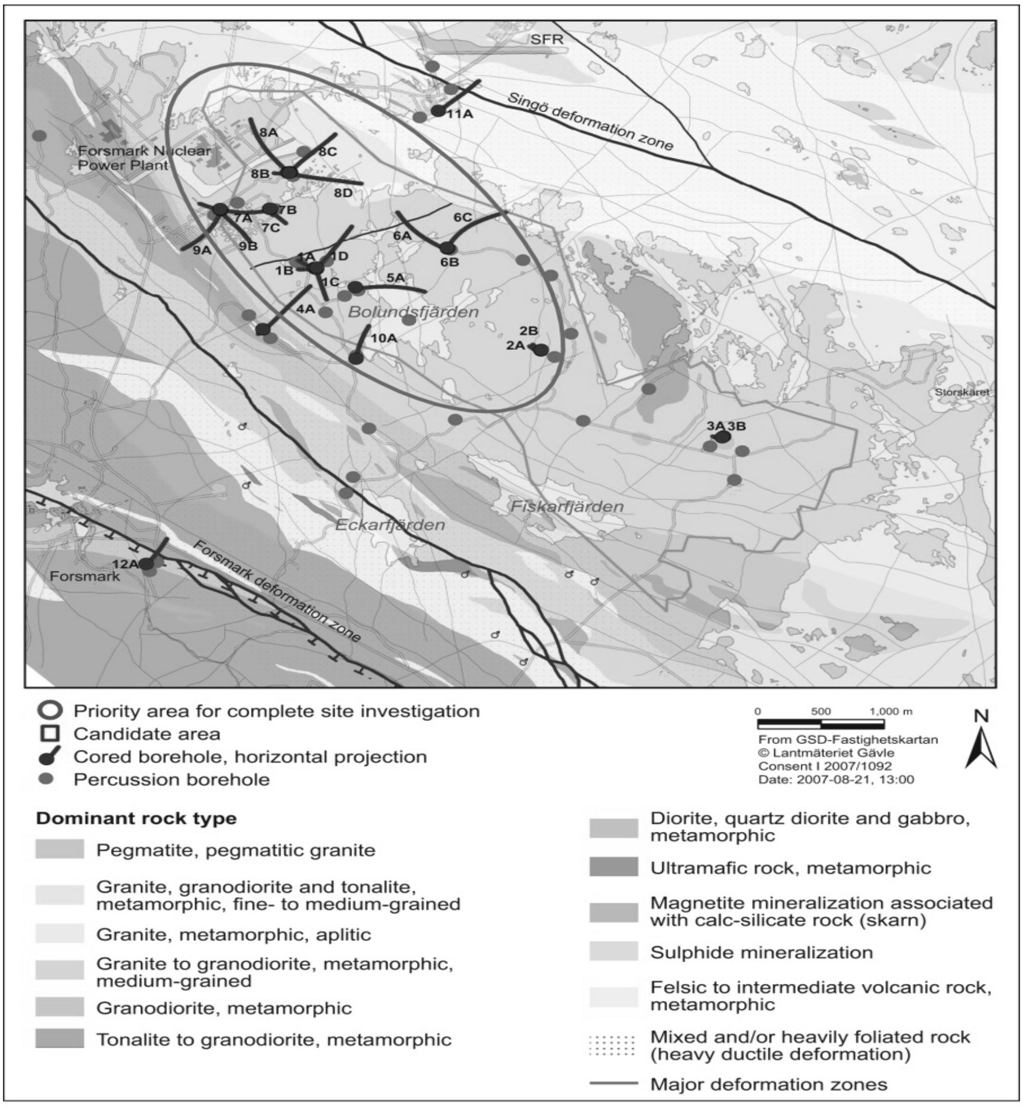

Fig. 2-1 Cored and percussion drilled boreholes in Forsmark – a descriptive map of the boreholes and their direction. The tectonic lens mentioned in the text is situated between two regional deformation zones: the Eckarfjärden deformation zone and the Singö deformation zone.

2.2 Groundwater level monitoring in bedrock

In order to enable monitoring in sections hydraulically isolated from one another, the deep core drilled or percussion drilled boreholes are equipped with a single packer or a multi-packer system with hydraulically inflatable rubber packers, such that the fractures in the boreholes are isolated from one another. The groundwater level can thus be measured in each section (Fig. 2-2). In this way the system also prevents uncontrolled mixing of groundwater with different hydraulic heads and/or hydrochemical composition.

Most cored boreholes in Forsmark, some of them steep, others inclined and with a maximum length of c. 1 000 m, are denominated “telescopic boreholes”, because they have an upper, c. 100 m long percussion drilled part (the telescopic part) with a diameter of 200 mm, and below this the cored part with a diameter of 76 mm, the latter offering void space for up to ten monitoring sections in one borehole. However, the bedrock at Forsmark is characterized by long sections without open fractures, and the sectioning of the core drilled boreholes is restricted to in average 5-6 sections. The diameter of the percussion drilled boreholes is restricted to 140 mm, which allows groundwater measurements in maximum four sections.

A thin plastic tubing connects each borehole section with another tubing of larger diameter in the upper telescopic part. Mini-packers installed in the larger tubings confine, when inflated, the water volume between the monitored section and the mini-packer, ensuring rapid responses when pressure changes occur in the respective borehole sections. A pressure sensor installed above the mini-packer, but connected with a tubing to the confined water volume below the mini-packer, registers the groundwater pressure in each section, and the pressure is converted to groundwater level. The sampling frequency can be set down to one sample per second.

One or two sections in the cored or percussion drilled boreholes may be supplied with equipment for groundwater sampling and groundwater flow measurements by tracer dilution technique. Thus, SKB´s monitoring equipment for deep boreholes constitutes a multi-purpose system, which allows monitoring of groundwater levels and groundwater flow as well as hydrochemical monitoring.

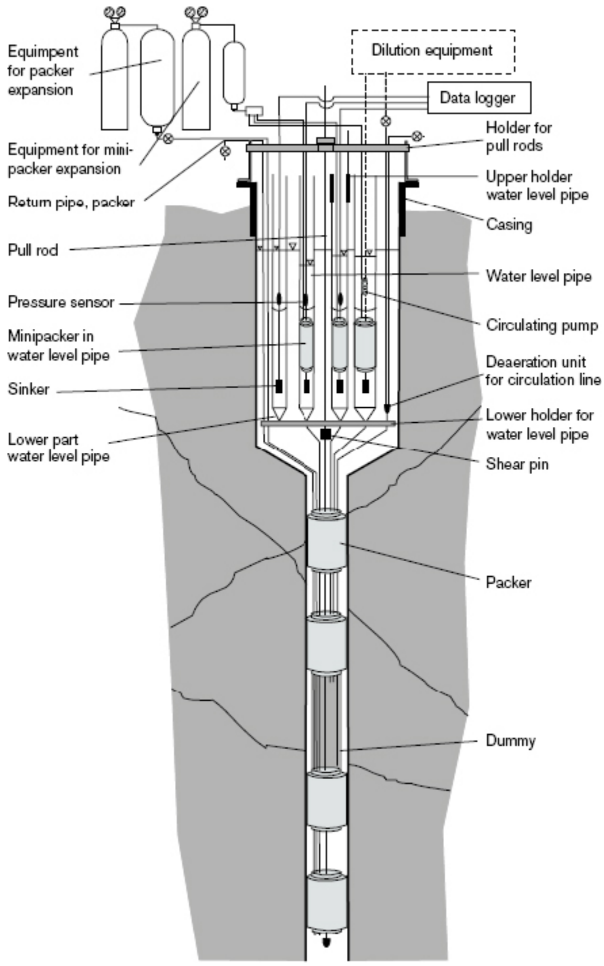

Fig 2-2. Principle of the SKB system for monitoring of groundwater in boreholes equipped with multi-packer systems.

2.3 Groundwater level monitoring in Quaternary deposits

Groundwater level monitoring in Quaternary deposits is carried out in open wells, generally metallic standpipes or plastic tubes (plastic tubes are used for sampling purposes). The monitoring equipment for boreholes in till and sand consists of a pressure transducer connected to a data logger. Boreholes in clay or other cohesive soils are instead supplied with a BAT-type filter tip used for pore pressure measurements.

3. Results

Results of the groundwater monitoring are stored in SKB´s database Sicada (after quality control of the HMS-data). SKB staff and researchers can apply for data from Sicada for different modelling or other purposes. Figure 3-1 shows an example of presentation of groundwater levels, representing the same time period, in two different boreholes 25 metres apart, a groundwater well in Quaternary deposits and a percussion drilled borehole with three isolated sections.

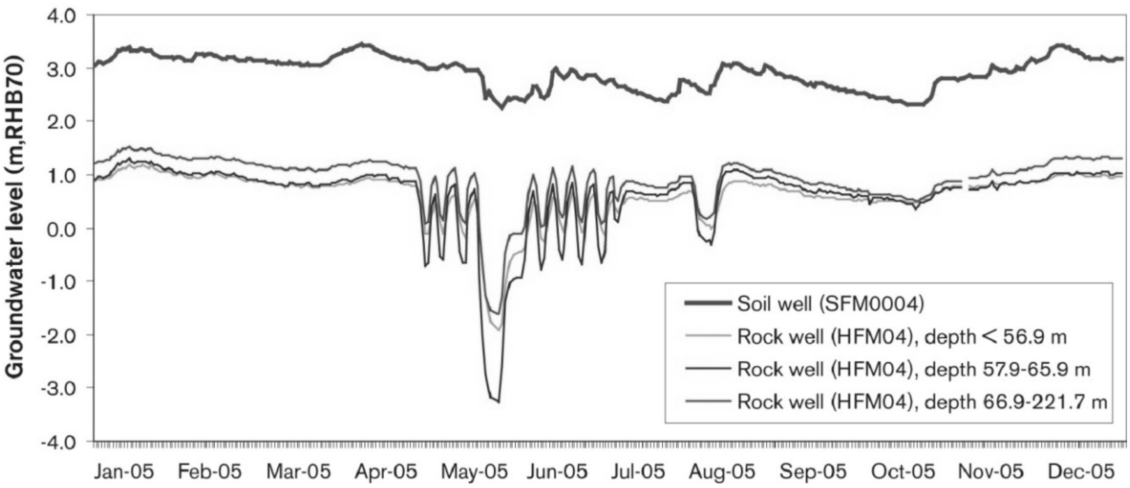

Fig 3-1. Groundwater levels in Quaternary deposits and rock in two nearby boreholes in Forsmark.

The groundwater monitoring in Forsmark has so far revealed patterns of coincidental time dependent variability regarding groundwater levels, groundwater flow and groundwater chemical composition. As concerns variations of groundwater levels in Quaternary deposits and point water heads in bedrock, the monitoring results indicate a strong coupling to variations in rainfall/snow melt and evapotranspiration, whereas sea water level changes have only limited influence.

4. Outlook

The slim-hole concept, along with the multi-purpose monitoring application, has resulted in a highly cost-effective collection of high-quality data on which the currently on-going monitoring at Forsmark benefits today. Monitoring groundwater in bedrock in combination with monitoring groundwater in Quaternary deposits will add to better understanding of the interplay and exchanges between the surface and bedrock systems (and vice versa). Knowledge about the undisturbed conditions strengthens the ability to reveal and quantify changes that may occur during the excavation of the repository, and for distinguishing naturally induced changes from those caused by anthropogenic activities.

References

[1] SKB 2007. Forsmark site investigation. Programme for long-term observations of geosphere and biosphere after completed site investigations. SKB R-07-34, Svensk Kärnbränslehantering AB.

[2] SKB 2011. Framework programme for detailed characterisation in connection with construction and operation of a final repository for spent nuclear fuel. SKB R-11-14, Svensk Kärnbränslehantering AB.

Monitoring the hydrogeological effects of construction of ONKALO underground research facility at Olkiluoto in South-West Finland

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Summary
Spent nuclear fuel from Finnish reactors is planned to be disposed of in the repository constructed at a depth of -420 m in crystalline bedrock on the Olkiluoto Site. Posiva has constructed an underground research facility ONKALO that reached the repository level in 2010. The underground construction will affect the surrounding rock mass and the groundwater system. In order to identify the magnitude and extent of such effects hydrogeological models have been constructed and a hydro-monitoring system has been set up. A hydrogeological structure model (HZ model) including the data for groundwater flow modelling has been created. Two hydraulically significant fault zone systems HZ19 and HZ20 intersect ONKALO. The Olkiluoto surface hydrological model (SHYD) links overburden and groundwater in bedrock into one continuous hydraulic system. SHYD is used to predict both short-term and long-term effects of ONKALO. Hydrogeological measurements and the surface hydrological model indicate that ONKALO inflow has a temporal effect on groundwater level in overburden and in shallow bedrock drillholes during summer months, but this effect disappears after rainy periods. In deep bedrock drillholes the effect of ONKALO on the pressure head has been significant especially deep in the rock where HZ20 intersects ONKALO. Changes in flow conditions measured with Posiva Flow Log (PFL) tool have been significant within major zones but also within poorly conductive zones and single fractures.

1. Introduction

Spent nuclear fuel from Finnish reactors is planned to be disposed of in a repository constructed at a depth of -420 m in crystalline bedrock on the Olkiluoto Site. Posiva has constructed underground rock characterisation facility ONKALO, which reached the repository level in 2010. Underground construction of ONKALO and the subsequent construction of the repository will affect the surrounding rock mass and the groundwater system. In order to identify the magnitude and extent of such effects, a monitoring and modelling system has been set up.

2. Methodology

Extensive hydrological monitoring has been carried out in Olkiluoto since 1989. Originally surface-based, monitoring has been continued and augmented by additional monitoring equipment specifically designed to monitor the effects that the ONKALO construction project has on the groundwater flow system. The construction of ONKALO began in 2004. Hydrological monitoring currently covers inflow of groundwater into ONKALO, changes induced in the hydraulic head in 31 drillholes with ca. 170 packed-off measurement sections, groundwater table level in ca. 100 shallow holes (on average c. 20 m), evolution of hydraulic properties (i.e. changes in hydraulic conductivity) and changes in groundwater flow rates and directions measured with Posiva Flow Log (PFL). (Figures 1 and 2)

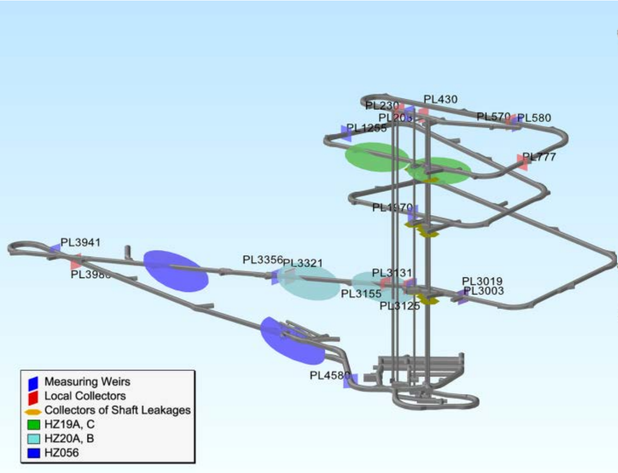

Figure 1. ONKALO, measuring weirs and the intersections of the major hydrogeological zones.

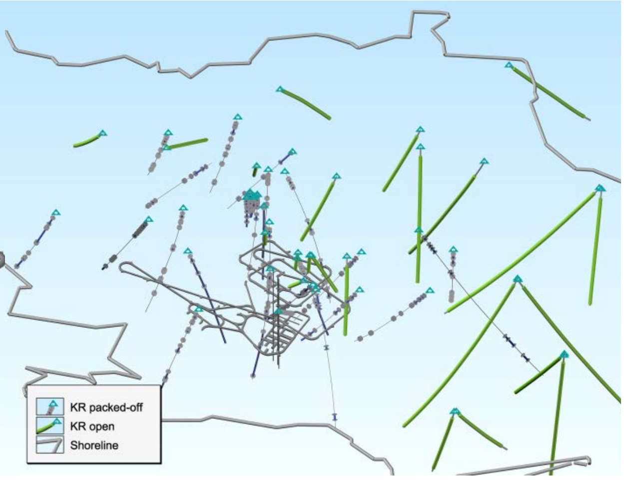

Figure 2. Illustration of the deep open and packed-off drillholes.

A hydrogeological structure model (HZ model) [4] including the data for groundwater flow modelling has been created. The HZ model is based on the integration of geological, geophysical and hydrological results over a period of 20 years. Two hydraulically significant fault zone systems HZ19 and HZ20 intersect ONKALO.

The Olkiluoto surface hydrological model (SHYD) [1, 2, 3] links groundwater in the overburden and in the bedrock into one continuous hydraulic system. SHYD model provides boundary conditions for the deep groundwater flow model (FEFTRA) [6], which is used to model the hydrogeological evolution of Olkiluoto Island.

3. Results

Total leakage into ONKALO, currently monitored with 9 measuring weirs, is ca. 40 l/min.

Flow responses have been detected with the Posiva Flow Log (PFL DIFF-tool) in holes selected for the monitoring programme on a yearly basis. Changes in flow conditions have been significant within main hydraulically conductive zones, but also within poorly conductive zones and single fractures (Fig. 3.).

Temporal changes in groundwater table have been observed, but permanent effects of less than 0.5 m can be seen only in a couple of shallow drillholes close to ONKALO. Measurements and the hydrogeological model indicate that ONKALO inflow has a temporal effect on groundwater level in the overburden during summer months, but this effect disappears after rainy periods (Fig. 4).

In drillholes the effect of ONKALO on the pressure head has been significant, especially at depth (c. -300 m) where HZ20 intersects ONKALO (Fig.5). Drawdowns within the HZ20 have been temporarily over 30 m but have stabilized at the end of 2011 to around 12 meters near ONKALO.

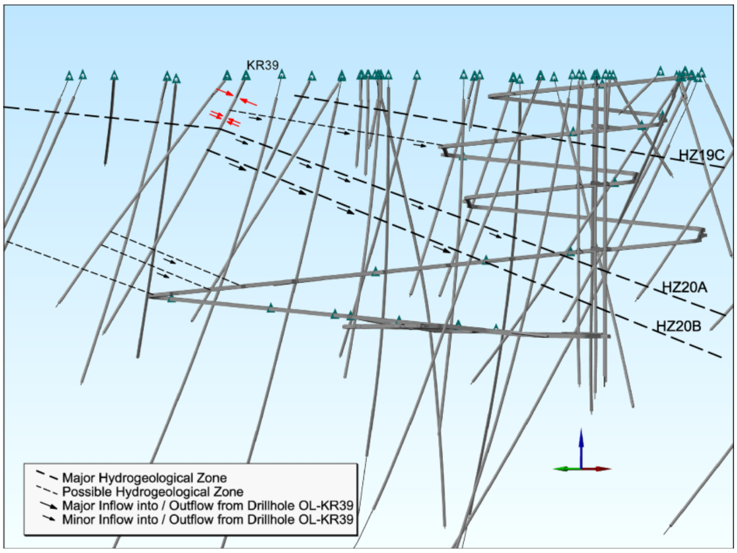

Figure 3. Flow responses (PFL DIFF) in drillhole OL-KR39 caused by ONKALO

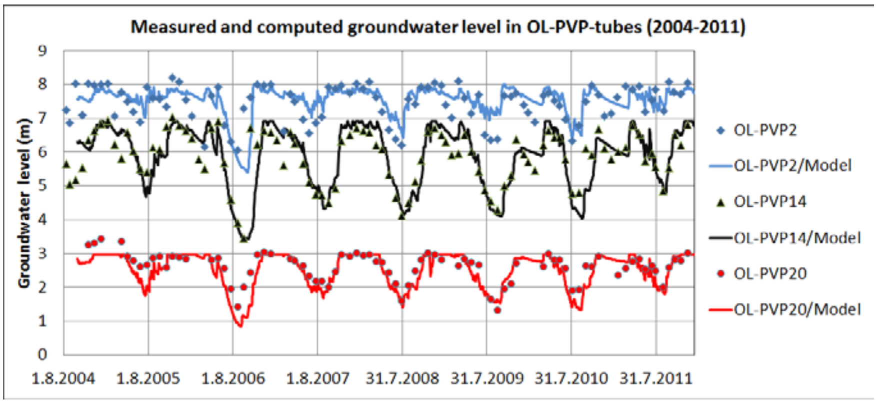

Figure 4. Observations (dots) and numerical flow simulation results (solid line) of three shallow groundwater tubes in the overburden.

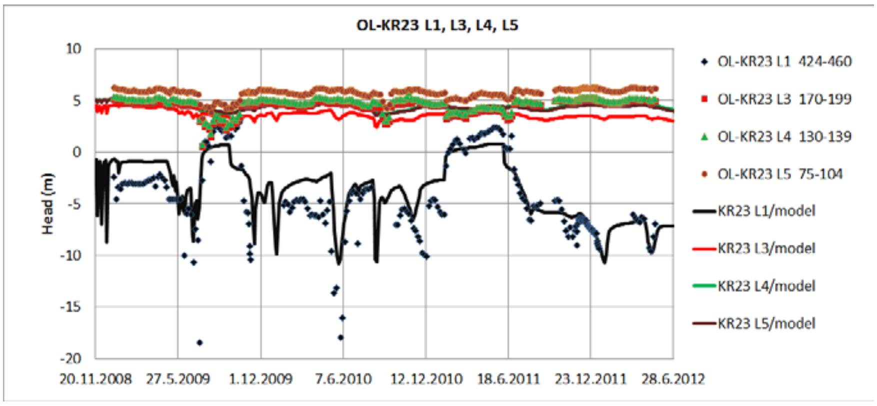

Figure 5. Observations (dots) and numerical flow simulation results (solid line) of packed-off drillhole OL-KR23. L1 represents the hydrogeological zone HZ20A.

The inflow at ONKALO has caused significant pressure head changes in several packed-off sections in drillholes. The collection of drawdowns in major zones as a function of distance from ONKALO is presented in Fig. 6. Lower but significant drawdowns within deformation zone HZ20 have been observed 1 km from ONKALO (Fig. 6). Most of the determined drawdowns within deformation zone HZ19 have varied between 1–2 m.

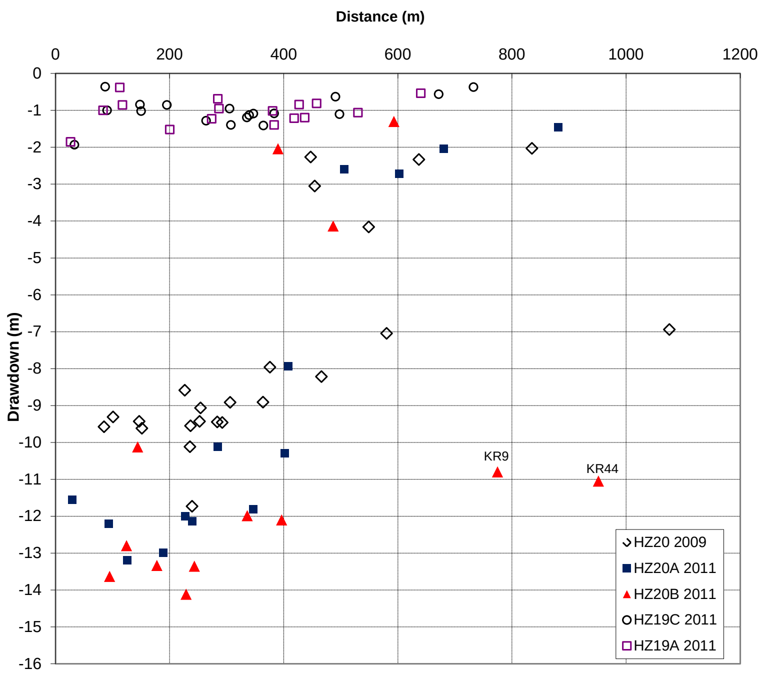

Figure 6. Observed drawdown as a function of distance from ONKALO in major hydrogeological zones.

4. Conclusions

The bedrock in Olkiluoto is transport limited and there is more supply of water in the overburden than the bedrock can transmit. This is the reason why the ONKALO effect cannot be seen in shallow measurement points. However, the influence of permanent and temporary inflow can be clearly seen in deep packed-off drillholes.

The approach adopted in Olkiluoto successfully combines monitoring results, structural HZ model and numerical flow model. The latest SHYD model includes also the effect of density caused by saline groundwater.

The applied approach enables prediction [2] of both short-term and long-term hydrogeological effects of the construction of ONKALO and the repository for final disposal of nuclear waste.

References

[1] Karvonen, T. 2008. Surface and near-surface hydrological model of Olkiluoto Island. Eurajoki, Finland: Posiva Oy. Working Report 2008-17.

[2] Karvonen, T. 2010. Prediction of long-term influence of ONKALO and Korvensuo Reservoir on groundwater level and water balance components on Olkiluoto Island. Eurajoki, Finland: Posiva Oy. Working Report 2010-55.

[3] Karvonen, T. 2011. Olkiluoto Surface and Near-Surface Hydrological Modelling in 2010. Eurajoki, Finland: Posiva Oy. Working report 2011-50.

[4] Vaittinen, T., Ahokas, H., Nummela, J., Paulamäki, S. 2011. Hydrogeological Structure Model of the Olkiluoto Site – Update in 2010. Eurajoki, Finland: Posiva Oy. Working Report 2011-65.

[5] Vaittinen, T., Ahokas, H., Nummela, J., Pentti, E., Penttinen, T., Pöllänen, J., Turku, J., Karvonen, T., Aro, S. 2012. Results of Monitoring at Olkiluoto in 2011 – Hydrology. Eurajoki, Finland: Posiva Oy. Working Report 2012-43 (in prep.).

[6] Löfman J. and Karvonen, T, 2012. Simulations of Hydrogeological Evolution at Olkiluoto. Eurajoki, Finland: Posiva Oy, Working Report 2012-35.

Testing a fiber optic system for long-term monitoring applications under in-situ conditions in the Opalinus Clay of the Mont Terri rock laboratory, Switzerland

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Host rocks for future nuclear waste repositories need to be monitored before and during construction and over the first decades of operation. Conventional sensors often lack sufficient reliability for long-term monitoring. Furthermore, conventional monitoring systems with densely packed sensors require space and extensive down-hole power supplies. Long-term monitoring in geological disposal sites, requires maintenance-free systems that provide reliable and continued deployment over several decades without intervention. Furthermore, these systems need to withstand different and time-varying environmental conditions within the repository, such as mechanical strain, hydraulic pressure, chemical corrosion, interactions with pore water/host rock, buffer materials, steel containers, elevated temperatures, and radiation levels near the waste material. Fiber optic (FO) monitoring systems, among other techniques, appears to be very promising for fulfilling the high requirements in underground repositories.

In future nuclear waste repositories, FO sensors may play a key role in data transmission of signals from conventional sensors as well as detecting parameters such as temperature, strain, or radiation levels. These FO systems will be installed predominantly in boreholes backfilled with bentonite as buffer material. To provide a tested technology for monitoring any future repository, we initiated a preparatory experiment dealing with the effect of ageing on an FO system at the Mont Terri rock laboratory in 2012. This preparatory experiment (called "MO") tests suitable optic fibers under natural conditions and will be used to evaluate long term (>5 years) ageing effects. Our test design is based on a commercially available fiber optic system wrapped onto a grid and subjected to a heating source. We developed and installed the test device at Mont Terri rock laboratory in a borehole backfilled with bentonite. Three commercially available types of Brillouin Optical Time Domain Analysis (BOTDA) cables and four types of Fiber Bragg Gratings (FBG) sensors together with standard PT1000 sensors are measuring the temperature distribution along a 2.5 m packed-off and heated interval.

Besides monitoring the behavior of frequency shifts and spectra over time, we will dismantle the device at the end of the monitoring period and check ageing effects by directly analyzing material properties in the laboratory. Lab tests on a preliminary cable set have already been carried out at Swiss Federal Laboratories for Materials Science & Technology (EMPA**)** to evaluate the initial chemical, mechanical, and microscopic properties of the individual cable coatings. An identical second set of devices is stored on site and will be analyzed together with the third down-hole set to compare the long-term ageing effects.

Monitoring over the first year of the experiment shows the different responses of the chosen sensors, reflecting the harsh down-hole conditions and emphasizing the need for the present testing program.

Rn Gas Emission Distribution in the Soil-Atmosphere Interface: Lessons Learned from CO_2 Storage Monitoring

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Summary

The detection of the failure of the seal/barrier integrity is a fundamental part in the monitoring plan of any deep geological storage of waste (nuclear, CO2). Considering the depth of storage (commonly >500 m) and the reaction with engineered barriers and the geosphere, fluids with pollutants from repositories are expected to reach surface levels long time (several thousands of years) after failure. Monitoring methods based on changes in water geochemistry, especially from shallow groundwater, may fail in providing valuable tracers of early leakage. In contrast, gas fluxes (e.g., H2, Rn, CO2) are thought to flow faster through the geosphere, if fractured enough, and can be detected at the soil-atmosphere interface. One of the trace gases of interest in monitoring of nuclear waste repositories is Rn. This gas was also used for a) geochemical prospection of oil reservoirs, b) monitoring of CO2-bearing flows, and c) understanding flow pattern in fractured rock.

In the frame of the OXY-CFB300 project, the pattern of gas flow in the soil-atmosphere interface was investigated by using a number of methodologies involving Rn isotopes. The aim of this research was that to improve monitoring strategies by understanding how gases flow up to the surface, and to provide recommendations about which monitoring methods are more cost-effective. In this project, a number of natural sites of CO2-emission were studied in central Spain. In some of them, CO2 flow at surface is significantly decreased due to the presence of a clay-rich seal, and CO2-detection methods, when applied in proximity of the main CO2 emission sites, are often unable to discriminate the deep-seated imprinting from that related to biological respiration. The use of Rn isotopes has resulted very valuable to detect the emission of deep gases since Rn is barely produced at surface. The methods used were (1) scintillation detector EDA RD-200, (2) solid state nuclear track detectors (SSNTD), (3) ionization chamber and (4) alpha spectroscopy SARAD RTM 2100. Some of them are capable of measuring the isotopes separately (SARAD), whereas others just detect the bulk radon concentration. These methods have also distinct procedures and acquisition times.

Interestingly, the results show that the distribution of Rn isotopic emission clearly defines the main paths for ascending fluids at the soil-atmosphere interface, which in many cases consists of a network of small (< 1 m2) spots. This is not apparently observed for other gases such as CO2. In addition, Rn isotopes behave differently. In some cases, thoron (220Rn) does not seem related to both CO2 and 222Rn, the highest radon-thoron ratio being associated with the highest CO2 fluxes. From this project, it can be assessed that the lessons learned from Rn detection in deep geological storage of CO2 can be suitable for monitoring strategies in nuclear waste repositories, especially

in those where low permeability seals (clays) limit the ascent of fluids from the storage levels.

1. Introduction

Emanometry along with other radiometric methods for the detection of radon isotopes have been used in a number of scientific fields such as uranium prospection [1], characterisation of fractured media for storage of wastes (e.g., [2], [3]), geothermal resources [4] and oil-polluted soils [5]. In very recent times [6], radon isotopes (^{222}Rn and ^{220}Rn) have been applied to distinguish the CO_2 emission from deep sources from those related to surface biological activity. The aim of this approach is the development of methodologies able to discriminate biological CO_2 emissions from potential leakage of CO_2 stored in commercial sites, since low-intensity emission is expected (if it occurs) at early times of leakage. This work reports the capacities and limitations of some radiometric field methods to detect radon isotopes that have been applied to locate and characterise these low-intensity emission and the implications for the leakage detection of other waste storage in geological media like the spent nuclear fuel.

Concentration of radon is markedly low in many soils (in the order of several tenths of Bq·m^{-2}) due to the fast decay (half-life= 3.8 days in the case of ^{222}Rn) that prevents accumulation in pores. In contrast, a number of studies have shown that very high soil concentration of Rn isotopes are linked to strong CO_2 fluxes, that allow the transport of trace gases (including Rn) to long distances [7], [8], [9], [10], [11], [12]. In these sites, always related to gas flow channelled through fractures, soil Rn concentration reaches up to 500,000 Bq·m^{-3}. The strong contrast between radon concentration from deep sources and from surface environments helps the distinction of CO_2 leakage, and to identify the nature of potential leakage paths. In addition, due to the different decay series of radon isotopes (^{220}Rn, thorium decay series, and ^{222}Rn, 238-uranium series), the relative concentration of both isotopes may provide clues of the rocks interacting with the gas flux.

In the frame of the OXY-CFB300 project (EEPR program), which aims at the development of technologies of carbon capture and storage (CCS), a number of methodologies of measuring radon isotopes have been studied for the detection of small, low-intensity emission in the Campo de Calatrava region in Central Spain (Fig. 1.1, left), where CO_2 from mantle degassing flows out either as free phase (vents) or dissolved in groundwater (Fig. 1.1, right). This region hosts a late Miocene-Quaternary volcanic province (CVP) and consists of a series of scattered vents and outcrops of mafic lava flows and pyroclastic deposits of alkaline composition in a domain some 4000 km^2 in area, within the Iberian Hercynian Massif, close to the external sectors of the Alpine Betic Ranges. The gas discharges are largely dominated by CO_2 (up to 99,9%), while N_2 and Ar (both atmospheric in origin) are between 709 and 11,849 and 7 and 313 □mol/mol, respectively [13].

Fig. 1.1. (left) Location of the Campo de Calatrava region in Central Spain. (right) Gas measurement in one CO_2-bearing pool.

2. Methodology

Four different field methods of measurement of radon concentration in soil have been tested (Fig. 2.1): (1) alpha spectroscopy detectors SARAD-RTM-2100, (2) solid state nuclear track detectors (SSNTD), (3) Lucas cell EDA-RD-200 detector, and (4), an ionization chamber VOS-RM-2. A brief description of the methods is shown as follows:

SARAD RTM 2100

In this method, the radon concentration is calculated from the detection of its daughters Po isotopes, ^{218}Po, ^{216}Po and ^{214}Po. These isotopes are ionized and collected over the surface of an alpha detector. The Rn gas is collected from the soil at 1 meter depth to avoid atmospheric dilution, and both ^{222}Rn and ^{220}Rn isotope daughters are measured at the same time. The acquisition time is 15-20 minutes per sample.

Solid state nuclear track detectors (SSNTD)

These detectors consist of a sensitive material to nuclear radiation, such as photographic emulsion, polymers o glass. In this project, films of alidiglicol carbonate ($C_{12}H_{18}O_7$) have been used. On these surfaces, the concentration of radon is measured by counting the nanometric tracks left by radiation.
These sensors are of low efficiency so long acquisition times are required (7 to 21 days), and they need a further lab treatment. Once collected from the field site, the detectors are cleaned with a NaOH bath at 90ºC to make visible the tracks. Then, under an optical microscope, the tracks are counted.

EDA RD-200

The detector used in this device is a scintillation cell covered by a thin film of ZnS(g) that emits a photon when excited by alpha particles from Rn decay. Then, the photon emission is converted to digital signal and recorded. The use of this method in the field is quite convenient due to the short acquisition times (less than 5 minutes) and the small amount of soil required. The measurements are taken at 40 cm deep in the soil.

Ionization chamber VOS-RM-2

This device consists of an ionization chamber with an electrical potential gradient. The Rn gas isotopes are ionized and the ion current from electrical poles can be measured and transformed to Rn concentration. This is a robust and cost-effective method, with relatively fast measurements (15 minutes per sample), and recommended for the characterisation of fractures zones. However, the main limitation is that it is not able to distinguish between isotopes.

Fig. 2.1. Methods used for the detection of Rn isotopes: SARAD RTM 2100 (top left), SSNT detectors (bottom left), Ionization chamber VOS-RM-2 (centre), and EDA RD-200 (right).

For the measurement of CO_2 flux, an accumulation chamber (West Systems) has been used.

3. Results

The results from the combined measurement of CO_2 soil flux and Rn isotopes concentration in Campo de Calatrava show a clear correlation between both parameters, especially with ^{222}Rn (Fig. 3.1). CO_2 soil flux typically is around 10-40 g·m^{-2}·d^{-1} but reaches extreme values higher to 5000 g·m^{-2}·d^{-1}. The total Rn activity in the soil ranges from <1000 to 450000 Bq·m^{-}

[3] with a major contribution from ^{222}Rn in most cases. Rn isotope measurements, then, help to the detection of CO_2 emission spots of very small extension and of low intensity, comparable to biological respiration (up to 50 $g \cdot m^{-2} \cdot d^{-1}$). The very weak concentration of Rn in the areas with no CO_2 flux from depth allows the distinction between biological CO_2 and mantle CO_2. ^{222}Rn is notably less concentrated in soil where CO_2 emission is related to biological activity whereas increases several orders of magnitude in deep CO_2 flows even being of similar intensity.

The data provided by the four methods tested are quite comparable. The most favourable methods from the quality of measurements and cost point of views appear to be the SARAD and the Ionization chamber RM-2. In both cases, measurements are quite fast but need at least two people be involved in the measurement task. The EDA RD-200 methods are cheaper and easy to use but the sensitivity is significantly lower. Finally, the SSNT detectors are not recommended for the coverage of large areas due to their expensive cost.

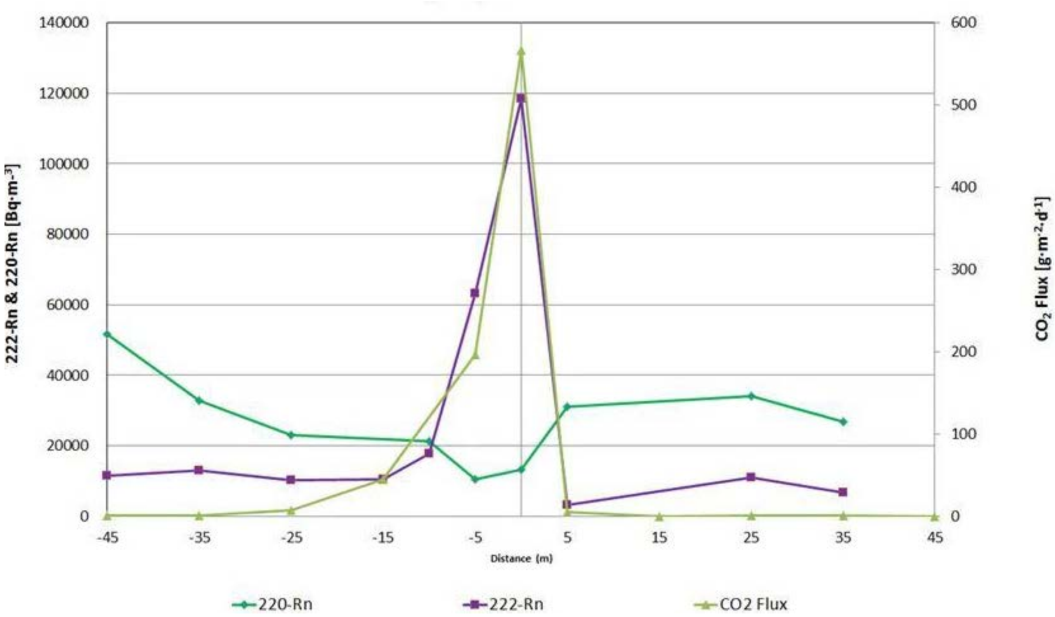

Fig. 3.1. Measurements of CO_2 flux and radon isotopes in La Sima site (Campo de Calatrava). CO_2 flux is positively correlated with ^{222}Rn.

4. Discussion: Lessons learned

In addition to the testing of measurement methodologies, a remarkable result of this study is the observation that gas emission from deep sources through sedimentary cover (even seal formations) and surface soils comes out in very small spots, some of them as small as few square centimetres and always related to fracture systems (Fig. 4.1). Therefore, no evidence for widespread diffuse emission through sediments has been detected. The reason behind is likely the formation of channelling inside fracture zones where water and gas are preferentially driven. This has important consequences in terms of the design of monitoring campaigns that also can be further applied to monitoring of deep geological repositories of nuclear waste. The small size of the emission spots implies that the detection of leakage becomes extremely difficult and makes inconvenient many monitoring methodologies due to the large extension to be covered. In addition, remote monitoring techniques (satellite, unmanned aerial vehicle or plane) that can cover large areas, could be inapplicable due to the small size of the emission. On the other hand, the link between emissions and fractures lead

to a decrease of the potential area to be monitored in some extent depending on the fault density.
The use of methods such as SARAD detectors is proved to be rather effective to detect leakage not only from the detection point of view but also from the cost, and especially if the potentially affected area is restricted to fault zones. The short acquisition time (some minutes) makes feasible the design of relatively large sampling grids in km^2-sized areas.

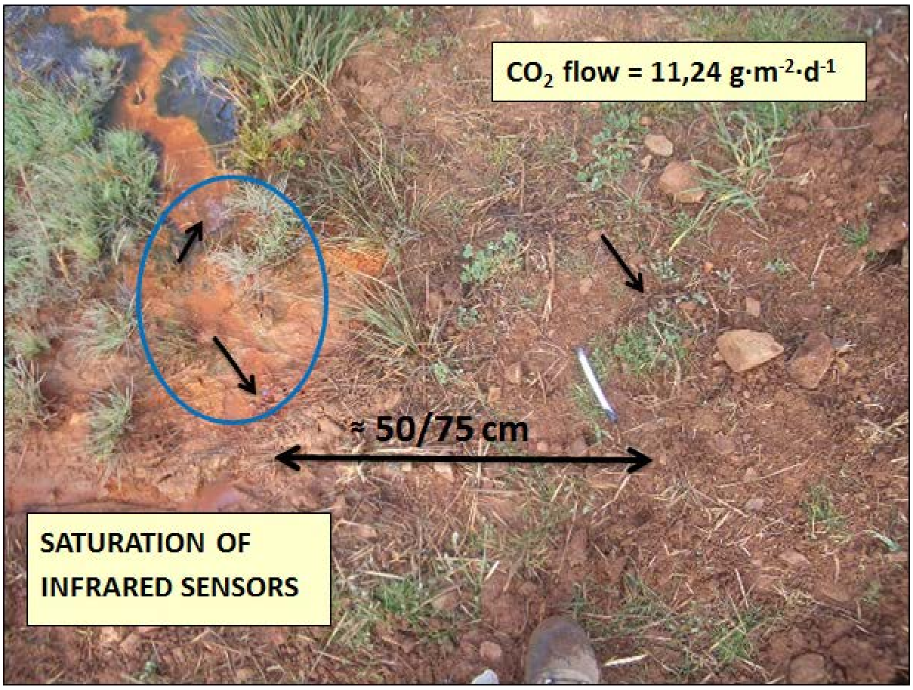

Fig. 4.1. Example of channelled emission and flow through very small spots in the Campo de Calatrava region. To the left (blue circle), high CO_2 (+trace gases) flux (>5000 $g \cdot m^{-2} \cdot d^{-1}$); some centimetres to the right, background emission related to biological activity.

5. Conclusions

The use of Rn isotopes has proved to provide valuable information of gas leakage from deep sources. Methods tested in the Campo de Calatrava region show that leakage is exclusively linked to channels in fracture zones and that some emissions cannot be detected by accumulation chambers measuring CO_2 since their intensity is comparable to biological background. Some of these methods are effective enough to be included in monitoring campaigns not only for CO_2 geological storage but also for nuclear waste repositories.

6. Acknowledgements

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References

[1] Sutton, W.R., and N.M. Soonwala (1975). A soil radium method for uranium prospecting. Mineral Exploration 5, 51.

[2] Gates, AE., L.C.S., Gundersen, and L.D. Malizzi (1990). Comparison of radioactive element distribution between similar faulted crystalline terranes : glaciated versus unglaciated. Geophysical Research Letters 17, 813-816.

[3] Reimer, G.M. (1992). Using soil-gas and geology to estimate regional radon potential. Radiation 45, 219-222.

[4] Cox, M.E. (1980). Ground radon surveys of a geothermal area in Hawaii. Geophysical Research 7, 283-286.

[5] García-González, J.E., M.F. Ortega, E. Chacón, L.F. Mazadiego, and E. De Miguel (2008). Field validation of radon monitoring as a screening methodology for NAPL-contaminated sites. Applied Geochemistry 23, 2753-2758.

[6] Elío, J., M. Ortega, M., E. Chacón, L.F., Mazadiego, and F. Grandia (2012). Sampling strategies using the “accumulation chamber” for monitoring geological storage of CO_2. International Journal of Greenhouse Gas Control 9, 303-311.

[7] Etiope, G., and G. Martinelli (2002). Migration of carrier and trace gases in the geosphere: an overview. Physics of the Earth and Planetary Interiors 129, 185-204.

[8] Etiope, G., M. Guerra, and A. Raschi (2005). Carbon dioxide and radon geohazards over a gas-bearing fault in the Siena graben (Central Italy). Terrestrial, atmospheric and oceanic sciences 16-4, 885-896.

[9] Giammanco, S., K.W.W. Sims, and M. Neri (2007). Measurements of ^{220}Rn and ^{222}Rn and CO_2 emissions in soil and fumarole gases on Mt. Etna volcano (Italy): Implications for gas transport and shallow ground fracture. An electronic journal of the earth sciences 8-10, 1-14.

[10] Voltattorni, N., A. Sciarra, G. Caramanna, D. Cinti, L. Pizzino, and F. Quattrocchi (2009). Gas geochemistry of natural analogues for the studies of geological CO_2 sequestration. Applied Geochemistry 24, 1339-1346.

[11] Michel-le Pierres, K., F. Gal, M. Brach, and S. Guignat (2010). Radon, helium and CO_2 measurements in soils overlying a former exploited oilfield, Pechelbronn district, Bas-Rhin, France. Journal of environmental radioactivity 101, 835-846.

[12] Albany, O.R., A.K. Fairbanks, W.V. Morgantown, P.A. Pittsburgh, and TX Sugar Land (2009-2012). Measurements of ^{222}Rn, ^{220}Rn, and CO_2 emissions in natural CO_2 fields in Wyoming: Monitoring, verification, and accounting techniques for determining gas transport and caprock integrity. National Energy Technology Laboratory (NETL). Project facts Carbon Sequestration. 2009-2012.

[13] Vaselli, O., B. Nisi, F. Tassi, L. Giannini, A. Delgado-Huertas (2011). Water and gas geochemistry from the CO2-rich field of Campo de Calatrava (Castilla-La Mancha). Ciudad de la Energía, Internal Report.

Geophysical monitoring of a gas permeable seal

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Summary

Gas permeable seals provide a solution to increase the gas transport capacity from backfilled underground repositories without compromising long-term safety. The Gas Permeable Seal Test (GAST) in the Grimsel Test Site (GTS) is a demonstration experiment in real-scale (~12.5m long and 3.5m diameter) to show the effective functioning of a gas permeable tunnel seal under comparable boundary conditions. A seismic tomography monitoring system has been implemented inside the seal to visualise gas transport paths within a rectangular cross section of ~1.80m in width and 1.34m in height. Results from a design study to optimise the seismic array showed that elastic anomalies of approximately 20 x 20 cm^2 can be resolved.

The necessary high water and gas injection pressures raised questions about operational safety and predictability of a potential failure especially at the confining bulkhead. Therefore the instrumentation had been supplemented with an acoustic emission (AE) monitoring system to be able to detect possible cracks in the bulkhead.

1. Introduction

Gases (hydrogen, methane, carbon dioxide) may accumulate in the emplacement caverns of a geological repository for low/intermediate-level waste (L/ILW) due to the corrosion and degradation of the wastes [1]. Gas permeable backfill and tunnel seals have been proposed as a viable option to release a part of the gas and ensure limited gas pressures even in tight host rocks.

This approach is now evaluated by Nagra in the framework of the concept for an engineered gas transport system (EGTS), aiming at a limited the gas overpressures in the backfilled underground structures of a repository on an acceptable level without compromising the radionuclide retention capacity of the engineered barrier system (EBS).

The main design elements of the EGTS are (i) specially designed backfill materials for the emplacement caverns, characterized by high porosity and high compressive strength and (ii) gas permeable tunnel seals, consisting of sand/bentonite mixtures with a bentonite content of 20% to 30%. Sand/bentonite mixtures with a low bentonite content exhibit low permeability to water, whereas the gas permeability is enhanced.

To demonstrate the effective functioning of gas permeable tunnel seals a large scale experiment has been implemented in the Grimsel Test Site. After full saturation of the sealing system hydraulic and gas tests will be performed to evaluate the efficiency and the correct functioning of the seal.

A number of conventional hydro-mechanical instruments have been installed to monitor the evolution of pressures and saturation inside the seal. These instruments provide valuable information, but limited to the immediate vicinity of each sensor. Tomographic methods on the other hand also offer a possibility to image larger areas. Because seismic velocities are sensitive to changing water content in sand or bentonite [2; 3] we consider P-wave velocities as being indicative for the presence of a gas phase. Consequently seismic tomography can be employed to image saturation/desaturation processes and, more specifically, to visualise the possible formation of gas flow paths within a sand/bentonite seal.

This paper describes the GAST experiment layout and outlines the instrumentation with a seismic tomography monitoring system. We present the results from a design study to optimise the geometry of the seismic array and to describe the emplacement layout. Moreover, a second seismic system to detect acoustic emissions is introduced; this has the potential to detect safety-relevant cracks in the experiment's bulkhead.

2. GAST Experiment Layout

The Gas Permeable Seal Test (GAST) in the Grimsel Test Site (GTS) is a real-scale experiment (Fig. 2-1) to demonstrate the feasibility of a tunnel seal with sufficient gas transport capacity and, at the same time, high radionuclide retention capacity. The GAST experiment focuses on the specific behaviour of a compacted sand/bentonite seal during water saturation and a later gas invasion, deliberately excluding the expected dynamic behaviour of the clay host rock and the extended EDZ. The construction at the back end of a laboratory tunnel in crystalline rock provides a stiff boundary with negligible EDZ [4], because the hydraulic conductivity of the EDZ in the vicinity of the GAST tunnel is expected to be in the same range or lower as in the seal.

The seal element consists of 23 layers of compacted sand/bentonite with a length of 8m and target intrinsic permeability of 1E-18 m^2. Vertical sand filters were emplaced at both ends for later water and gas injections. Two walls, made of compacted bentonite blocks and granular bentonite, constituted the watertight seal at the tunnel end and at the confining bulkhead. The radial interfaces and head space were filled with granular bentonite material to obtain a tight seal against the surrounding host rock and to prevent preferential water and/or gas flow paths along interfaces. A network of conventional instruments was installed in 15 vertical sections along the construction. In total 23 pressure cells, 39 pore pressure sensors, 38 TDR's, 20 water content sensors and 30 suction sensors were installed to monitor the hydro-mechanical evolution of the experiment.

The seismic tomography monitoring system was emplaced inside the seal and ~1.60m from the seals back end (Fig. 2-1). The AE system was installed on the external side of the concrete bulkhead.

Starting in July 2012 the experiment is being artificially saturated by water injections into the sand filter near the bulkhead with a maximum injection pressure of 5 MPa. Scoping calculations indicated that full saturation may be possible in about four to five years.

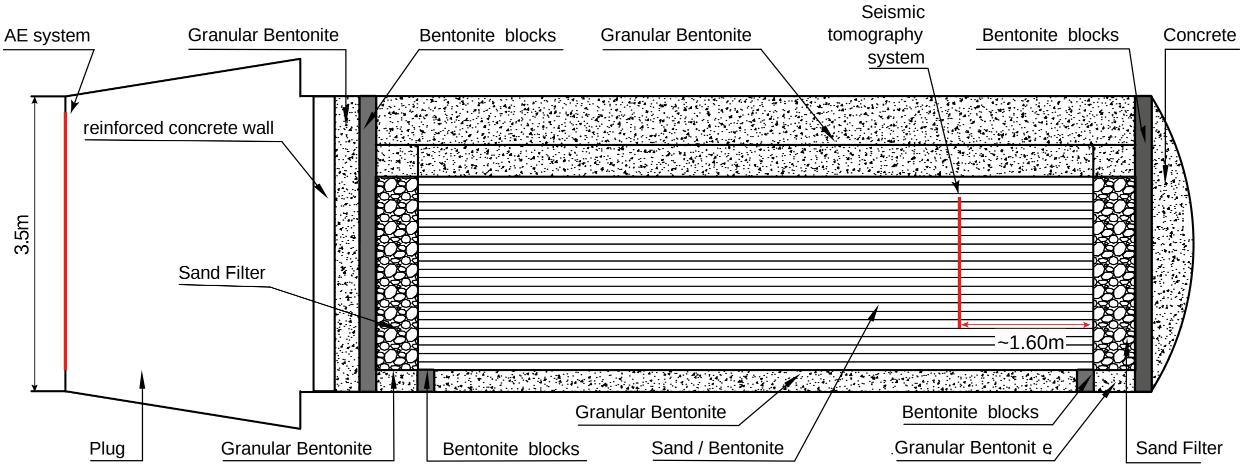

Figure 2-1: GAST experimental layout in a longitudinal cross section and location of the seismic tomography and AE systems (in red).

3. Seismic Tomography System

Obtaining a detailed picture of localised flow processes (such as gas transport) inside the seal material is a challenge for hydro-mechanical instruments. Forward modelling and tomographic inversions of P-wave travel times showed that elastic anomalies can be resolved if an area larger than approximately 20 x 20 cm^2 is affected by a passing saturation front. This result was obtained for a layout with 16 sources and 16 receivers that were regularly distributed on the boundary of a 170 x 250 cm^2 elliptical cross-section (Fig. 3-1a and 3-1b). The inversion was repeated with a full-waveform acoustic inversion technique and demonstrated its superior resolution capabilities (Fig. 3-1c).

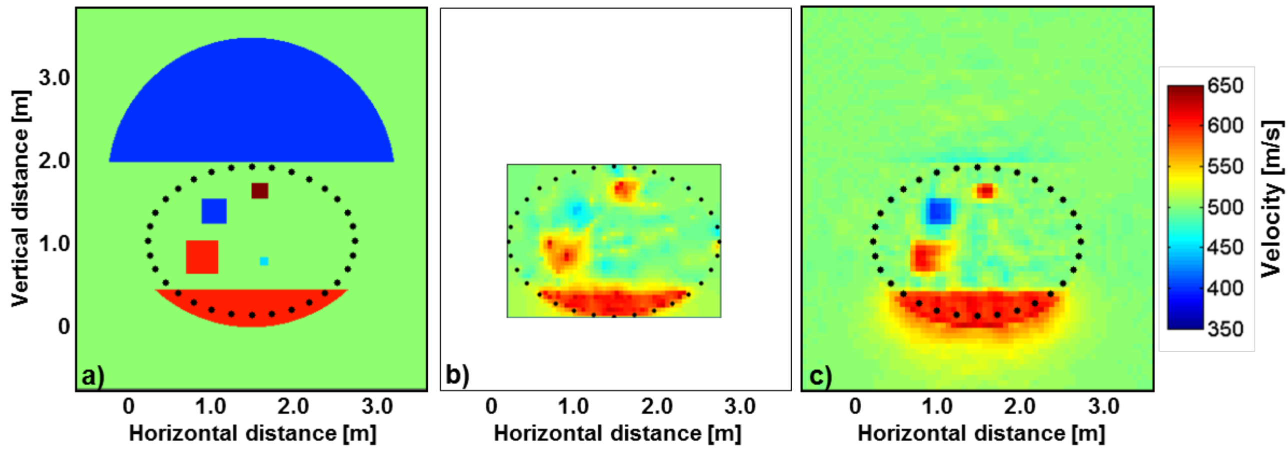

Figure 3-1: (a) Results from a design study for the seismic tomography monitoring system. (a) Initial seismic velocity model for computing traveltimes and waveforms, (b) inlay with velocities from traveltime inversions and (c) velocities from full waveform inversion. Black dots: source and receiver positions.

In parallel seismic velocities of partially saturated sand/bentonite samples were measured in the laboratory. We obtained P-wave velocities of 560 – 590 m/s and very low quality factors Q of ~1. The numerical models and velocity measurements indicated that the propagation of seismic waves through the sand/bentonite mixture is generally feasible, but that the unsaturated material is highly attenuating.

The final tomographic sensor layout was deployed about 1.6 m from the back end of the seal (Fig. 2-1). It consisted of 32 ultrasonic low-frequency sensors (5-20 kHz) that were emplaced along the boundaries of a rectangular cross-sectional area of ~1.80 x ~1.34 m (horizontal x vertical) length (Fig. 3-2). For simplicity, the ultrasonic sensors have been emplaced following the 10 cm thick horizontal layers of the compacted sand/bentonite. For this reason the original plan to place the sensors along an ellipse was sacrificed. Two additional sensors were emplaced in the rectangular centre of the rectangle to provide additional ray coverage at shorter ray lengths. Cylindrical steel housings protected the sensor from the high water and gas pressures of up to 5 MPa.

To test the receiver performance during construction and obtain first information on seismic velocities, lump hammer strokes were imposed on the actual uppermost compacted sand/bentonite layers. Three suites of measurements were performed and recordings from source-receiver distances of up to 1.9 m were acquired. Analysis of the first arriving wave trains allowed average velocities of the layers between the hammer position and the buried geophones to be determined. Average velocities for the three suites were 520, 585 and 549 m/s, which is broadly consistent with the values obtained in the laboratory. The velocities were highest in the centre of the tunnel, and they decreased slightly towards the side walls. This could be an indication that the compaction near the sidewalls was less effective than in the centre.

After completion of the GAST experiment all the transmitters were activated, and the data acquisition was started. The deployed transmitters generated acoustic waves that were detected over distances of ~20 cm. This is the result of the highly attenuating sand/bentonite mixture, and, probably more important, a consequence of poor coupling of the sensors to the medium of interest. It is expected that the water saturation and the associated swelling of the bentonite will improve the coupling conditions, such that measurements of all possible source-receiver combinations (Fig. 3-2) can be carried out.

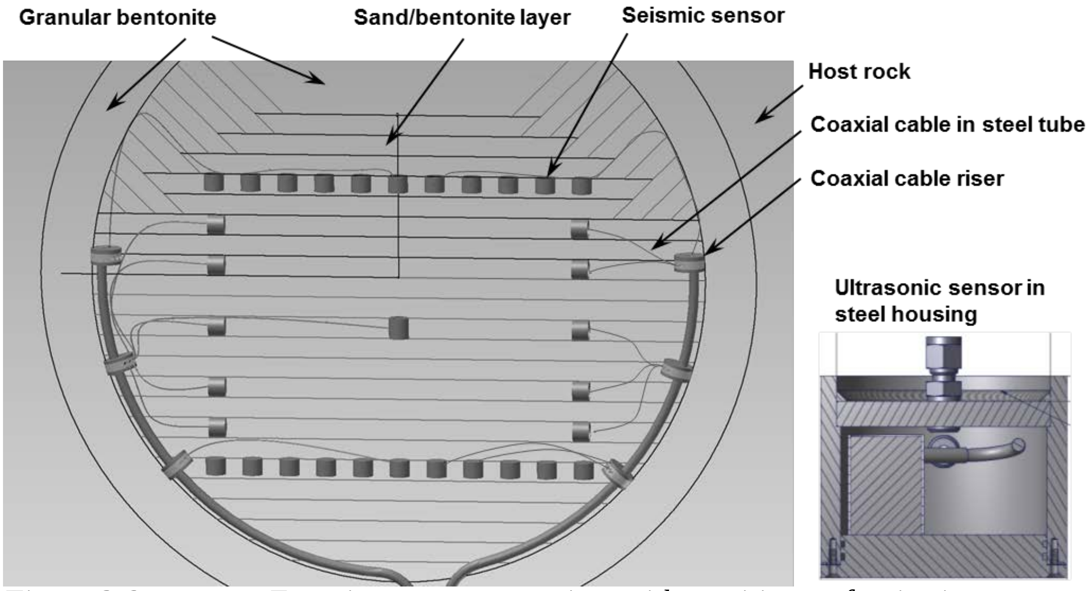

Figure 3-2: Experiment cross section with positions of seismic sensors (left) and sketch of the steel cylinder housing the ultrasonic sensor (right)

4. Acoustic Emissions (AE) System

The concrete bulkhead at the experiment's front side (Fig. 2-1) was designed to withstand the mechanical load from a maximum water pressure of 5 MPa plus 1 MPa of swelling pressure. Since the plug is expected to bend slightly outwards when loaded, superficial cracks on the air side are likely to occur, but they are not expected to be critical for the mechanical strength of the experimental layout. Nevertheless for safety reasons an acoustic emission (AE) monitoring system was installed. Such a system would allow detecting the development of small cracks in the plug prior to catastrophic failure. For distinguishing between surficial and deeper events (i.e. crack formation), accurate locations are required. Reasonably good location accuracy of the events over the entire plug is expected to be obtained with 12 sensors that are regularly distributed over the plug surface (Fig. 4-1a). A critical measure of the location accuracy is the nearest distance of a sensor to the epicentre. Fig. 4-1b shows that for every possible epicentre location on the plug the corresponding minimum distance to the closest sensor is smaller than one meter. This indicates that the distinction between surficial and deep-seated events will be possible.

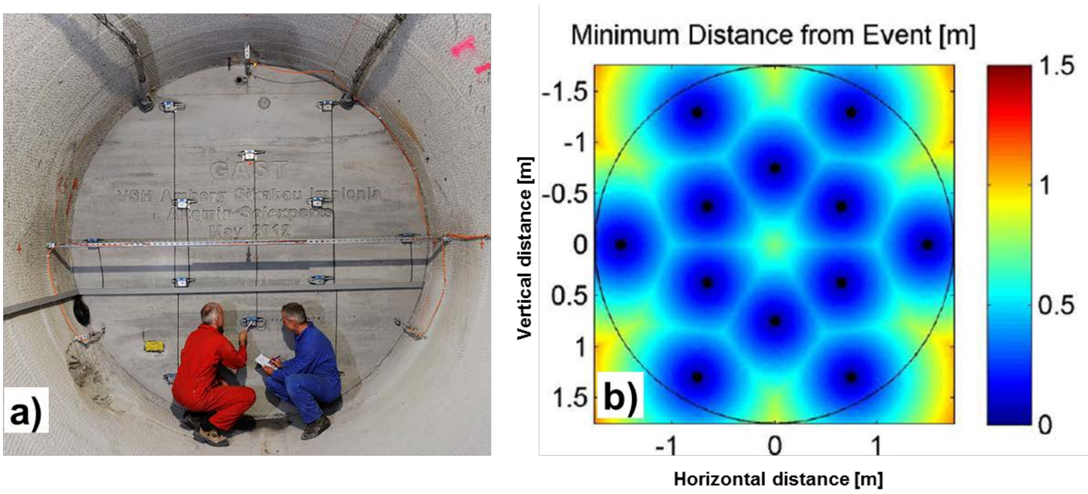

Figure 4-1: AE monitoring sensors distributed over the concrete plug (a) and minimum epicentral distance from an event to the closest sensor (b) (Photo: Comet, Switzerland)

5. Discussion and Conclusions

Within the framework of a gas permeable tunnel seal experiment we installed two geophysical monitoring systems: (i) a seismic tomography system and (ii) an acoustic emission system.

The first monitoring system aims at imaging saturation/desaturation processes and at the visualisation of gas flow paths within a sand/bentonite seal. Results from a design study showed that elastic anomalies can be resolved if an area larger than approximately 20 x 20 cm^2 is affected by a passing saturation front. Laboratory measurements and test measurements after installation of the tomography system revealed high attenuation of seismic waves within the compacted but unsaturated sand/bentonite mixture. To date the transmitters deployed within the seal material generated acoustic waves that were detected over distances of ~20 cm. By further optimizing the acquisition parameters, the signal quality can be likely further improved. Once the sand/bentonite mixture is water saturated, the coupling of the sensors should be such that signals may be recorded over larger distances.

The second monitoring system is recording acoustic emissions that may be generated within the confining concrete plug by high water and gas injection pressures. A system with 12 sensors has been installed on the air side of the concrete bulkhead. We expect reasonable location accuracy over the entire bulkhead surface that allows distinguishing between surficial and deeper events.

The addition of the geophysical monitoring data is expected to strengthen the qualitative and quantitative evaluation of the behaviour of the seal.

Acknowledgements

This research project is financed by NAGRA. We thank Patrick Steiner (Solexperts AG) for drawing Fig. 3-2.

References

[1] Nagra (2008) “Effects of post-disposal gas generation in a repository for low- and intermediate-level waste sited in the Opalinus Clay of Northern Switzerland”, Nagra Tech. Rep. NTB 08-07, Nagra, Wettingen, Switzerland.

[2] Tisato N. and Marelli S. (2012) “Laboratory measurements of the longitudinal and transverse wave velocities of compacted bentonite as a function of water content, temperature and confining pressure”, submitted to Journal of Geophysical Research.

[3] Barrière, J., Bordes, C., Brito, D., Sénéchal, P. and Perroud, H. (2012) “Laboratory monitoring of *P* waves in partially saturated sand”, Geophysical J. I., doi: 10.1111/j.1365-246X.2012.05691.x.

[4] Marschall, P., Fein, E., Kull, H., Lanyon, W., Liedke, L., Müller-Lyda, I. & Shao, H. (1999) “Conclusions of the Tunnel Near-Field Programme (CTN), Nagra Tech. Rep. NTB 99-07, Nagra, Wettingen, Switzerland.

Monitoring pore pressures from different perspectives – lab / in-situ / modelling

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Summary

It is widely agreed that the overall detection of geohydraulic conditions and their changes due to geomechanical disturbances via in situ measurements is one of the most relevant prerequisites for reliable physical modelling and numerical simulation of coupled processes. With respect to disposal in argillaceous formations, GRS therefore has participated in the French research programme in the Meuse/Haute-Marne Underground Research Laboratory (MHM-URL), in the framework of a co-operation agreement between the German Federal Ministry of Economics and Technology (BMWi) and the French Agence Naionale Pour la Gestion de Déchets Radioactifs (ANDRA). GRS is also involved in various experiments together with several European partners at the Mont Terri URL. In various experiments, monitoring of pore pressure and pore pressure changes is one of the major tasks. In this paper, selected examples from GRS' experience in the field of pore pressure measurement will be presented from the perspectives of laboratory and in-situ-experimental findings, and compared to numerical modelling work.

1. Introduction

The international experience gained in the field of geological radioactive waste disposal furnishes evidence of a significant coupling between thermal, hydraulic, mechanical and chemical processes (THMC-coupling) in claystone rock mass. The fabric components, saturation level and the pore water pressure determine the long-term load bearing behaviour of the claystone rock mass affected by the impact of excavation activity and waste storage related re-sealing aspects. The elevated pore water pressure encountered in the normally water-saturated claystone formation contributes to the overall stress state. As a consequence, pore water pressure variations will influence the effective stress and thus lead to time-dependent deformation.

2. Laboratory Investigations

2.1 Methodology

In the last years, GRS has intensively investigated the damage as well as the re-sealing behaviour of highly-consolidated clay rocks with laboratory experiments on claystone samples. Currently, a series of new lab experiments have been performed on fully-saturated and re-sealed samples of the Callovo-Oxfordian (COX) argillite [1].

A test for examining pore pressure changes by thermal loading was carried out on a nearly-saturated COX sample with a saturation degree of 95.2 %. The sample axis was nearly parallel to the bedding planes. In order to achieve full saturation, the synthetic pore water was firstly sprayed upon the sample surface. After sealing the sample in jacket, the test was started with water injection into both end faces at pressure of 1 MPa und confining stress of 1.5 MPa over 7 days.

2.2 Typical Results and Discussion

Figure 2-1 shows the test process in a triaxial cell in terms of the applied stress and temperature, the resulted water back-pressures and deformations. During the re-saturation phase at low confining stress, swelling took place to a large volume increase of 4 %. At undrained conditions, the response of the pore-water pressure to mechanical loading was examined by increasing the confining stress up to 15 MPa (step 1). The compression led to an increase of the back-pressure at the top and bottom to an identical value of 13.5 MPa remaining constant, indicating the existence of a hydraulic interconnection between both end sides. At this point, a full saturation seemed to be reached. Following the testing procedure the pore pressure was dropped down to 1 MPa by switching off the inlet and outlet valves for short time (step 2). This increased the effective stress and thus led to large compaction recovering the previous expansion. After 21 days of testing the sample was heated by elevating temperature from 30 to 50, 70 and 90 °C at a rate of 0.6 °C/h, keeping for days to month each (step 3). The temperature increase caused the back-pressure rising. The maximum water pressure was reached at 7.8 MPa at both end sides by heating step from 50 to 70 °C. At each increased temperature the water pressure dissipated with time. This indicates that the pore water moved in any way, else the pressure value must maintain. Accompanying the pore-water pressure decrease, a gradual consolidation took place and reached at a volume reduction of 3.5 % over one month. To ensure full saturation of the sample, the inlet pressure was increased to 4 MPa again (step 4) and then the confining stress was lowered down to 6 MPa (step 5). This led to a volume expansion of approx. 2 %. After switching off the inlet, the temperature was increased from 90 to 98 °C. As unexpected, this heating phase led the back- pressure dropping down rather than rising up. This effect might be caused by some leakage of thermally-induced water vapour with high vapour pressures through the “undrained” system. The subsequent cooling phase down to 30 °C (step 6) produced an extraction, reloading to 15 MPa resulted in a small compaction, and re-heating to 50, 70 and 90 °C again (step 7) generated expansion. However, no significant changes in the water back-pressure were observed.

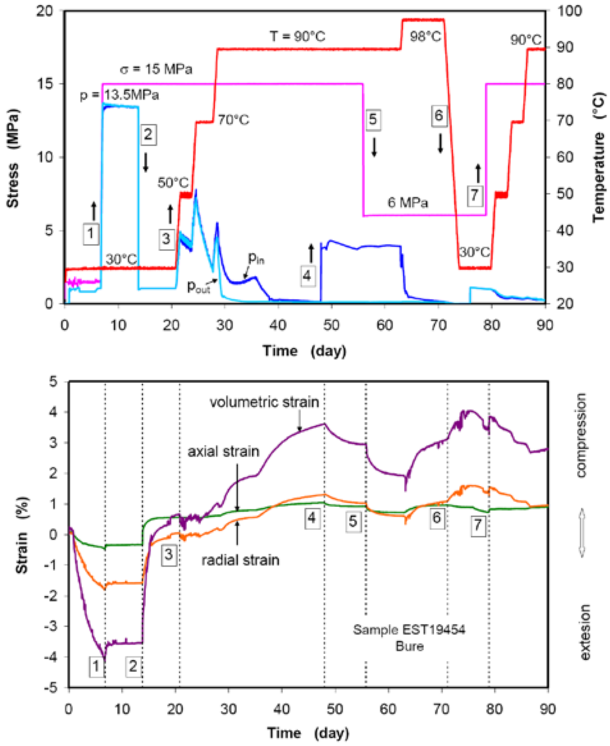

Figure 2-1: Evolution of thermally-induced pore-water pressure observed at the ends of a COX sample; (a) applied temperature, confining stress, and response of water back-pressures and (b) response of axial, radial and volumetric strain

3. In-situ-Investigations and interpretative modelling

3.1 Methodology

In order to investigate the thermal properties and to enhance the knowledge about the THM processes of the COX clay rock, an in-situ heating experiment called TER was performed at the MHM-URL from the beginning of 2006 to the end of 2009 [1]. The concept of the heating experiment was designed to heat the clay formation in an undisturbed zone by using an electric heater. The experiment was located at the main level at 490 m depth. Thermally-induced pore pressure changes were recorded by means of the GRS mini-packer systems which were successfully used before in the HE-D heating experiment in the MT-URL [2].

The measurement equipment used by GRS for the measurement of pore-water pressure consists of the slim-hole packer systems (mini-packer), a sensor rack with piezometric pressure transducers and PT100 temperature probes, a data acquisition system, and a computer with modem for data transfer (Figure 3-1). The mini-packer has a diameter of 20 mm and a length of 55 mm. In order to simultaneously measure the temperature, a PT100 sensor was additionally fixed at the bottom end. The mini-packer was installed at a distance of 3 mm to the borehole end and fixed by mechanically squeezing a rubber-ring of 10 mm length. The test interval volume of about 1 cm^3 is filled with PEARSON water through a 1/4”-sized inflow line. The air in the interval is displaced through the outflow line. The water pressure in the test interval is recorded by a piezo-resistive transducer connected to the outflow line. The system applied is designed for a maximum pressure of 5 MPa.

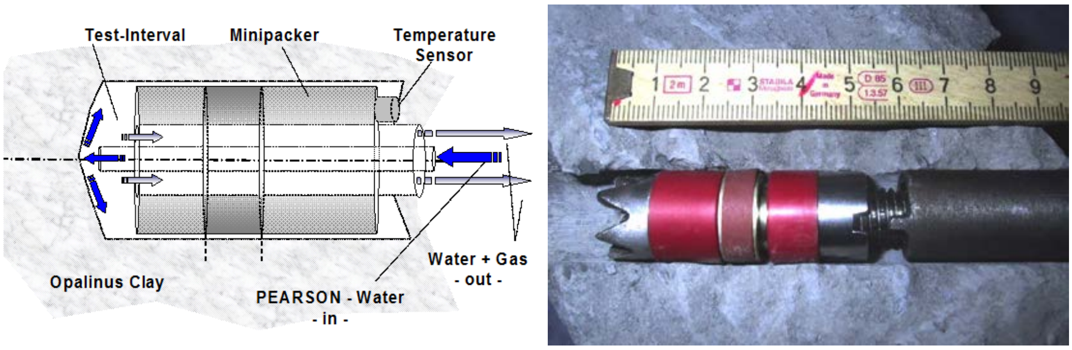

Figure 3-1: GRS mini-packer system for monitoring pore pressure and temperature; (a) construction of the mini-packer and (b) prototype of 20 mm diameter

Figure 3-2 (a) shows the positions of the measuring sensors with respect to the heating packer used in the TER heating experiment at the MHM-URL. In total, 5 mini-packer systems were installed in slim boreholes with diameters of 20 mm. They were located in the same vertical plane crossing the heater axis, at 0.5 m up to 1.5 m distance to the heating borehole axis. At each position, both the pore pressure and the temperature were measured. The instrumentation layout made it possible to monitor the temperature at the pore pressure sensor locations in three directions: In boreholes TER1401/02 parallel, in borehole TER1403 inclined (angle of 45 °), and in boreholes TER1404/05 perpendicular to the bedding planes.

Figure 3-1 (b) illustrates the heating phases with four heating/cooling cycles. Unfortunately, in each cycle several heating interruptions happened for days to month due to heater failure because of different reasons. Additionally, some uncertainties were recognized during the experiment, as for instance the correct measurement of the heater power and the quality of the heater contact to the rock. This yielded some difficulties for the precise determination of the thermal parameters from the measurements, as well as for the definition of model boundary conditions.

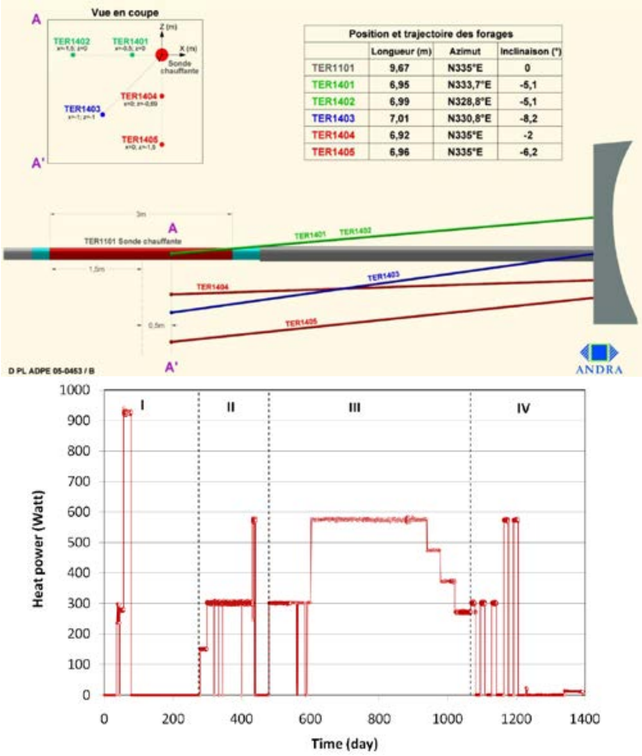

Figure 3-2: Layout of the TER test arrangement with heater borehole TER1101 and pore pressure instrumentation boreholes TER1401-05; (a) positions of pore pressure and temperature sensors and (b) applied heat power with heating/cooling cycles

3.2 Typical Results and Discussion

The TER heating experiment was simulated with a 2D-axisymmetric model, using the THM-coupled simulation tool CODE_BRIGHT developed by UPC [3]. When the experiment was finished, interpretative calculations were conducted and the results were compared to the measured data of temperature and pore-water pressure as shown in figure 3-2. During the first heating phase, the temperature reached a maximum of 100 °C. After cooling down deduced by equipment failure, the further power supply was limited to a heater temperature below 80 °C. The comparison in figure 3-2 (a) indicates that the value of 2 times the given power fits the model with the measurements relatively well. Figure 3-2 (b) illustrates exemplarily for TER1401 the evolution of the pore water pressure and the temperature measured in the near-field at a distance of 0.5 m to the heater compared to the modelling results. Before heating, lower initial pore water pressure values than the pre-given value of 4.5 MPa were measured. Consequently, an averaged pore pressure of 2.6 MPa was applied to the model. The measurements show that, in each heating/cooling cycle the temperature increase leads to a rising pore pressure and the temperature decrease causes a pore pressure reduction. During the first heating phase, a maximum pore pressure of 4.0 up to 6.5 MPa was reached, depending to the distance to the heater. During the last cooling phase, the measured pore pressure dropped down to atmospheric pressure. This area might be slightly de-saturated, as indicated by the calculated negative values of pore pressure.

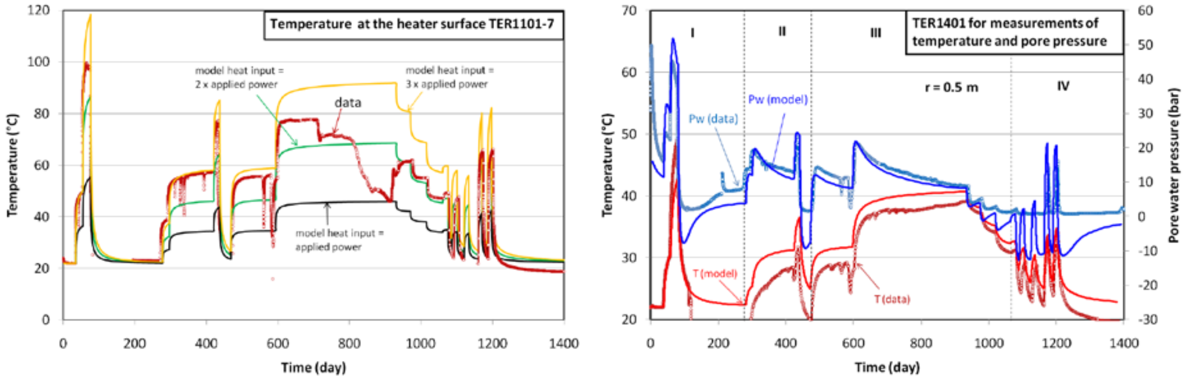

Figure 3-2: Interpretative modelling results compared to TER measurement data; (a) temperature evolution at the heater/rock interface at TER1101-7 and (b) response of temperature and pore pressure at TER1401

4. Conclusions

In unsaturated and/or drained conditions, heating causes mobilisation and expulsion of the pore water from the rock, giving rise to pore collapse and thus consolidation. The thermally-induced consolidation enhances the stiffness and strength of the clay rock. No thermal fracturing was observed in lab. In saturated and undrained conditions, the thermal expansion is predominately controlled by the pore water because of its much higher expansion effect compared to that of the solid grains. Heating increases the pore-water pressure in the saturated claystone. The comparison of modelling results and measured date investigated within the TER heating experiment suggests that the temperature evolution at most of the sensors measured during multiple heating/cooling cycles is reasonably represented by the model in general.

5. Acknowledgements

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References

[1] Zhang, C.-L.; Czaikowski, O.; Rothfuchs, T. (2010): Thermo-Hydro-Mechanical Behaviour of the Callovo-Oxfordian Clay Rock. Final Report within the Framework of GRS/ANDRA Cooperation Programme and the EC TIMODAZ Project, GRS-266, Dec. 2010.

[2] Zhang, C.-L.; Rothfuchs, T.; Jockwer, N.; Wieczorek, K.; Dittrich, J.; Müller, J.; Hartwig, L.; Komischke, M. (2007): Thermal Effects on the Opalinus Clay to Heating – A Joint Heating Experiment of ANDRA and GRS at the Mont Terri URL (HE-D Project), GRS-224, Feb. 2007.

[3] CODE-BRIGHT, A 3-D program for thermo-hydro-mechanical analysis in geological media, User's Guide, Universidad Politécnica de Cataluña (UPC), 2002.

Development of Miniaturized Wireless Transmitter and Borehole type Receiver with Low Frequency Magnetic Waves

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Summary

To achieve the monitoring of geological repository balancing with the detriments caused by monitoring, RWMC has been developing a series of wireless transmission system as a collaborative research with ANDRA. In the presence of rock masses and bentonite, high-frequency electromagnetic waves are excessively attenuated. Consequently, the authors have been developing a wireless data transmission system that can be used in media such as rock and bentonite by using a very low frequency (approximately 8.5 kHz) electromagnetic wave as the data carrier. This presentation focuses on recent development of miniaturized wireless transmitter and borehole type receivers to fit into barriers such as bentonite buffer, backfill and plug.

1. Introduction

To confirm the performance of a geological disposal system, the authors have been studying the feasibility of monitoring the phenomenological evolution in barriers such as bentonite buffer, backfill, and plug emplaced in various locations in the underground of a geological repository. As stated in series paper [1] and [2], authors propose monitoring system that uses miniaturized transmitter and borehole type receivers as wireless data transmission in order to protect any degradation of materials in the repository, and also to protect the formation of pathways through barriers.

2. Objectives

The objectives of development of the miniaturized transmitter and borehole type receivers are to use them:

Miniaturized transmitter

- in a engineered barrier such as bentonite buffer, backfill or plug to accomplish minimum deterioration of barriers by the presence of cables,
- in a natural barrier.

Borehole type receiver

- in a low electrical noise condition and in a low attenuation of electrical propagation where steel components around the gallery only little affect the signals,
- in order to detect any direction of signals emitted from transmitters,
- in reducing the distance between the signals from the transmitter and receiver by inserting them in a borehole.

The arrangement options of the miniaturized transmitters and borehole type receivers are illustrated in (Fig.1). When boreholes could be used for hosting the receiving antenna, Option 1 is applicable. When it is difficult to use boreholes, Option 2 could be recommended. When the transmission distance is longer than that of miniaturized transmitter, a relay transmission system could be applied.

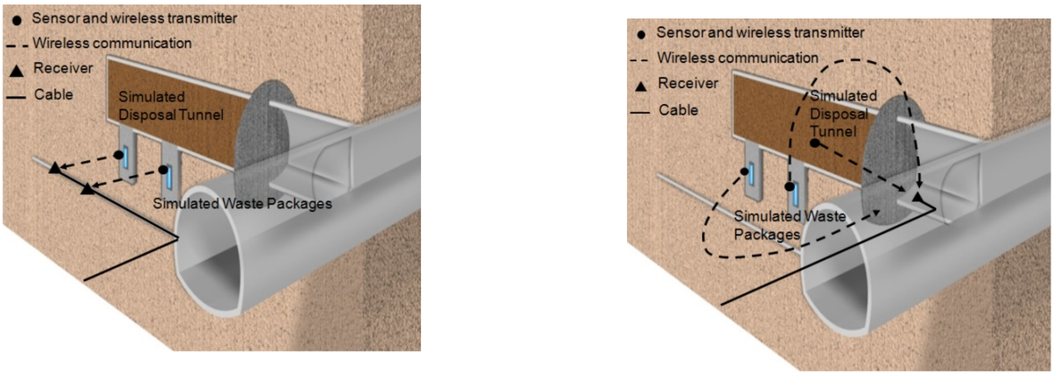


Figure 1: Arrangement of miniaturized transmitter with borehole type receiver (left, Option 1) and without borehole type receiver (right, Option 2)

3. Miniaturized transmitter development

The authors performed feasibility tests to develop miniaturized transmitters for wireless transmission monitoring inside a geological repository, including the design and manufacture of an optimum wireless transmission system. The system was designed to deal with the prevailing conditions and to meet specified requirements, such as the electrical conductivity of the media, transmission distance, transmission period, and sensor location. The transmitters with pressure resistance for each 1MPa and 10MPa have a built-in temperature sensor and a connector for an external sensor; the sizes are 48 mm in diameter and 160 mm long for the 1MPa transmitter (Fig.2. (d)), and 60 mm in diameter and 240 mm long for the 10MPa transmitter (Fig.2. (f)). The transmitter enhanced with 10MPa pressure resistance can be applied to a swelling pressure of bentonite and hydrostatic pressure at 500m depth. A copper coil with an amorphous core is inserted in a pressure-tight PVC case for 1MPa (Fig.2. (c)) and a copper coil with a stainless core is inserted in a pressure-tight PVC case for 10MPa (e). The interior space of the antenna is occupied by the lithium battery (b). A thermometer is installed inside the transmitter, 1 sensor can be connected outside the transmitter, and cables from a sensor are connected to the adapter which is installed inside the cylinder of the transmitter (Fig.2. (a)). Transmission tests were carried out on the surface in order to confirm the performance of the transmitter. The distance between transmitter and receiver ranged from 5 m to 15 m (Fig. 3). The antenna of transmitter was oriented perpendicular (direction X) to the receiving antenna. The miniaturized transmitter can send data 12m against electromagnetic noise background of 25 mV_{rms}. The graph shows that the received voltages matched to the design values, meaning that the antenna performed as intended.

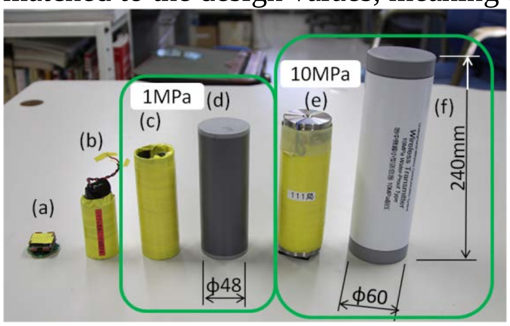


Figure 2: Transmitters for 1MPa and 10MPa

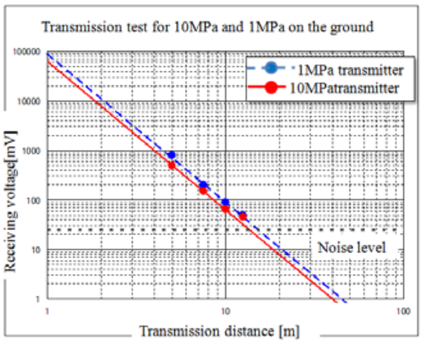
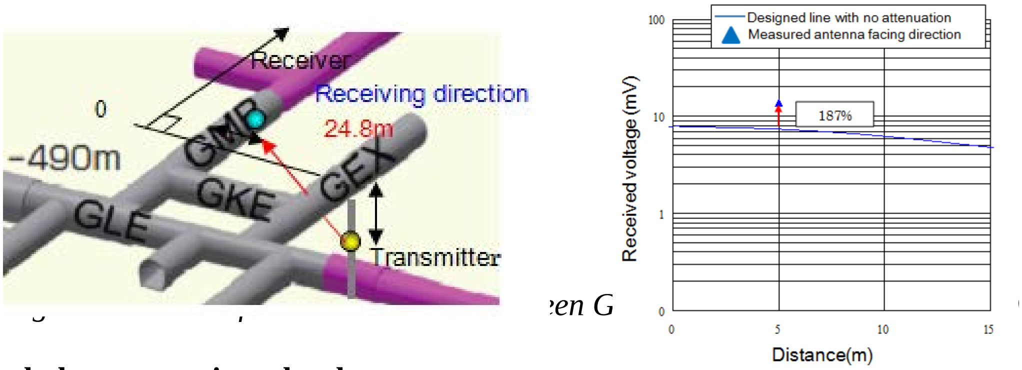


Fig ... ne ground

The maximum transmission distance depends on the ambient level of electromagnetic noise. When a noise level is under 1.0 mV, the transmission distance becomes 40m using both transmitters.

3.1 Transmission test through the rock

The transmission test was conducted through a sedimentary formation of Callovo-Oxfordian argillaceous rock at 490m depth inside the MHMURL between the two drifts GEX and GMR with a distance of 24.8m.The transmitter was set in the vertical borehole at the level of -4m from the surface of GEX gallery and the receiver was set on the surface of GMR gallery (Fig.4). In the graph, the line shows the design value with zero attenuation. The received voltages at 5 m from the 0 point in GMR gallery were 13.8 mV, where 7.4mV was the design value. This result means that the received voltage was amplified by the steel components in the GMR gallery by drawing the electromagnetic flux towards the steel pipes. Thus, the steel components do not always attenuate the electromagnetic propagation.



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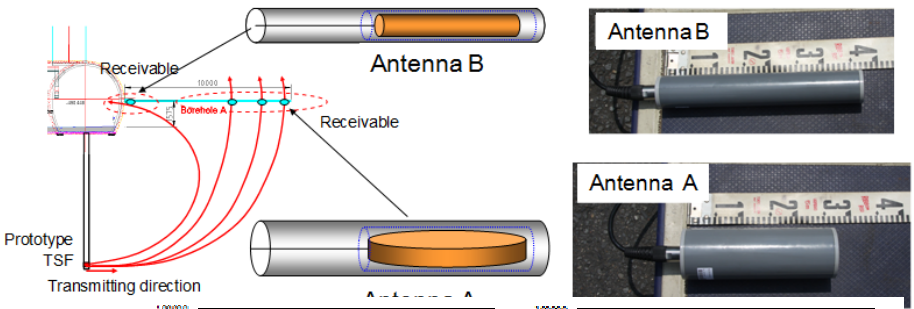
4. Borehole type receiver development

The authors developed two types of receiving antennas (Fig.5.). Antenna A can receive the electromagnetic flux perpendicular to the borehole axis. Antenna B can receive the electromagnetic flux parallel to the borehole axis. The size is 89 mm in diameter and 260 mm long for antenna A, and 50 mm in diameter and 370 mm long for antenna B. The receiving voltage by using antenna B reduced quickly according to the relative positioning of transmitter and receiver. This shows that the density of electromagnetic flux in this part became lower than other part. But the receiving voltage at a distance of 13m was 380mV (Fig.6), which is almost the same level as that of the ground test. This revealed that the borehole to borehole transmission was effective in the repository monitoring.



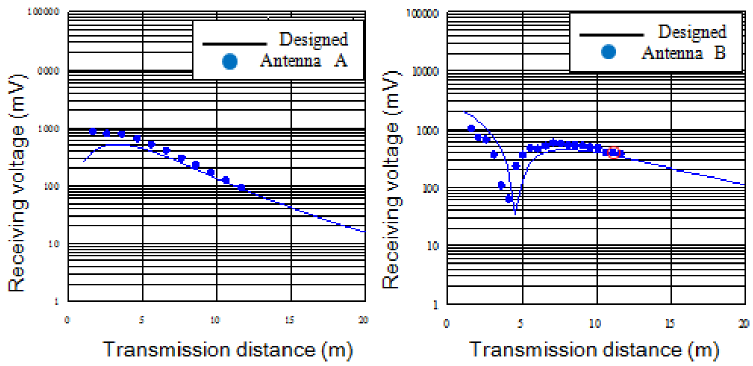


Fig.6. Rece… a B (right)

6. Conclusions

The miniaturized transmission with 1MPa achieved a transmission distance of 25 m through the rock in the URL gallery. The transmitter with 10MPa has almost the same ability. The transmission with VLF (very low frequency; 8.5Hz) is practical, when the received voltage is larger than the noise level. The attenuation through rock is very small according to the numerical analysis (Fig.6). In case that the electromagnetic flux is attenuated largely by the steel components in the gallery, borehole receivers such as antenna A or B are recommended in order to reduce the effect of noise and attenuation by components of the sub-surface system.

7. Acknowledgements

This research and development was partially financed by the Agency of Natural Resources and Energy, the Ministry of Economy, Trade and Industry of Japan (Development of Advanced Engineering of the Disposal System, FY2011).

References

[1] Tanabe, et al., Basic Requirment of Monitoring Activites in Geological Disposal and Role of Wireless Data Transmission, Proceeding of the MoDeRn international repository monitoring conference and workshop S4P11 (2013)

[2] Eto, et al., Development of wireless monitoring system for stepwise backfill/sealing of geoplogical respository, Poceedings of the MoDeRn international respository monitoring conference and workshop, S4P13 (2013)

Development of Wireless Monitoring System for Stepwise Backfill/Sealing of Geological Repository

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Summary

Technical requirements of wireless transmission during the monitoring of a geological repository are thought to change in accordance with stepwise backfilling/sealing in the repository. Wireless transmitters for different distance, i.e. short-range, mid-range and long-range, and relay systems have been developed in a collaborative research between RWMC and Andra including verification tests in the Meuse / Haute-Marne Underground Research Laboratory (CMHM URL) in France. This paper discusses the application of the equipment in combination, to adapt the variable requirements during stepwise backfilling/sealing.

1. Introduction

The IAEA noted that the benefits from gaining data on the behavior of the system components of a deep geological facility for the disposal of radioactive waste need to be balanced against any detriments resulting from the process of monitoring [1]. Monitoring cables that pass through barriers could affect the confinement performance of the barriers. To achieve the monitoring of geological repository balancing with the detriments from the process of monitoring, RWMC has been developing a series of wireless transmission systems with different sizes of transmission antenna and transmission distances as a collaborative study with ANDRA. The role of a wireless data transmission system to satisfy the balancing with the detriments was discussed in Tanabe et al. (2013) [2] in detail.

2. Development of Wireless Monitoring System

2.1 Frequency of Electromagnetic Waves for Transmission

Wireless communication applications such as radio and television broadcasting use very high frequency (VHF, e.g. 30 MHz) and ultra high frequency electromagnetic waves (UHF, e.g. 3 GHz). However, in media with electromagnetic conductivity, such as rock masses and bentonite, high-frequency electromagnetic waves are excessively attenuated. To avoid this excess attenuation and to perform a long-distance data transmission, the authors have been developing a wireless data transmission system that can be used in media such as rock and bentonite by using a very low frequency (VLF, approximately 10 kHz) electromagnetic wave as the data carrier.

2.2 Concept of Wireless Transmission in Relation to Distance

Three concepts for wireless transmission monitoring of geological disposal have been developed. Some of the key design components are the following:

- Short-range transmission: The transmission distance for this concept is assumed to be less than 20m. The transmitter has a built-in temperature sensor and a connector for external sensors, and is 50 mm in diameter and 130 mm long (Fig.1). Other specifications of the transmitter are described in Suzuki et al. (2012a) [3]. The performance of the transmitter was confirmed in the Callovo-Oxfordian argillites layer in the Meuse / Haute-Marne Underground Research Laboratory (CMHM URL) in France to demonstrate a transmission of 25m through the host rock [4].

- Mid-range transmission: The transmission distance in this concept is less than 100 m. The antenna for the transmission of such distance will have several tens cm in diameter. Figure 2 shows the mid-range transmission antenna for which the performance was confirmed to show a 50m transmission between two tunnels in different levels of the CMHM URL [4], though the steel supports around tunnels have a significant attenuation of VLF electromagnetic waves. The diameter of the antenna is 70 cm.
- Long-range transmission: The transmission distance is greater than one hundred meters. Figure 3 shows the transmission antenna of a square, 3m each side, designed to generate a electromagnetic field, ten-times stronger than the mid-range transmission antenna. Design investigations of an antenna for longer distances (500m c.a.) are currently being performed.

Figure 1: Short-range transmitter

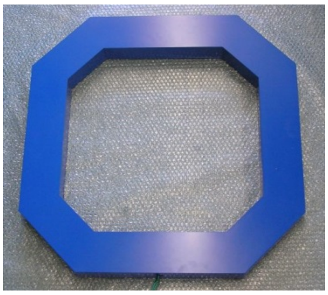

Figure 2: Mid-range transmission antenna

Figure 3: Long-range transmission antenna (prototype)

3. Stepwise Backfill/Sealing of Geological Repository and Arrangement of Wireless Transmission Systems

3.1 Summary of backfilling procedure

Technical requirements for the wireless transmission system will change in accordance with different stages in a stepwise backfill/sealing of geological repository. The concept of geological disposal in Japan (vertical emplacement option) includes vitrified waste, overpack and bentonite buffer, and these components are emplaced into a disposal pit. A number of disposal pits are drilled in a disposal tunnel, and a number of disposal tunnels are connected to main tunnels. A disposal panel consists of these disposal and main tunnels. Separate disposal panels are linked by connecting tunnels (Fig.4a). In the HLW repository, construction, operation and backfilling can be carried out in parallel in separate panels [5]. Backfilling of a panel will start from the backfilling of a disposal tunnel, and installation of a plug between the disposal tunnel and the main tunnel will follow. After the backfilling of all disposal tunnels, the main tunnel will be backfilled. During the stage towards the closure of repository, connecting tunnels and the shaft or ramp to the underground facilities will also be backfilled and closed with plugs.

3.2 Application of Wireless Transmission Systems

In the monitoring of a geological repository, technical requirements for wireless transmission likely will change in accordance with different stages of backfilling/sealing, especially for the requirement of transmission distance, because the size of the transmission antenna and the consumption/supply of energy for the relay transmission will increase with the distance. Combination of different types of transmitter and relay systems is thought to be adaptable to the change of the requirement in transmission situation and distance.

For example, we consider 1) the monitoring of a backfill and plug will be pursued in a geological repository and 2) the monitoring for a bentonite buffer will be pursued in an underground research facility close to a geological repository with a simulated waste.

1) In the former case, the monitoring sensors and transmitters are installed in a backfill and a plug. The data are transmitted to the receiver placed in outside the plug of a disposal panel, during the period that the connecting tunnel is kept open (Fig.4a). The middle-range transmission antennas (Fig.2) will be suitable for the transmission through the plug with a distance of several tens of meters. After the connecting tunnel is partially backfilled, the receiver will probably be placed outside the plug in the connecting tunnel (Fig.4b). A relay system could be applied to transmit data from the receiver R1 to the receiver R2 in the case of fig.4b. The mid-range (Fig.2) or long-range (Fig.3) transmission antennas will be chosen for the transmission between the receiver R1 and the receiver R2 depending on the distance of the two receivers. The development of a relay system is currently underway, and future development of a mesh network system will guarantee the data transmission when malfunction of one receiver occurs. Long-range transmitters may also be applied to transmit data to the ground surface directly. After all the panels are backfilled and sealed by plugs, the data which has been obtained can serve for the decision making procedure of the final closure of the repository.

2) In the latter case, the monitoring sensors and transmitters are installed in a bentonite buffer near a simulated waste package in a disposal pit. The data are transmitted to the receiver placed outside of the plug or in a borehole drilled near the demonstration facility. The development of borehole type receivers was discussed in Suzuki et al. (2013) [6]. The short-range transmitters will be chosen to install in the bentonite buffer because of a tight spatial limitation. If the tunnel outside the plug will be backfilled, the relay system could be applied. The data which have been obtained can serve as input for the decision making process regarding the final closure of the repository.

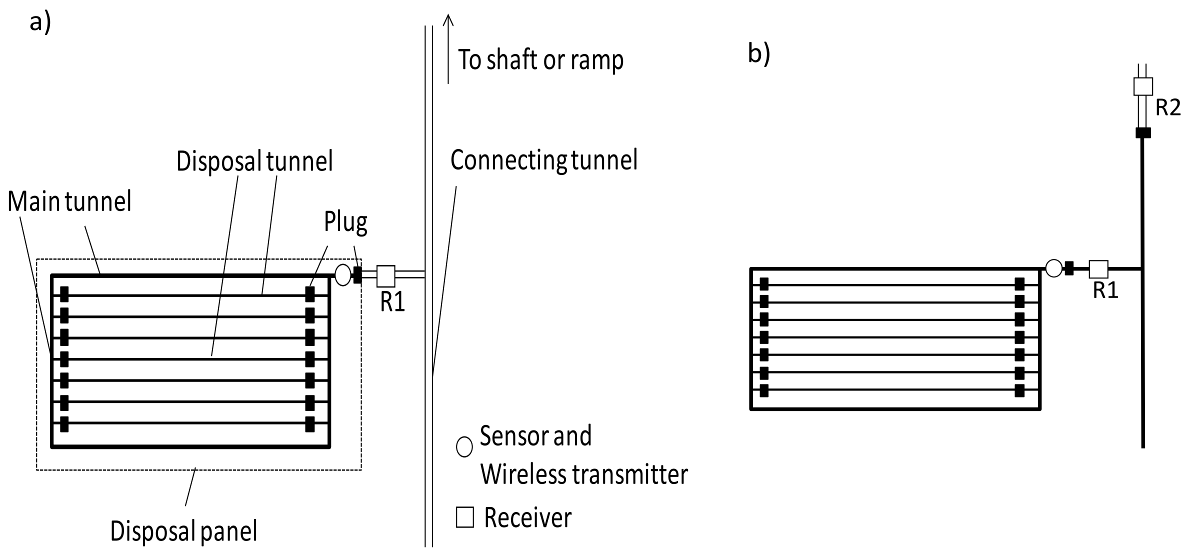

Fig. 4 Schematic example of wireless monitoring at repository

a) Disposal panel: backfilled, connecting tunnel: open

b) Disposal panel: backfilled, connecting tunnel: partially backfilled

5. Conclusion

Technical requirements for wireless transmission for the monitoring of geological repository are thought to change in accordance with a stepwise backfilling and sealing of the repository. Combination of different types of transmitter and relay systems will be a solution to fit into the changing requirements.

6. Acknowledgements

This research and development was partially financed by the Agency of Natural Resources and Energy, the Ministry of Economy, Trade and Industry of Japan (Development of Advanced Engineering of the Disposal System, FY2011 and FY2012).

References

[1] IAEA (2001), Monitoring of geological repositories for high level radioactive waste, TECDOC-1208.

[2] TANABE, et al. (2013). Basic Requirement of Monitoring Activities in Geological Disposal and Role of Wireless Data Transmission, Proceedings of the MoDeRn international repository monitoring conference and workshop, S4P14 (2013).

[3] Suzuki, et al. (2012a). Development of Wireless Data Transmission System for the Monitoring in Geological Disposal of Radioactive Waste, Proceedings of WM2012 Conference, February 26 – March 1, 2012, Phoenix, USA, in CD.

[4] Suzuki, et al. (2012b). Wireless Monitoring Study in the Meuse / Haute-Marne Underground Research Laboratory, France, Ibid, in CD.

[5] NUMO (2008). Geological disposal of radioactive waste in Japan, Jury 2008.

[6] Suzuki, et. al. (2013), Development of miniaturized wireless transmitter and borehole type receiver with low frequency magnetic waves, Proceedings of the MoDeRn international repository monitoring conference and workshop, S4P12.

Basic Requirement of Monitoring Activities in Geological Disposal and Role of Wireless Data Transmission

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Summary
An objective of monitoring to confirm the basis for the post-closure long term safety of the geological disposal of radioactive waste has been considered to play an important role and monitoring should be continued from the development phase through the backfilling/sealing phase of a geological repository. In developing a monitoring system to meet the requirements above, the benefits from gaining data on the behaviour of the system components need to be balanced against any detriments resulting from the process of monitoring. With this in mind, the authors assume as a basic requirement that monitoring activities must not be allowed to damage barrier functions and performance, and have defined the boundary conditions of monitoring at the time before the final closure of the geological repository. This paper also provides a role of a wireless data transmission system to satisfy the basic requirement.

1. Introduction

Geological disposal has been adopted in Japan in order to isolate high-level radioactive wastes from the human environment for more than tens of thousands of years. One of the important principles of geological disposal is that post-closure long term safety is provided by means of engineered and natural barriers; it does not depend on monitoring or institutional controls after the facility has been closed [1]. The main objective of monitoring in a geological repository is to confirm the basis for the long term safety, to support operational safety, to detect any environmental impact and to support nuclear safeguards.
From a technical standpoint, the first objective of monitoring to confirm the basis for the long term safety has been considered to play an important role and monitoring should be continued from development phase through backfilling/sealing phase of the repository. Additionally, there may be strong social pressure to continue monitoring during all phases of geological repository. In developing a monitoring system to meet the needs above, the benefits from gaining data on the behaviour of the system components need to be balanced against any detriments resulting from the process of monitoring. Special attention should be taken when considering monitoring of engineered and natural barriers.
This paper provides a basic requirement of monitoring activities in geological disposal and a role of the wireless data transmission system. The outline of research and development of the wireless data transmission system and its future R&D plan are also explained.

2. Basic requirements for monitoring activities in geological disposal

To provide information for various objectives, monitoring may be required for various phases throughout a geological repository development programme and at various locations in and around the geological repository. In developing monitoring programmes, the benefits from gaining data on the behaviour of the system components need to be balanced against any detriments resulting from the process of monitoring. Potential detriments may include [2]:

(1) radiation doses to personnel carrying out monitoring;

(2) degradation of materials in the repository resulting from delay in putting engineered barriers in place whilst monitoring programmes are completed (potentially leading to incomplete development of engineered barrier design properties);

(3) formation of pathways through the barriers by the installation of monitoring equipment, leading to increased potential for radionuclide migration within or around the repository;

(4) an increased likelihood of human intrusion or adverse impacts by natural or induced processes (e.g. flooding) if repository access is kept open to allow monitoring;

(5) interference with other repository operations.

The formation of potential water pathways, as in (3) above, must be avoided by all means possible in order to build confidence in the long-term safety of the geological disposal concept because it is difficult to apply engineering measures to this problem and particularly difficult to compensate for this disadvantage by other means. With this in mind, the authors assume as a basic requirement that monitoring activities must not be allowed to damage barrier functions and performance [3].

3. Boundary conditions of monitoring at the time before geological repository closure

In order to examine what monitoring parameters should be measured, the authors have defined the boundary conditions of monitoring at the time before geological repository closure as follows. These boundary conditions were defined in consideration of the basic requirements for monitoring described in Chapter 2.

3.1 Engineered barriers

The authors consider that monitoring of engineered barriers of the geological repository should not be performed in the disposal tunnels and can only be performed in main and connecting tunnels that are accessible during the pre-closure phase of the repository (as shown in Fig.1). For the closure phase, the cables of monitoring that may help form water pathways must be removed.

If information gained from monitoring of engineered barriers is needed, a demonstration facility (DF), ex. a proto-type repository or a pilot facility, situated in or beside an underground rock characterization facility (URCF), ex. ONKALO, where simulated waste packages with heaters, etc., are emplaced, should be constructed in a separate location away from the actual waste emplacement area, and monitoring of engineered barriers in a simulated disposal tunnel should be performed at this facility. Monitoring will be discontinued after the repository closure since the access tunnel cables that may aid water pathway formation must be removed from the geological repository at the closure phase (see the left in Fig. 2).

If information gained from the monitoring of engineered barriers and waste packages is needed, DF where actual waste packages are emplaced, should be constructed and monitoring should be performed at URCF to gain such necessary information (see the right in Fig. 2). In this case, sensors and cables in the disposal tunnels must be removed after monitoring. Then, waste packages will be retrieved and will be emplaced again with an intact bentonite buffer and the simulated disposal tunnels will be backfilled. At the following repository closure phase, the waste packages in DF will be incorporated in the geological repository if this action is in compliance with the regulatory licensing process.

3.2 Natural barriers

Monitoring of the geological media can be conducted using boreholes that have already been excavated and used in preliminary and detailed investigation phases, in order to prevent a decline in barrier functions and performance. Non-intrusive monitoring, such as geophysical exploration methods, can generally be carried out from the surface and in the underground at any time. Near-field monitoring at an underground facility, should also be performed under the same conditions described in 3.1, including DF and/or URCF.

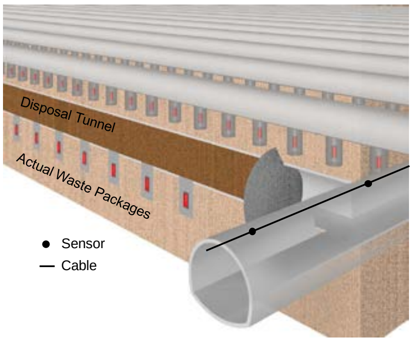

Figure.1: Pre-closure monitoring in geological repository with wired data transmission system

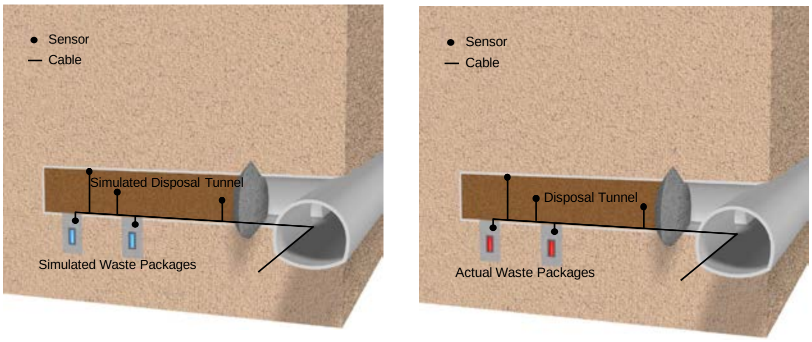

Figure.2:Pre-closure monitoring in DF with wired data transmission system (left; emplacement of simulated waste packages, right; emplacement of actual waste packages

4. Effect of a Wireless Data Transmission System on boundary conditions of geological repository monitoring

The authors have been developing a wireless data transmission system for a geological repository.

An advantage of the wireless data transmission system is that cables which increase the potential for water pathways are not needed. On the other hand, there are disadvantages compared with wired data transmission system such as the limited data transmission distance, the low data transmission rate, and the need to consider battery life in addition to the service life of the measuring instruments (sensors). If these issues of the wireless data transmission system would be solved, the boundary conditions of geological repository monitoring mentioned above could be drastically altered.

By applying the wireless data transmission system, monitoring may be performed for backfill and plugs apart from waste packages in the actual repository area even after the seal of disposal tunnels, main tunnels and a part of connecting tunnels (as shown in Fig. 3). However, the authors consider the monitoring should not be performed for the bentonite buffer near waste packages in the disposal tunnels to avoid to damage of barrier functions and performance. If the data of bentonite buffer and backfill near waste packages is needed, it could be monitored by a wireless data transmission system in DF with little disturbance of buffer and backfill performance (see the left in Fig. 4). Even if an actual waste package needs to be emplaced and bentonite buffer and backfill is monitored, the waste packages in DF might be incorporated in the geological repository without retrieval and re-emplacement, if this action is in compliance with the regulatory licensing process (see the right in Fig. 4). In Fig. 4, it is shown that sensors are also installed in a plug, and all data is transmitted to borehole type receivers settled in a borehole as an example.

So as to improve the applicability of the wireless data transmission systems, RWMC has been promoting a stepwise R&D plan. The first stage of the development mainly consists of four items, A) Development of a miniaturized transmitter which has high resistance to pressure,

B) Development of a borehole-type receiving antenna, C) Evaluation of a possibility of long distance transmission, and D) Development of a relay system [4], [5].

Over the following years, continuous development of the wireless data transmission system will keep on improving its applicability. In the future, wireless data transmission systems are expected to provide effective tools that should be considered in any discussion of monitoring when building consensus among the public.

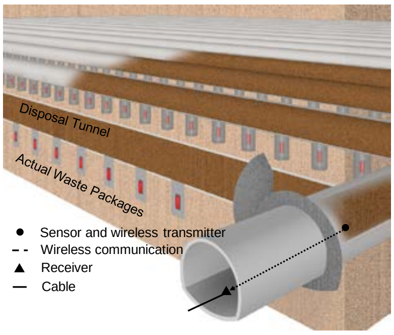

Figure.3: Pre-closure monitoring in geological repository with wireless data

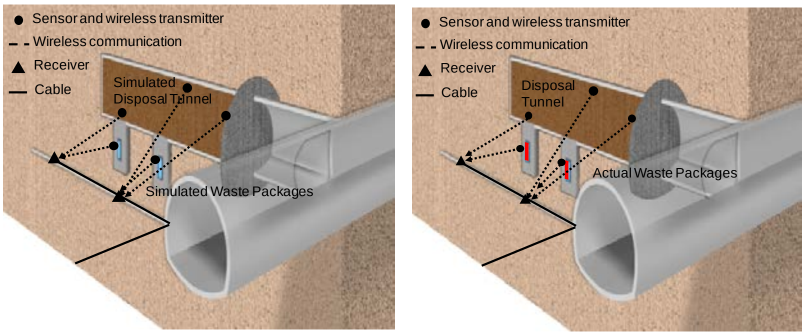

Figure.4: Pre-closure monitoring in DF with wireless data transmission system (left; emplacement of simulated waste packages, right; emplacement of actual waste packages

5. Conclusion

An objective of monitoring to confirm the basis for the long term safety has been considered to play an important role and monitoring should be continued from the development phase through the backfilling/sealing phase of the geological repository. In developing a monitoring system to meet the requirements above, the benefits from gaining data on the behaviour of the system components need to be balanced against any detriments resulting from the process of monitoring. With this in mind, the authors have been studying a possible strategy for the implementation of a monitoring system. The main conclusions can be summarized as follows.

- The authors assume as a basic requirement that monitoring activities must not be allowed to damage barrier functions and performance, and have defined the boundary conditions of monitoring at the time before geological repository closure.
- A role of the wireless data transmission system to satisfy the basic requirement is provided in this study. In the future, a wireless data transmission system is expected to provide effective tools and information that should be considered in any discussion of monitoring when building consensus among the public.

6. Acknowledgements

This research and development was financed by the Agency of Natural Resources and Energy of the Ministry of Economy, Trade and Industry of Japan (Development of Advanced Engineering of the Disposal System, FY2011).

References

[1] International Atomic Energy Agency, Geological disposal of radioactive waste, IAEA Safety Standards Series No. WS-R-4 (2006).

[2] International Atomic Energy Agency, Monitoring of geological repositories for high level radioactive waste, IAEA-TECDOC-1208 (2001).

[3] Suyama, et. al., Study on a monitoring strategy to support decision making for geological repository closure, Journal of Nuclear Fuel Cycle and Environment, Vol.17 No.2 (2010).

[4] Eto, et. al., Development of wireless monitoring system for stepwise backfill/sealing of geological repository, Proceedings of the MoDeRn international repository monitoring conference and workshop, S4P13 (2013).

[5] Suzuki, et. al., Development of miniaturized wireless transmitter and borehole type receiver with low frequency magnetic waves, Ibid, S4P12 (2013).

The Application of DIC to Detect Potential Onset of Micro-cracking in the Concrete Buffer of the Supercontainer

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Summary
The Supercontainer is the Belgian reference concept for the packaging of vitrified high-level radioactive waste (HLW) and spent fuel. In a previous test performed to evaluate its construction feasibility, micro-cracks developed on the surface of the concrete buffer. The surficial nature of the micro-cracks should neither jeopardize the functionality nor the safety of the Supercontainer. However, through-going cracks should be avoided as they can create preferential pathways for the migration of aggressive species.
This paper presents the results of a test performed to evaluate the suitability of using Digital Image Correlation (DIC) to detect the onset of micro-cracking in the concrete buffer. Preliminary tests showed that the DIC method can measure micro-cracks with a crack opening resolution of approximately 12.5 microns, which is sufficiently small to detect the formation of potential micro-cracks in the concrete buffer of the Supercontainer.

1. Introduction

The Supercontainer is the reference concept proposed by ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, for the packaging of high-level radioactive waste (HLW) and spent fuel [1, 2]. Its conceptual design appears in Figure 1. It is based on a multiple barrier system that includes an outer steel envelope, a concrete buffer and a water-tight carbon steel overpack containing one or more waste canisters. The concrete buffer has a thickness of 54 to 70 cm (depending on the waste to be placed in the Supercontainer) and completely surrounds the overpack. The long-term safety function of the overpack is to contain the radionuclides during the thermal phase, which will last several thousands of years.
ONDRAF/NIRAS is presently evaluating the feasibility to construct the Supercontainer. Part of this evaluation includes experimental testing using half-scale models [3] of the Supercontainer. The half-scale tests use the real diameter of 2.1 m of a Supercontainer while its height is reduced to 3.5 m, which is approximately half of the height of a real Supercontainer.
Research focused on the early age behaviour of the phase 1 concrete buffer indicates that the risk of cracking of the outer buffer during the early age is low [4]. However, micro-cracking was observed in a previous half-scale test. A new test being planned will use DIC to verify

these findings and to learn more about the origin and development of micro-cracks in the concrete buffer.

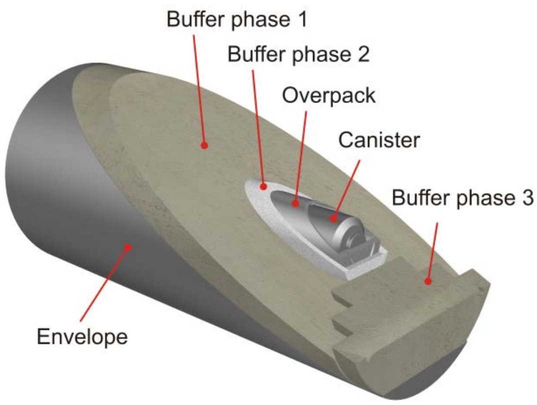

Figure 1: Belgian Supercontainer concept

2. DIC overview

DIC is a full-field image analysis method, based on grey value digital images, that can determine the contour and displacements of an object under load in three dimensions [5, 6, 7]. Three-dimensional digital image correlation uses two digital cameras to view a test subject and determine its location and shape in space. The technology is a combination of single camera image correlation and two camera photogrammetry. Photogrammetry is a measurement technology in which the three-dimensional coordinates of points on an object are determined by measurements made in two or more photographic images taken from different positions. In practice, a random high contrast digital pattern is fixed on the surface of the test object to supply a grid of unique points to correlate. This pattern then deforms or moves along with the object. The deformation under different load conditions is recorded by the digital cameras and then evaluated by specially designed software. Figure 2 shows a typical DIC setup.

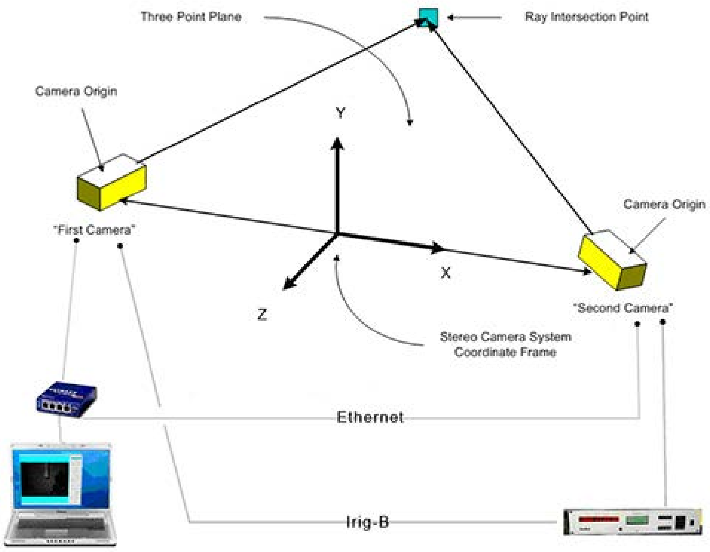

Figure 2: Typical DIC setup

The initial image processing involves defining a unique correlation area known as the area of interest (AOI) across the imaging area. The size of the AOI varies according to the surface one wants to monitor. Usually the first image is taken in a non-deformed state while subsequent images are taken at different load stages. These facets are tracked in each successive image with sub-pixel accuracy. Sub-pixels are separately addressed elements of a pixel. To attain tracking with sub-pixel resolution, an image-based tracking algorithm is used. Then, using photogrammetric principles the 3D coordinates of the entire surface of the specimen are precisely calculated. The results are the 3D shape of the component, the 3D displacements and the plane strain tensor.

3. Test setup

Generally, the grey digital image pattern is printed on a plastic film and subsequently glued onto the surface of the AOI of the object. In the case of the concrete buffer, gluing the image on the concrete surface after the first hours following concrete casting is not possible due to the presence of free moisture in the concrete surface. The moisture prevents the glue from adhering to the wet concrete surface. To solve this problem, a technique was developed whereby the digital pattern is projected directly onto the concrete surface without the need to glue it. This technique was tested on a reinforced concrete beam, as shown in Figure 3. The beam was loaded to failure on a four point bending test to determine the crack-opening resolution of the DIC system.

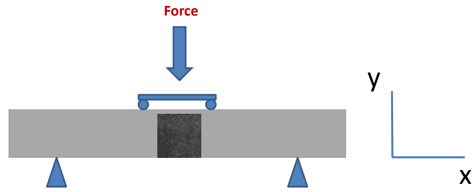

Figure 3: Four point bending test on reinforced steel beam with 30cmx30cm digital pattern directly sprayed onto concrete surface

4. Results

Contour plots of the displacement in the horizontal X-direction for three different times appear in Figure 4. They correspond to three moments in time represented by images numbered 176, 268 and 297, respectively taken during the test. The contours clearly show the development and propagation of two major sets of vertical cracks across the beam.

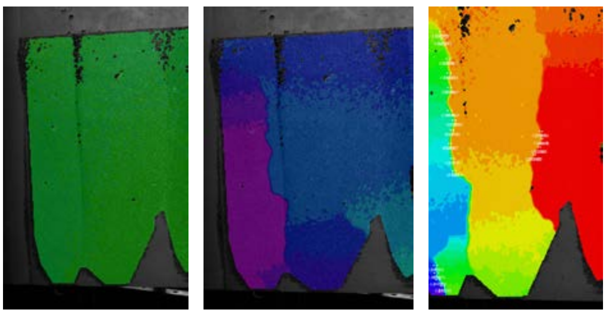

Image 176 268 297

Figure 4: Contour plots showing displacements in the X-direction as a function of time

Figure 5 shows the displacement for the total of 297 images taken during the test. The results indicate two distinct trends of X-displacement as a function of time represented here by an increase in the number of captured pictures taken during the test. The first part of the test, represented by the first 176 pictures, shows a relatively small and linear rate of displacement. After picture 176, however the rate of displacement increases exponentially. This point corresponds to approximately 12.5 µm, which also corresponds to the resolution of the DIC measurements for this setup. This resolution is sufficiently high to detect the onset of micro cracks in the concrete buffer.

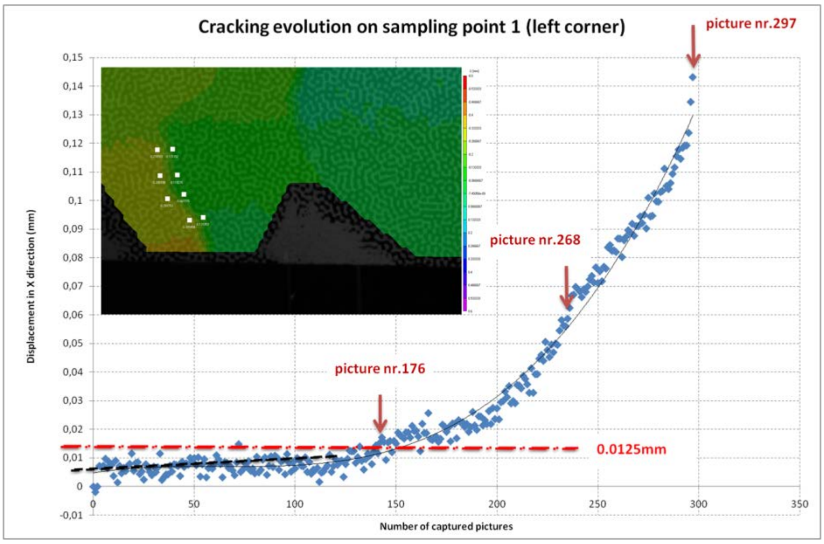

Figure 7: Crack evolution measured at point 1 of the digital pattern

5. Conclusions

Tests performed to evaluate the feasibility of using the DIC technique to monitor the onset and progression of potential micro-cracks in the concrete buffer of the Belgian Supercontainer indicate that DIC is a suitable technique to monitor the evolution of micro-cracks at the surface of the concrete buffer. In particular, the tests successfully demonstrated the possibility of applying the AOI digital pattern at the early stages of curing using a spray-on technique. This avoids the problems associated with the lack of adhesion when gluing the digital image on a wet concrete surface. The test results further indicate a crack-opening resolution of approximately 12.5 µm for DIC measurements, which is sufficient high to detect the onset of potential micro-cracks in the concrete buffer of the Supercontainer.

References

[1] ONDRAF/NIRAS (2009), "The Long-Term Safety Strategy for the Geological Disposal of Radioactive Waste," ONDRAF/NIRAS report NIROND-TR 2009-14 E.

[2] ONDRAF/NIRAS (2010), "Feasibility strategy and Feasibility Assessment Methodology for the geological disposal of radioactive waste," ONDRAF/NIRAS report NIROND-TR 2010-19 E.

[3] Lou Areias, Bart Craeye, Geert De Schutter, H Van Humbeeck, W Wacquier, L Villers and A Van Cotthem, (2010) “Half-scale test: an important step to demonstrate the

feasibility of the Belgian super container concept for disposal of HLW" Proceedings of the 13th international conference on environmental remediation and radioactive waste management.2.p.287-296.

[4] Bart Craeye (2010) "Early-Age Thermo-Mechanical Behaviour of Concrete Supercontainers for Radwaste Disposal" PhD thesis, University of Ghent.

[5] Vasilakos, I., Belkassem, B., Sol, H., Verbert, J., Duflou, J. (2009), "Study of deformation phenomena in Single Point Incremental Forming by means of Digital Image Correlation technique", Optical Measurement Techniques for Structures and Systems, pp. 379-388

[6] Lecompte D., (2007) "Elasto-plastic material parameter identification by inverse modeling of static tests using digital image correlation", PhD thesis, VUB.

[7] D. Lecompte, S Cooreman, S. Coppieters, J. Vantomme, H. Sol, D Debruyne (2009) 'Parameter identification for anisotropic plasticity model using digital image correlation: Comparison between uni-axial and bi-axial tensile testing,' Revue Européene de Mechanique Numerique, Vol 18/3, April 2009, pages 393-418.

Measurements in Prototype Repository Test at Äspö HRL

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Summary

Since 2001 the Prototype Repository at Äspö Hard Rock Laboratory has been carried out as a large-scale experimental installation of the KBS-3 Swedish/Finnish concept for final disposal of spent nuclear fuel. The Prototype Repository consists of a total of six full-scale deposition holes with a centre distance of 6 m, located in a TBM tunnel at a depth of 450 m. Each deposition hole is fitted with a full-scale bentonite buffer, consisting of altogether 14 blocks and a full-scale canister, Figure 1. The canisters are equipped with heaters to simulate the heat from spent nuclear fuel. There are two sections of the installation; The inner Section (I) consisting of four deposition holes (no. 1-4) with buffer and canister, and the outer Section (II) consisting of two deposition holes (no.5-6). The deposition tunnel is filled with a mixture of crushed rock and bentonite (30% of bentonite). A massive concrete plug, designed to withstand full water and swelling pressures from the backfill of the deposition tunnel, separates the test area from the open tunnel system and a second plug separates the two sections.

This layout provides two more or less independent test sections. The outer section was retrieved during 2011. Sensors were installed both in the rock, backfill and buffer for measuring various parameters. Altogether more than 750 sensors were installed. In November 2010 when the dismantling of the outer section started about 350 of the installed sensors still giving reliable readings.

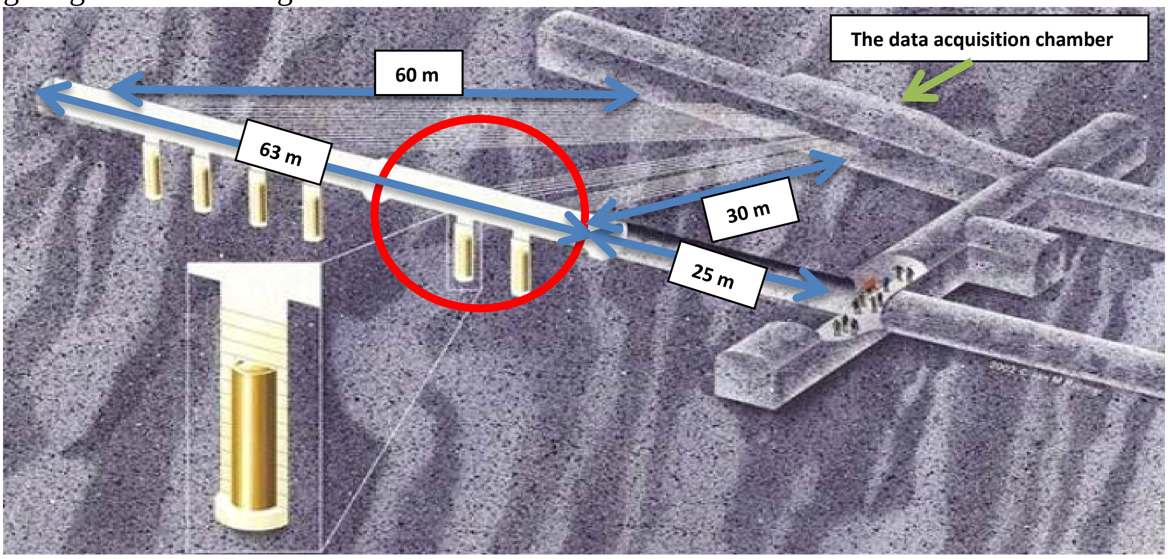

Figure 1: Schematic view of the layout of the Prototype Repository (the outer section II marked red).

At the dismantling of the outer section, some of the installed sensors were retrieved. These sensors were investigated and checked. Although the amount of retrieved sensors is limited compared to the number of installed sensors this investigation might give hint of which type of sensors are suitable for this type of measurements. Investigation and recalibrating of the sensors after dismantling is on-going.

1. Introduction

This paper describes the monitoring in Prototype Repository Test at Äspö HRL in Sweden. The instruments, data acquisition system and reliability of the sensors in both sections are briefly described.

The Prototype Repository Test was installed in 2001 and 2003 and consists of two sections that can be dismantled and excavated at different times since they are separated by a plug. Section II was dismantled and excavated in 2011 in order to study the situation after 10 years while section I will remain running for another about 10 years. Section I consists of four full-scale deposition holes, copper canisters equipped with electrical heaters, bentonite blocks and a deposition tunnel backfilled with a mixture of bentonite and crushed rock and ends with a concrete plug as shown in Figure 2. Section II consists of two full-scale deposition holes with a backfilled tunnel section and ends also with a concrete plug, but is otherwise identical to Section I.

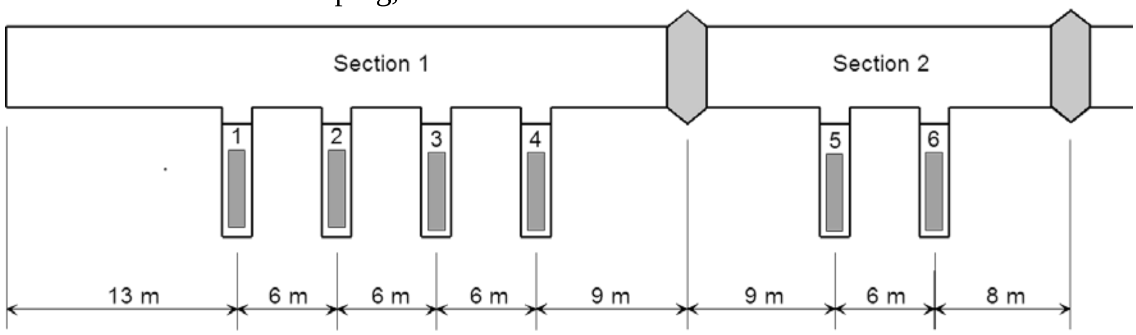

Figure 2. Schematic view of the Prototype Repository.

The bentonite buffer in deposition holes 1, 3, 5 and 6, the backfill and the surrounding rock are instrumented with gauges for measuring temperature, water pressure, total pressure, relative humidity, and electrical resistivity. Furthermore the displacement of the canisters in deposition holes 3 and 6 is measured. The temperature is measured on the surface of all the canisters on every meter in length with the use of fibre optic cables. The instruments are connected to data collection systems by cables protected by tubes, which are led through the rock in watertight lead throughs.

Sensors are installed in the surrounding rock for measuring temperature, water pressure and stress and strains in the rock mass. The relative humidity is also measured in the rock close the surface of the deposition hole 6.

In addition to those instruments there are geo-electric measurements in the backfill (by GRS) and acoustic emission measurement in the rock (by ACS).

The challenge at the installation of the sensors was to try to ensure that both the sensors and the cables could withstand the water pressure, the swelling pressure from the buffer and backfill and high temperatures during the trial period of up to 20 years, which is planned for Section 1. Another difficulty was the large cable lengths (up to 105 m) used in the test. All the cables were drawn trough the rock (30m-60 m) to a nearby tunnel where the data acquisition system was situated see Figure 1.

2. Brief description of the instruments

The strategy in the selection of type of sensors used in the test was to use at least two different suppliers and if possible also different techniques of each type of measurements in order to avoid that systematic errors and defects should hazard all measurements of a parameter i.e. the measurements of pore pressure. Furthermore it was important that the sensors could withstand the expected water pressure, swelling pressure and high temperatures. The instruments used in the buffer, backfill and rock (temperature) are briefly described in the sections below.

2.1 Measurements of temperature

Buffer, backfill and rock

Thermocouples are used for measuring the temperature. In addition to the thermocouples, there are also parallel measurements of temperature in other measurements e.g. in the vibrating wire sensors for measuring total pressure and pore pressure and in the relative humidity sensors

Canister

Temperature is measured on the surface of the canister with optical fiber cables, installed in several loops on the surface of the canisters. An optical measuring system called FTR (Fiber Temperature Laser Radar) is used. In Section II also three thermocouples of type PT100 are installed on each of the canister (No 5 and 6).

2.2 Measurement of total pressure in the buffer and backfill

The total pressure in the buffer and backfill is measured with the following two types of sensors:

- Total pressure cells with vibrating wire transducers (Geokon).
- Total pressure cells with piezo resistive transducers (Kulite).

Both types of sensors were manufactured in titanium. In order to protect the electrical cables to the sensors from the expected high swelling and water pressures they were lead trough tubes of titanium in the bentonite in the deposition holes. The titanium tubes were welded to the sensor. In the backfill and trough the rock towards the nearby tunnel the cables were protected with polyamide tubes. The positions of the lead throughs are shown in Figure 1. [1]

2.3 Measurement of pore water pressure in the buffer and backfill

Pore water pressure is measured with the following instrument types:

- Pore pressure cells with vibrating wire transducer (Geokon).
- Pore pressure cells with piezo resistive transducer (Kulite).

The encapsulation and the protection of the cables were made in the same way as for the total pressure sensors. Furthermore titanium filters were used on the tip of the sensors to ensure that only water pressure is acting on the membrane of the sensors.

2.4 Measurement of the water saturation process in the buffer and backfill

The water saturation process is recorded by measuring the relative humidity in the pore system of both the buffer and the backfill. The measured relative humidity can be converted to total suction (negative water pressure), which is related to the degree of water saturation and the swelling pressure. When the materials are fully saturated, the sensors are measuring 100% RH and when free water is accumulated in the sensors, they stop giving reliable values.

The following techniques and devices are used:

- Relative humidity sensor of capacitive type (Vaisala and Rotronic). The measuring range is 0-100 % RH. These measuring devices were encapsulated in titanium. One difference between Rotronic and Vaisala is that the Vaisala instruments have a maximum allowed length of cable from the sensor to an electronic box of 10 m. In order to protect the electronic box from high pore and swelling pressures it was built in to a vessel, which was placed in the backfill.
- Wescor soil psychrometer. Two methods have been developed for this equipment. These are the psychrometrics (wet bulb) and the hygrometric (dew point) methods. Psychrometrics (wet bulb) method is used for measurement of suction in Prototype Test. The measuring range is 95.5-99.6 %

RH which corresponds to a suction of –0.5 to –6 MPa. Psychrometers were placed in the backfill in both sections and in the buffer in the two deposition holes in Section II.

3. Data acquisition system

Data scan intelligent units and Campbell logger are used for collecting the data from the installed sensors in the Prototype Repository. The instruments are connected to data collection systems by cables protected by tubes, which are led through the rock in watertight lead throughs. A PC is communicating with the data scan system.

A software, Orchestrator (SCADAPRO), is used for storage and presentation of measured results.

The raw data stored with Orchestrator are checked, processed and (for some data) converted to calibrated values every month. The results are presented as plots and checked for overload, underload, abnormal noise, drift, stuck-at, bias and loss.

Some failures have been caused by problem with data scan units or Campbell loggers that had to be placed outside the data acquisition chamber due to cable length restrictions. The humid environment in the tunnel is the main reason for those failures.

The measured raw data can also be check directly with online plot in the PC by the software. The alarm function in the software is used for detecting failure of the heater power in the experiments. An alarm is sent to the staff at Äspö HRL if the power is below or above certain limits.

4. Reliability of the sensors

In Section I

At present about 261 (excluding water pressure sensors in the rock and the displacement sensors for the canister) out of totally 363 installed sensors are out of order. In Figure 3 the numbers of still working sensors in the buffer and the backfill of section I are plotted as function of time from start of the test in the Section I at September 2001. The figure shows that the majority of the broken sensors are RH-sensors and thermocouples (in deposition hole 3). In the beginning of November 2004 the drainage of the inner part of section I and the drainage through the outer plug were closed. The figure shows that the numbers of broken sensors increased after the closing of the drainage of the tunnel in the beginning of November 2004. [2]

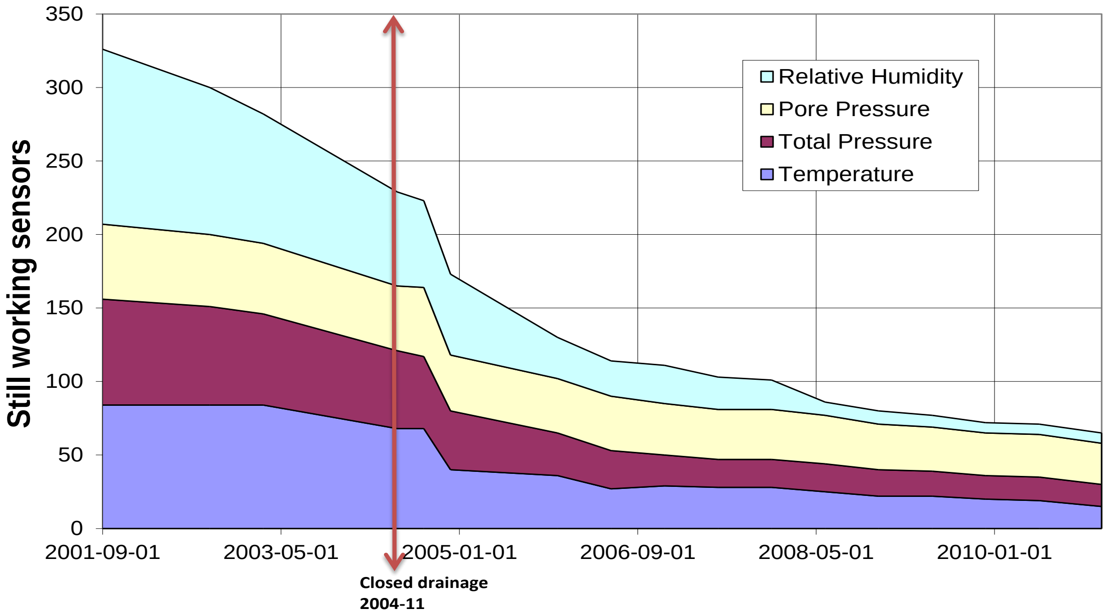

Figure 3: The number of still working sensors placed in the buffer and backfill in Section 1 as function of time. The coloured fields represent the four types of installed sensors.

In Section II

At present about 142 (excluding water pressure sensors in the rock and the displacement sensors for the canister) out of totally 394 installed sensors are out of order. In Figure 4 the numbers of still working sensors in the backfill and the buffer of section II at start dismantling are plotted as function of time from the start of test in the section, May 2003. The figure shows that the majority of the broken sensors are RH-sensors and that the numbers of broken sensors increased after the closing of the drainage of the tunnel.

The measured processes in the buffer and the backfill were slow until about 20 days after the drainage of the tunnel was closed. Very small changes of the measured parameters have occurred up to that date. After that the readings from some of the total and pore pressure sensors placed in the buffer have reacted strongly (quick increase in pressure). Also the total and pore pressure sensors placed in the backfill have recorded high pressures caused by the closing of the drainage. [2]
After dismantling of section II the retrieved sensors are checked and recalibrated. Investigation and recalibrating of the sensors after dismantling are still ongoing but will briefly be commented in the next section.

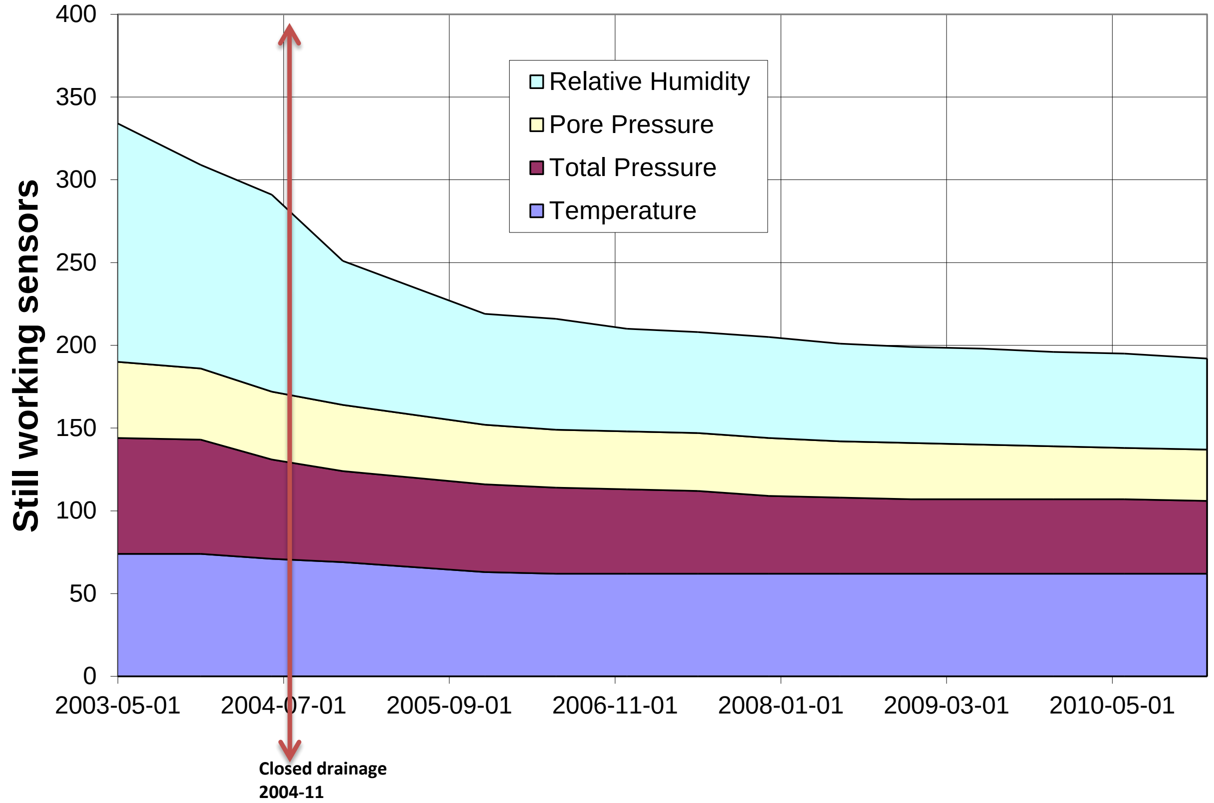

Figure 4: The numbers of still working sensors placed in the buffer and backfill in Section 2 as function of time. The coloured fields are representing the four types of installed sensors.

5. Recalibration and investigation of sensors after dismantling

The main priority at the dismantling of the outer section was to take large number samples of the bentonite as soon as possible for analyses. A core drill was therefore used at the dismantling and many of the sensors were thereby damaged. Some of the installed sensors were randomly retrieved. These sensors were investigated and checked. Although the amount of retrieved sensors is limited compared to the number of installed sensors this investigation might give a hint of which type of sensors are suitable for this type of measurements. Investigation of total pressure sensors shows that the displacement of the buffer during the experiment has affected many of the sensors, since the welds to the sensors and the tube are sensitive to movements. These welds were broken in many of the Geokon total pressure sensors. The electronic boxes for the relative humidity sensors of type Vaisala showed damages caused by water entered the devices. No damages were observed on the Wescor soil psychrometers. Investigation and recalibrating of the sensors is still on-going.

6. Conclusion

A general conclusion is that the measuring systems work well, but sensors successively tend to fail probably due to water leakage to the devices through the damaged weld and connection to tube after closing the drainage. 261 of the 363 installed sensors in section I (excluding water pressure sensors in the rock, geo-electric measurements) are out of order, the majority (75 of 119) being RH-sensors that fail at water saturation.
142 of the 394 installed sensors in Section II (excluding water pressure sensors in the rock, geo-electric measurements, stress and strain in the rock and displacement of canister) were

out of order at the start of dismantling. Furthermore almost all suction sensors placed in the backfill are not giving reliable values due to high degree of saturation (RH 100%).
The drainages of the inner section together with the drainage of the outer plug were closed at the beginning of November 2004. The pressure (pore pressure and total pressure) in the backfill and in some parts of the buffer in the six deposition holes increased after this date. The number of broken sensors increased after this quick increasing of the pressure.
The degree of water saturation of backfill in Section II was higher than in Section I before closing of drainage in the beginning of November 2004. This may be the main reason that fewer sensors were damaged in Section II compare to Section I. The higher water saturation of the bentonite has probably functioned as isolation to protect the sensors from high water pressure after closing the drainage.

References

[1] L Börgesson, D Gunnarsson, L-E Jaohannesson, T Sanden (2002), Prototype Repository-Installation of buffer, canisters, backfill and instruments in Section I

[2] R Goudarzi (2012), Prototype Repository-Sensor data report no 24

Development of optical fiber vibration sensors based on light polarization properties

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Summary
Our work consisted in developing point and quasi-distributed vibration sensors based on the use of an optical fiber and using the light polarization properties as the measurand. A point sensor, measuring the vibrations at one position, is first presented. This sensor can measure accelerations up to 140 m/s^2 with limited distortions, with a sensitivity equal to 9.98 mV/(m/s^2)). A quasi-distributed sensor, measuring the vibrations at several sensing positions, is then presented. It will also be shown that these two sensors are based on the use of a mechanical transducer, which crushes the optical fiber over a 3 mm length when subject to a vibration.

1. Introduction

Vibrations are of high importance as they are a health and ageing indicator of civil structures (bridges, buildings, dams, for instance) and industrial machines (e.g. rotating machines). Monitoring vibrations allows to prevent damages and avoid serious consequences such as collapses and possible injuries. Many kinds of vibration sensors are commercially available and are mainly based on mechanical sensors. However, optical fiber vibration sensors have several advantages, inherent to the use of the fiber: they can provide quasi-distributed (multi-point) and distributed (continuous) information along the fiber with only one interrogating element. They are also usable in harsh environments, in which conventional sensors cannot be used, such as electromagnetically-disturbed, humid, nuclear and high temperature media. This paper focuses on the development of a point and a quasi-distributed sensor based on the state of polarization (SOP). This optical parameter has some advantages such as its sensitivity to external perturbations, the setup simplicity and the transduction efficiency. The general working principle of a polarimetric sensor is explained in Section 2. Sections 3 and 4 are dedicated to the development of the point and the quasi-distributed sensors, respectively. The last section is devoted to practical aspects and to the performances.

2. Working principle of a polarimetric sensor

A singlemode optical fiber allows the propagation of two degenerate modes with orthogonal polarizations [1]. This degeneracy only happens if the fiber is perfectly circular, which is not the case in practice as the core can be slightly elliptical and can also contain stress. This degeneracy is removed and for a particular pair of two orthogonal polarization states (*eigenmodes*), a difference between their refractive indices is introduced, which is called *birefringence*. This *birefringence* corresponds to a difference in the velocities of these eigenmodes and then to a difference in their propagation time. This has for effect to modify the light polarization state [1]. In our sensors, a vibration has for effect to modify the birefringence properties of the fiber, via the crushing of the fiber, using the transducer depicted in Fig. 1.

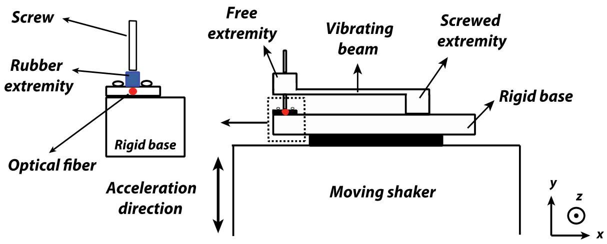


Figure 1: Mechanical transducer used to transform the mechanical perturbation into a birefringence modification

This MT is made of a rigid base and a vibrating beam. The base is screwed on the vibration source (shaker) while the beam is free to move at one of its ends (the other extremity is screwed on the base). A second screw, whose edge is covered with rubber and is in contact with the fiber, is placed at this free extremity. Note that the direction of this second screw is transversal to the fiber propagation axis *z*. When the shaker vibrates perpendicularly to this propagation axis, the inertia of the vibrating beam, via the presence of the second screw, induces a crushing of the fiber and modifies the birefringence, which in turn induces an SOP modification [1].

3. Development of a point polarimetric sensor [3]

The developed point polarimetric vibration sensor is schematically depicted in Fig. 2.

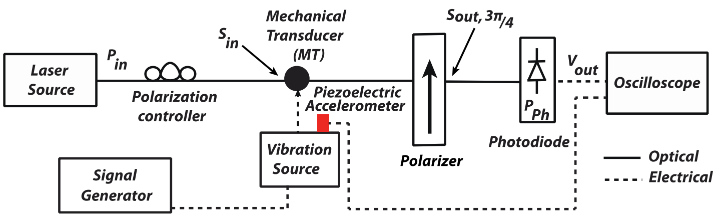
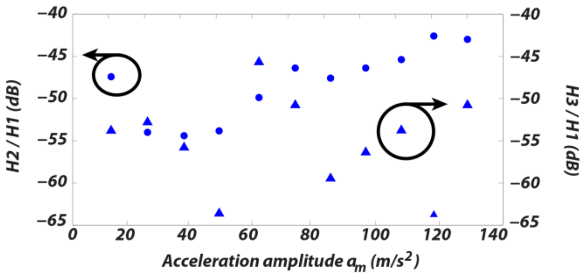


Figure 2: Experimental setup of the proposed point sensor (plain lines: optical links, dashed lines: electrical links)

Its working principle is as follows: light, with a power P_{in}, is emitted from a narrowband laser (in the experiments, its linewidth is 10 pm) and is launched in the fibre through a polarization controller, which allows us to change the input SOP. Light propagates in the fibre and reaches the mechanical transducer, which modifies the birefringence properties, as explained in Section 2. This has for effect to modify the light SOP to the rhythm of the vibration. Light then reaches a linear polarizer oriented at 3π/4 radians with respect to the reference horizontal *x* axis. As the light SOP is varying and as the polarizer axis is fixed, the transmitted power is then varying. This varying power is then converted in a varying voltage V_{out} by a photodiode. It can be shown mathematically [3] that the relation between the voltage and the applied acceleration is nonlinear and that applying a sine vibration with a frequency *f* leads to contributions at *f*, 2*f*, 3*f*…, resulting in distortions. These distortions depend, among others, on the acceleration level and on the input SOP. In the experiments, in order to have distortions as weak as possible, we change the polarization controller so that the peak-to-peak value of the AC part of the output voltage is maximal. Using this SOP, Fig. 3(a) and (b) show the evolution of the ratios H_2/H_1 and H_3/H_1 as a function of the acceleration level, up to 140 m/s^2 and the evolution of the peak value of the AC voltage as a function of the acceleration level, respectively. From Fig. 3(a), we can see that the ratios H_2/H_1 and H_3/H_1 stay below 1% (-40 dB), which means that the distortions are weak compared to the fundamental, even at an acceleration level of 140 m/s^2. From Fig. 3(b), we see that the peak value linearly increases as a function of the acceleration level, with a sensitivity equal to 9.98 $mV/(m/s^2)$.



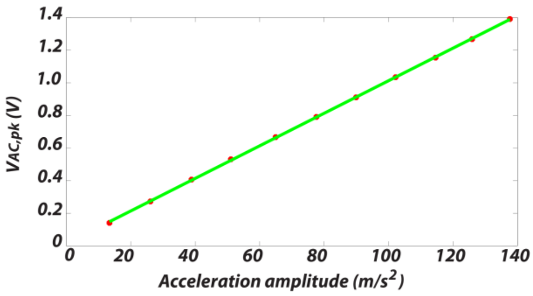


Figure 3: Evolution of the ratios H_2/H_1 and H_3/H_1 as a function of the acceleration level (a); Evolution of the peak value of the AC voltage as a function of the acceleration level (b).

4. Development of a quasi-distributed polarimetric sensor [4]

The quasi-distributed sensor is depicted in Fig. 4. Light is now emitted from a broadband source (here, an Amplified Spontaneous Emission (ASE) source) and is launched into the fibre under test (FUT) through a circulator and a polarizer, which fixes the input SOP. During its propagation along the FUT, considering the case of N=3 sensors, the lightwave is successively reflected by 6 FBGs with different Bragg wavelengths λ_{ij} (i=1, ..., N, depending on which sensor is considered and j=1,2, depending on the position of the FBG within the sensor).

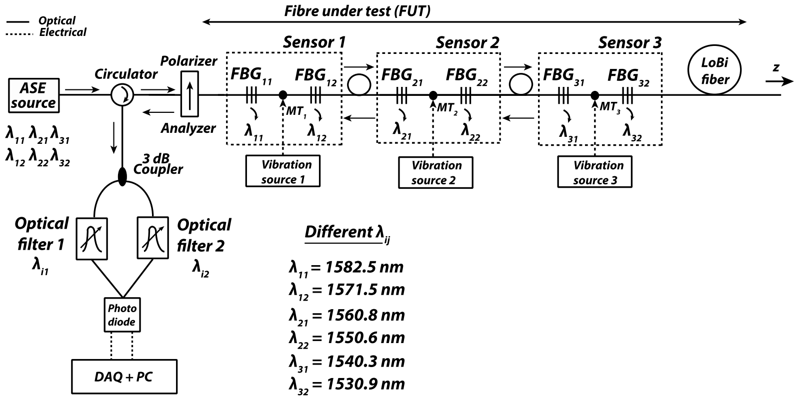


Figure. 4: Experimental setup of the quasi-distributed sensor (plain lines: optical links, dashed lines: electrical links)

As shown in this figure, these FBGs are placed in pairs around one MT (described in Section 2), constituting one sensor S_i (i=1,..., N), which crushes the optical fibre, modifies the birefringence and in turn changes the SOP. The reflected signals are guided back to the polarizer, which transforms the SOP variations into power variations. These contributions are splitted by a 3dB coupler and reach two tuneable optical filters, which are adjusted so as to select the signals reflected at λ_{i1} and λ_{i2}. The contributions are electrically converted, acquired with a data acquisition card (DAQ) and displayed on a PC. It can be shown that the present sensor can measure vibrations in a quasi-distributed manner. Fig. 5 shows the magnitude spectra of the signals guided back from FBG_{31} and FBG_{32} when a 300 Hz sine vibration is applied on MT_1, a 240 Hz and a 175 Hz sine vibrations are applied on MT_2 and a 110 Hz and a 300 Hz are applied on MT_3. We can see that these two spectra have contributions at the frequencies applied on MT_3 (110 Hz and 300 Hz) but also at 240 Hz and 175 Hz, which are applied on MT_2. Comparing these two spectra, it is only possible to deduce the presence of the 110 Hz sine vibration.

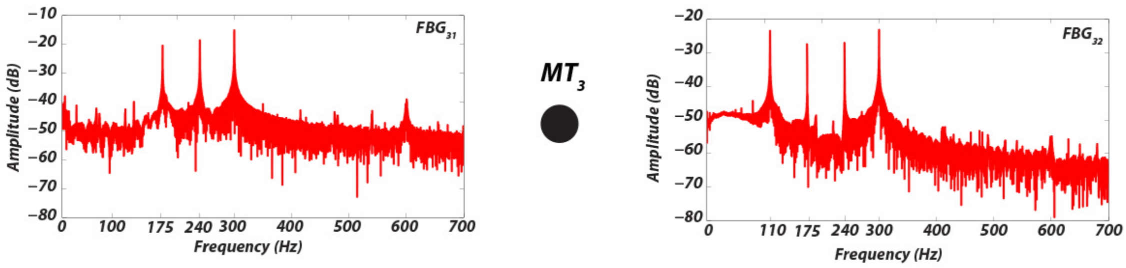


Figure 5. Magnitude spectra of the measured signals coming from FBG_{31} (left) and FBG_{32} (right).

This behaviour is due to the fact that when the SOP is modified at a position *z* by a MT, it is also modified between that position and the fibre end. To distinguish these *artefacts* from vibrations that are really applied on this MT, the phase shift between the electrical signals corresponding to the two FBGs surrounding this MT are measured. Depending on the value of this phase shift we can deduce if a frequency is applied or not.

5. Practical aspects and performances

The performances depend on the use of the mechanical transducer. This transducer is suitable for measuring vibrations up to 1 kHz as its resonance frequency is around 1200 Hz [2]. Moreover, accelerations from 1 to several tenths of m/s^2 can be detected with such sensors [3]. The presented sensors are not directly usable in high resolution geophysical seismic systems as the noise floor is of the order of 3 $\mu g/\sqrt{Hz}$. This is mainly due to the detector used and the performances could be improved by using very low noise detectors. These performances can be influenced by the non-polarization maintaining aspect of the fibers used. As shown in [3] the performances depend on the input SOP, meaning that if the SOP changes with time, the performances also change. Experiments are being carried out to get rid of this dependence. The proposed method consists in launching several input polarization states so as to deduce the birefringence properties of the birefringent element (MT). This method is based on previously published considerations [5]. Concerning the implementation into structures, the geometrical aspect of the mechanical transducer could be a limitation and efforts are currently being made on its miniaturization.

6. Acknowledgements

The authors would like to thank the financial support of the F.R.S.-FNRS (F.R.I.A). This project is within the frame of Actions de Recherche Concertées financées par le Ministère de la Communauté française - Direction générale de l'Enseignement non obligatoire et de la Recherche scientifique.

References

[1] M. Wuilpart and M. Tur, "Chapter 2. Polarization effects in optical fibers," in *Advanced Fiber Optics: Concepts and Technology*, L. Thévenaz, eds. (EPFL Press, 2011), pp. 29–86.

[2] P. Tihon, N. Linze, O. Verlinden, P. Mégret, and M. Wuilpart, "Design of a mechanical transducer for an optical fiber accelerometer based on polarization variation," Proc. SPIE 8439, 84390M (2012).

[3] N. Linze, P. Tihon, O. Verlinden, P. Mégret, and M. Wuilpart, "Linearity considerations in polarization-based vibration sensors", App. Opt. **51**, 6997-7004 (2012).

[4] N. Linze, P. Tihon, O. Verlinden, P. Mégret, M. Wuilpart, "Development of a Polarimetric Vibration Sensor for Quasi-Distributed Measurements", *Optical Fibre Sensors-22 (OFS)*, Proc. SPIE 8421, 84213A (2012).

[5] M. Wuilpart, P. Mégret, M. Blondel, A. J. Rogers, and Y. Defosse, "Measurement of the Spatial Distribution of Birefringence in Optical Fibers," IEEE Photon. Technol. Lett. **13**, 836–838 (2001).

Optical fibre distributed temperature monitoring in the radiation environment

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Summary
In this paper we present results of a distributed temperature measurement experiment performed in a low dose radiation environment of the Sub-Pile Room (SPR), which located under the material testing rector BR2 vessel (SCK•CEN, Mol, Belgium). Several optical fibres with different radiation sensitivity were installed inside the SPR and were used for the environment temperature monitoring during an operation cycle of the reactor. The measurement results obtained by means of an Optical Frequency Domain Reflectometer allow to reconstruct spatial distribution of temperature changes in the SPR related to the reactor operation, i.e. a temperature growth from 25 to 40 – 45°C during the reactor start-up, a stable temperature during reactor operation, and a decrease to the initial level after the reactor shut-down. In addition, the use of highly radiation sensitive fibres allowed radiation dose monitoring based on the assessment of the radiation induced attenuation effect. From such measurements we estimated the dose rate at the fibre location, which was in a range of 0.4 – 0.5 Gy/h. The total accumulated dose was 200 – 250 Gy. The gamma dose rate in the SPR changes with the location and this non-homogeneity was seen from the distributed attenuation measurement data.

1. Introduction

Since 1970s intensive research has been conducted into effects caused by ionizing radiation in optical fibres [1,2]. The high interest to those phenomena was provoked by the potential advantages of fibre exploitation in hostile environments for data transmission and sensing. The most important advantages of the fibre optic technologies are the small size, electro-magnetic field resistance, possibility of distributed measurement along the length of the fibre [3,4].

There are the two main directions with respect to the radiation sensitivity that optical fibre research is heading towards. To the first of them we can attribute the applications such as reliable data transmission over fibre optic links in harsh radiation environments (nuclear facilities, space), and sensing of external perturbation parameters (temperature, strain, pressure). In all of them minimization of the sensitivity to ionization radiation is the key point.

The second direction is the optical fibre dosimetry. In this case optical fibres are used as a sensing medium to measure an absorbed radiation dose. The dose value can be estimated based on the Radiation Induced Attenuation (RIA) [5,6]. This usually implies a high radiation

sensitivity. There are also other approaches to measure the absorbed dose with an optical fibre, for instance, by detecting the radiation induced shift of the Bragg wavelength of the fibre Bragg gratings sensitive to radiation [7]. Their operational principle is based on changes of the core Refractive Index (RI) of the exposed fibre, which consequently results in the Bragg wavelength shift.
Using optical fibres for the dose detection purpose also raises measured data interpretation problems, which are related with the complicated mechanism of the RIA dependence on environment conditions, for instance, on temperature. The main problem is that point defects generated by radiation anneal with time, with the annealing speed depending on temperature. Therefore the constant monitoring of temperature is required for an accurate estimation of the absorbed dose so that if temperature has changed the dose estimation model might be corrected in accordance to it by changing the parameter responsible for the annealing speed.

In this paper we discuss main problems of deploying and utilisation of an Optical Frequency Domain Reflectometry (OFDR) [8] based distributed temperature measuring system in a low dose radiation environment. An important advantage of the OFDR system for RIA measurements is its high spatial resolution, down to 2 cm. This system also allows to perform distributed temperature measurements [9] which is an important advantage for an optical fibre dosimetry system since the RIA is temperature-dependent.

2. Fibre cross-sensitivity

The Rayleigh scattering effect in optical fibres is caused by random fluctuations in the index profile along the fibre length. Local temperature variations result in reflectivity spectrum changes related with the thermo-optic effect and the fibre thermal expansion. The OFDR techniques of distributed temperature monitoring consist in measuring the complex reflection coefficient of a fibre as a function of wavelength [8]. First, the Rayleigh scatter signature of the fibre is measured and stored in a baseline state. The scattering profile is then measured in a perturbed state. The two profiles are divided into segments of an equal length, which define the temperature measurement resolution. The spectra calculated by taking the inverse Fourier transform of correspondent segments of the perturbed and reference traces are compared by means of taking its cross-correlation. The spectral shift of the cross-correlation peak represents temperature change in comparison to the reference temperature at the segment location.

A known problem for temperature measuring with many types of fibre sensors is its cross-sensitivity with stress. The same drawback exists for OFDR. Static stresses applied to the fibre are automatically cancelled thanks to the use of reference measuring procedure. However, vibrations are not suppressed in this way and can significantly deteriorate temperature measurements taken with an OFDR system. The time needed for one frequency sweep, i.e. to perform one single measurement, is about to 10 seconds. This means that vibrations with frequencies from 0.1 Hz and higher are important.

The experiment we discuss in this paper consists in OFDR temperature measurements performed in the Sub-Pile Room (SPR) of the BR2 nuclear reactor in Mol, Belgium. This is a hostile environment, where not only radiation but also significant vibrations are present. The fibres can be also subjected to an accidental mechanical impact and a protection is necessary. In the previous test [10] we used a plastic securing tube as a simple solution. It was found that this approach, doesn’t necessarily lead to a good result. There are several reasons for it. The first one is stresses applied to the fibre by the protection tube during the fibre installation.

From the measurement point of view stresses and temperature variations are indistinguishable. Therefore, it can result in fictive temperature variations. An additional source of stresses is related to the difference of the thermal expansion of the polymer and the fibre. Although the friction coefficient between the fibre and the inner side of the tube can be significantly reduced by means of some lubricant, fibre can never move loosely inside due to random bends. Therefore, temperature variation gives rise to additional fibre strain leading to local changes of the effective temperature sensitivity coefficient. Therefore, temperature measurements become noisy. That was observed in the previous test [10], when the data obtained with the first several meters were reasonable whereas demonstrated significantly lower sensitivity.

A potential solution we proposed in [10] was to develop a rigid non-flexible probe. The reason, why the rigidity of the probe is required, is that the probe calibrated in a laboratory environment can be installed in an environment of interest without significant disturbance of the sensing fibre. By term "calibration" we imply measuring of the effective distributed temperature sensitivity coefficient. The need of pre-calibration in laboratory environment results in an additional restriction on the probe size which is due to the later installing procedure and it is not always an easy task to transport and mount the system without disassembling it. Also calibration right in an experimental environment after installation is

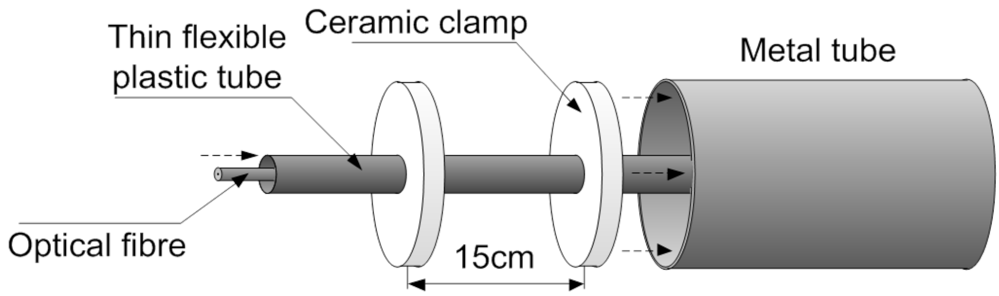


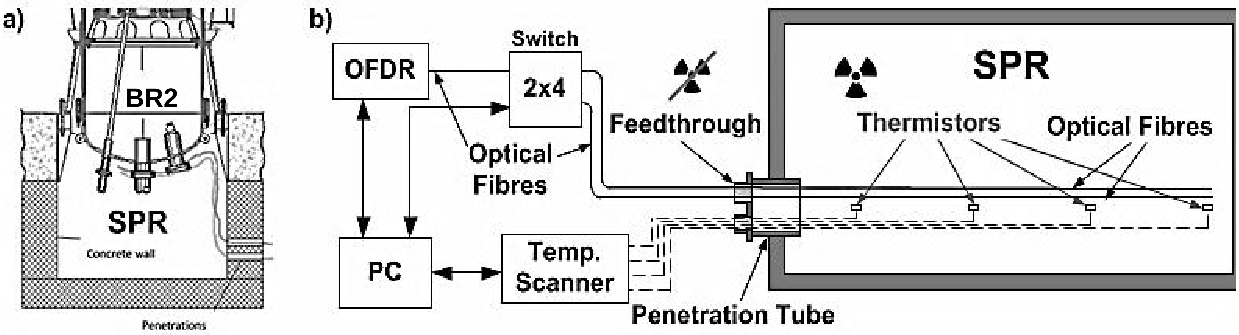
Figure 1: Optical fibre framework used in the SPR experiment.

almost never possible.

An outline of a structure designed according that idea is shown in Fig. 1. The structure consists of a metal tube with clamps equidistantly placed in it. Each clamp is a ceramic cylinder 1 mm thick and with a millimetre diameter hole along its axis. The following assembly procedure was used. First, a sensing fibre was inserted in an ~1 mm diameter plastic sleeve. The tube wall is thin enough to have the fibre loosened. Then the clamps were placed on the tube at regular intervals of ~30 cm and glued using standard cyanoacrylate glue. After glue drying, the structure was inserted into a sequence of metal tubes connected with plastic joints. The idea of this arrangement is to keep the sensing fibre without sharp bends so that the friction between the fibre and the plastic tube is negligible, whereas the plastic joints make the set-up foldable. The test measurements performed in the lab confirmed that clamps give no significant strain on the fibre.

3. Experiment

The optical measurements set-up was similar to the one described in [10]. The experiment was performed in the SPR, where the dose rate during the operation of the reactor varies from 0.005 to 5 Gy/h depending on the location. The dose-rate special non-homogeneity was already seen from the previous distributed attenuation measurements [10]. From the present data we estimate the average dose rate at the fibre location was in a range of 0.4 – 0.5 Gy/h, which means that the total accumulated dose was 200 – 250 Gy.



Figures 2 a) Location of Sub-Pile Room under BR2; b) Schematics of measurement set-up

The measurement equipment was placed outside of the SPR and connected it to the fibres inside using a dedicated feed-through, see Fig. 2. Four thermistors provided reference temperature measurements. The optical switch let to multiplex one OFDR for scanning four fibres. The setup was remotely controlled with a PC using a LabVIEW program. The backscattering profiles were acquired automatically every hour. Every 24 hours the reference profile was updated.

Four different types of optical fibres with length of about ~2.5 m were used in the experiment: Fibre 1 (Manufacture does not want to be named) doped with 6.5 mol.% P (F-Ph), the standard telecommunication Ge-doped fibre SMF-28 from Corning (C-Ge), DrakaElite^{TM} Radiation Hard (D-RH) fibre, and Al-doped fibre manufactured by Fibre Optic Research Centre of RAS (Moscow, Russia) the core of which was doped with 8 mol.% of Al and the cladding made of pure silica (M-AL). The radiation sensitivity of these fibres in the near infrared range was discussed in [11].

4. Results

The measurements began shortly before the reactor cycle start. The results of the distributed temperature measurements taken on the 2 m length of the D-RH are shown in Fig. 3. The result shows no periodic pattern which could be associated with the clamps' location. Therefore we assume that there were no stress introduced by the clamps. The observed behaviour can easily be correlated with the reactor operation. The initial temperature in the SPR of about 27 °C is taken as the reference zero point. It steeply increased in the first several hours by ~6 degrees after which it continued to raise but already more gradually. The OFDR measurements were interrupted after 16 days.

Fig.4 presents the results retrieved at 18.1 m distance where one of the reference thermistors was located. The thermistor and the OFDR temperature profiles almost perfectly repeat each other though the one taken with the OFDR looks a bit noisier. Results obtained with other fibres were less accurate in comparison to the thermistor. Their data were much noisier and sometimes deviated significantly from the thermistor temperature results. We are inclined to think that it was caused by some irregularities in the framework.

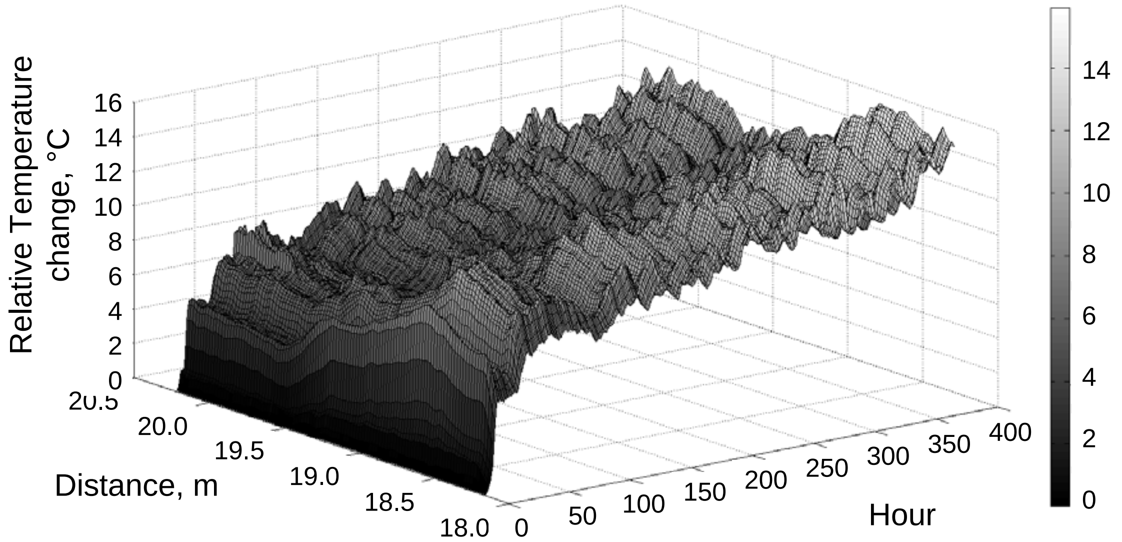


Figure 3: First 16 days of the distributed temperature measurements taken by means of the OFDR with the D-RH probe, the length of the probe is about 2.4 m.

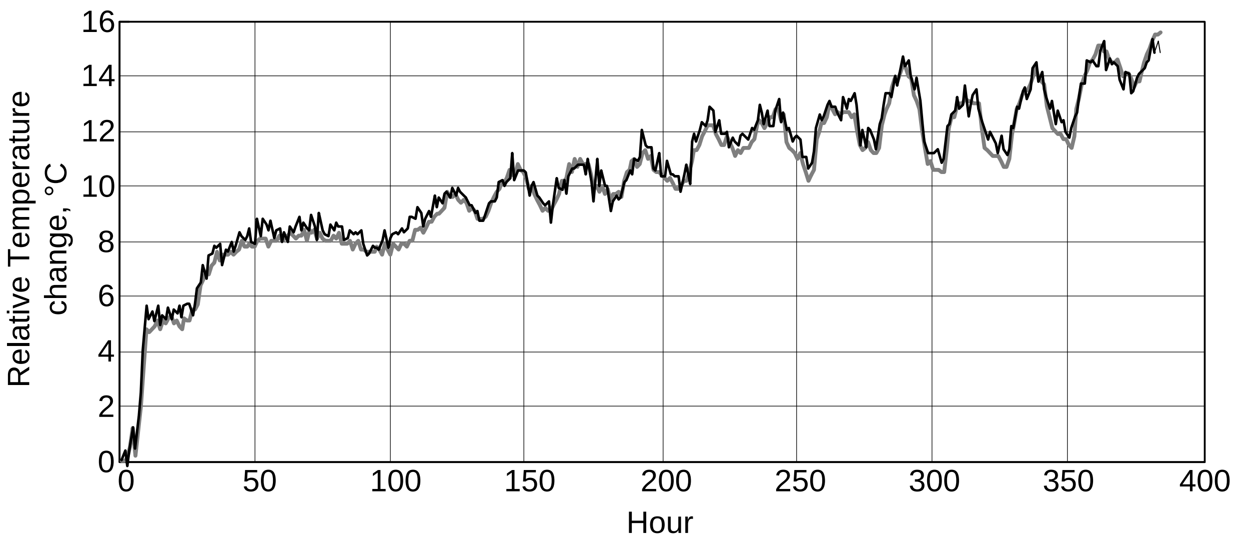


Figure 4: Relative temperature change measured at a distance of 18 meters from the beginning of the optical fibre network where one of the reference thermistors was installed. D-RH fibre - black thin line, thermistor – thick grey line.

5. Conclusion

We performed temperature measurements in a 0.4 – 0.5 Gy/h dose-rate radiation environment using different types of optical fibres and the OFDR technique. The main purpose was to check if the rigid non-flexible framework, which was introduced for reducing deteriorating effects of strains induced by the protecting sleeve, would allow for sufficiently accurate measurements in the industrial-like low dose-rate environment. The results obtained with the D-RH fibre agree well with the reference measurements retrieved from the thermistor. The developed framework allowed us to reduce external perturbations as well as accidental changes of the temperature sensitivity coefficient caused by random bends of a standard plastic protection tube. The results of the other fibres were not as much consistent in comparison with the D-RH. Though we still believe that the OFDR technology can be successfully used for distributed temperature measurements in harsh environments, relevant fibre installation techniques should be developed.

References

[1] B.D. Evans and G.H. Sicjels, Jr., “Permanent and Transient Radiation Induced Losses in Optical Fibre,”IEEE Transaction on Nuclear Science, vol. NS-21, 1974, pp. 113-118.

[2] W. Gaebler, D. Brauning, “Application of optical fibre waveguide in Radiation dosimetry”, 1st International Conference Fibre Optic Sensors, London, 1983, pp. 185-189

[3] M.Decréton, V.Massaut, P.Borgermans, “Potential benefit of fibre optics in nuclear applications — the case of the decommissioning and storage activities” SPIE Proc, 1994, Vol. 2425, pp.2-10

[4] F. Berghmans, et al., "An introduction to radiation effects on optical components and fibre optic sensors," in: Optical waveguide sensing and imaging, NATO Science for Peace and Security Series B - Physics and Biophysics, W. J. Bock, I. Gannot and S. Tanev, eds., pp. 127-65, Dordrecht, NL: Springer, 2008.

[5] H.Henschel, et al., “Fibre optic radiation sensor systems for particle accelerators,” Nucl. Instr. Meth. Phys. Res. A, vol. 526, 2004, pp. 537-550.

[6] R. H. West, "P-doped optical fibres in dosimetry", SPIE Proc.,vol. 4547, pp. 61-68, 2002.

[7] A. Faustov, et al., “Highly radiation sensitive Type IA FBGs for dosimetry applications”, IEEE TNS, paper accepted

[8] B. J. Soller, M. Wolfe, M. E. Froggatt, “Polarization resolved measurement of Rayleigh backscatter in fibre-optic components,” OFC Technical Digest, Los Angeles, March, 2005, paper NWD3.

[9] D.K. Gifford, et al., “Distributed fibre-optic temperature sensing using Rayleigh backscatter,” 3, pp. 511 – 512, ECOC 2005.

[10] A. Faustov, et al. “Distributed optical fibre temperature measurements in a low dose rate radiation environment based on Rayleigh backscattering”, SPIE Europe 2012, Brussels, to be published.

[11] A. Faustov, et al. “Comparison of gamma-radiation induced attenuation in Al-doped, P-doped and Ge-doped fibres for dosimetry”, in Proceedings of the Radecs 2012, Biarritz, September 2012.

Development of the Monitoring Programme for the New Low Level Waste Facilities at Dounreay

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Summary

Dounreay Site Restoration Limited (DSRL) is constructing near-surface facilities for disposal of its solid low-level radioactive waste (LLW) at Dounreay in Caithness, Scotland. DSRL has submitted an Environmental Safety Case (ESC) to the Scottish Environment Protection Agency (SEPA) in support of its application for authorisation of the New LLW Facilities (NLLWF) under the Radioactive Substances Act 1993 (RSA93). UK regulatory guidance for the authorisation of a radioactive waste disposal facility requires the operator to implement a programme to monitor for changes caused by construction of the facilities and emplacement of the waste. A high-level Monitoring Plan has been produced that includes monitoring objectives in four areas: (i) long-term safety case; (ii) operational safety case; (iii) environmental impact assessment; and (iv) other objectives, such as public reassurance. For each monitoring objective, the identified information requirements were defined in terms of monitoring parameters. The techniques that could be used to monitor these parameters were also identified. The monitoring parameters identified for each objective were grouped into monitoring programmes, each concerned with a set of related monitoring parameters (e.g., groundwater monitoring covers hydrogeological parameters and groundwater chemistry parameters). The duration of each monitoring programme was defined in terms of the stages of development of the NLLWF, as set out in the regulatory requirements. The Monitoring Plan was then derived as a top-level consolidation of monitoring programmes by considering overlaps between the identified programmes, the associated lists of monitoring parameters, and the timescales for their determination for each objective. The consolidated list of monitoring programmes represents the Monitoring Plan, which identifies the key parameters to be monitored during the authorisation of the NLLWF. This paper describes the NLLWF Monitoring Plan and implementation of the groundwater monitoring programme.

1. Introduction

The NLLWF site at Dounreay covers approximately 60 ha of poor-quality land located between a line of sea cliffs and a disused concrete runway. The NLLWF are being constructed in three phases and will comprise up to six concrete vaults, each approximately 80m long, 46m wide and 12.5m deep. Located in saturated fractured bedrock (Middle

Devonian siltstones and sandstones), the vaults will be concealed beneath at least 4m of capping material and re-instated soil at closure.

The Guidance on Requirements for Authorisation (GRA) for near-surface disposal facilities on land for solid radioactive wastes stipulates in Requirement R14 that the developer should carry out a programme to monitor for changes caused by construction, operation and closure of a facility [1]. This is to ensure that a facility performs within the parameters set out in the ESC. Thus, the principal purpose of monitoring is to provide assurance to the regulator (SEPA) that the disposal system is developing and performing as expected. Monitoring also assures worker health and safety, and protection of the environment from non-radiological impacts. The NLLWF Monitoring Plan draws together, at a high level, all of the monitoring requirements into an integrated set of monitoring programmes [2]. Although the NLLWF Monitoring Plan addresses the RSA93 authorisation requirements for a near-surface disposal facility, some of the processes for developing and implementing this plan are considered analogous for the development of a monitoring plan for a deep geological disposal facility.

2. Methodology for Deriving the Monitoring Plan

Monitoring is defined here as continuous or periodic observations and measurements of engineering, environmental, radiological and other parameters to help evaluate the behaviour of the disposal system or the impacts of the disposal facility and its operation on the environment. Monitoring does not cover site investigation activities or one-off measurements, except where such activities are used to define baselines, e.g. background groundwater quality.

There are several objectives for monitoring, and there is considerable overlap in terms of information requirements between these objectives. In developing the NLLWF Monitoring Plan, monitoring objectives were considered in four areas:

(i). *Long-term safety case*. A risk-based approach to selecting important monitoring concerns was adopted, as advocated by regulatory guidance. Results from the NLLWF post-closure radiological safety assessment that underlies the ESC were used to identify suitable monitoring parameters relevant to long-term performance and/or confidence in long-term performance. Note that there is not necessarily any need to monitor these parameters over a long period. Also, any post-closure monitoring programme must not compromise the environmental safety of the facilities [1].

(ii). *Operational safety case*. Following a risk-based approach, the Preliminary Safety Report and accompanying hazard and operability (HAZOP) study for the NLLWF were used to identify operational safety issues and associated monitoring parameters and requirements.

(iii). *Environmental impact assessment*. The Environmental Impact Assessment (EIA) of the facilities conducted for the planning application included a number of monitoring commitments to mitigate potential environmental impacts of the NLLWF. These commitments were consolidated into monitoring programmes.

(iv). *Other objectives*. Monitoring control of the NLLWF, waste management developments, the regulatory framework, and public reassurance and wider confidence issues were considered as additional objectives defining monitoring needs.

For each monitoring objective, the identified information requirements were defined in terms of monitoring parameters. The techniques that could be used to monitor these parameters were also identified. The monitoring parameters identified for each objective were grouped into monitoring programmes, each concerned with a set of related monitoring parameters (e.g., groundwater monitoring covers hydrogeological parameters and groundwater chemistry parameters). The duration of each monitoring programme was defined in terms of the stages of development of the disposal facilities, as set out in the regulatory requirements: Pre-construction, Construction, Operations (which will run in parallel with phased construction of vaults), Closure (which will proceed in parallel with phased operating of vaults), and Post-closure.

The Monitoring Plan was then derived as a top-level consolidation of monitoring programmes by considering overlaps between the identified programmes, the associated lists of monitoring parameters, and the timescales for their determination for each objective. The consolidated list of 24 monitoring programmes, in tabular form, represents the NLLWF Monitoring Plan, which identifies the parameters to be monitored during the period of authorisation. As necessary, monitoring programmes are specified in detail in separate project documents as required by the DSRL Management System.

3. Implementation of the Groundwater Monitoring Programme

Groundwater monitoring arrangements were discussed between DSRL and SEPA at an early stage to establish the locations of boreholes for monitoring baseline (background) groundwater levels and groundwater quality prior to any excavation works for the vaults. These discussions with the regulator set the performance measures for the chemical species of interest, which include 8 major ion species, 20 minor/trace ions, selected petroleum hydrocarbon compounds and polycyclic aromatic hydrocarbons, and parameters such as pH, temperature and electrical conductivity. Furthermore, in order to establish the baseline radiological quality of site groundwater, it was agreed to monitor for gross alpha and gross beta radioactivity, tritium, ^{90}Sr, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, and $^{239/240}$Pu. The choice of analytes was determined by the projected inventory of LLW and the need to comply with the hazardous waste regulations as well as the RSA93 authorisation requirements.

The agreed groundwater monitoring programme, including the frequencies of water level measurements and groundwater sampling, has been documented [3]. Implementation of the arrangements commenced in March 2009. In general, five different horizons are being monitored in approximately 30 boreholes: Made Ground deposits; natural superficial deposits of glacial diamict; weathered bedrock located between approximately 1m and 4m depth; altered bedrock between approximately 4m and 12m depth, broadly coinciding with the upper sections of the planned vaults; and unaltered bedrock lying between around 12m and 25m depth, which roughly coincides with the lower sections of the vaults.

Groundwater monitoring results are reported quarterly. Comparison of the initial groundwater quality data with defined performance measures (groundwater quality comparison criteria) has enabled the monitoring programme to be optimised, in agreement with SEPA. Annual reviews of the groundwater monitoring data accumulated from twelve monitoring rounds undertaken in 2009, 2010 and 2011 have been reported [4] [5] [6]. There is little variability in the groundwater levels or groundwater quality results from one year to another. These three years of groundwater monitoring, undertaken before the start of the excavation works, have provided the baseline groundwater quality data for the NLLWF site, as required by SEPA.

With an established baseline in place, the regulator can gauge how excavation, construction, operation, and closure of the NLLWF may affect groundwater levels and quality. Continued groundwater monitoring allows measurement of any perturbations of down-gradient groundwater parameters during excavation, vault construction, operations, and closure. Hydrochemistry and redox changes may occur down gradient as oxygen enters the cone of depression in groundwater levels caused by pumping to keep the excavations dry. Geochemical modelling has been useful in describing possible changes in pH, redox potential, and partial pressures of carbon dioxide. Degassing of CO_2 may change the pre-construction background levels of alkalinity and calcium in the groundwater. However, such changes do not impact the ESC, as the down-gradient hydrochemistry is assumed to return to its former natural reducing state after closure of the facilities.

4. Discussion

The developer will provide SEPA with a groundwater monitoring programme for the period of authorised operations that will propose monitoring points (positioned up and down hydraulic gradient, but fewer in number than the 30 used for establishing baselines), and control and trigger levels for the groundwater species of concern. Trigger levels, as required by the Landfill (Scotland) Regulations 2003, will be used to indicate concentrations that represent a significant change in water quality. Trigger levels are usually set in line with appropriate Minimum Reporting Values (for hazardous substances), and Environmental Assessment Limits (for non-hazardous substances) [7]. However, the NLLWF trigger levels, including radiological levels, will be derived, with SEPA agreement, from statistical analysis of the baseline groundwater monitoring results. Observations of groundwater monitoring data against the trigger levels will be evaluated by means of control levels for each down-gradient well [8]. Control levels, to be established from an understanding of monitoring data variability, will provide early warning of any potential issues [8].

5. Conclusions

Monitoring of the planned NLLWF is a requirement for authorisation under the RSA93, and a monitoring plan must form part of the ESC, covering the pre-construction, construction, operations, closure, and post-closure phases. Monitoring is also required for several other purposes, including environmental protection, operational safety, and public reassurance. A consolidated list of monitoring programmes over the authorised lifetime of the facilities represents the NLLWF Monitoring Plan. Implementation of the monitoring programmes helps to provide confidence to the regulator that the NLLWF disposal system is developing and performing as expected. The Monitoring Plan will be periodically reviewed and updated as necessary throughout the period of authorisation.

References

[1] Environment Agency, Northern Ireland Environment Agency, Scottish Environment Protection Agency (2009), Near-surface Disposal Facilities on land for Solid Radioactive Wastes, Guidance on Requirements for Authorisation.

[2] DSRL (2010), New Low Level Waste Facilities – Monitoring Plan 2010. DSRL report NLLWF/3/REP/GAL/0313/IS/02, August 2010.

[3] DSRL (2010), New Low Level Waste Facilities - Groundwater and Surface Water Monitoring Plan. DSRL report LLW/3/MON/GLD/0007/IS/05, October 2010.

[4] DSRL (2010), New Low Level Waste Facilities - Annual Groundwater and Surface Water Monitoring Review 2009. DSRL report NLLWF/3/REP/GLD/0307/IS/02, August 2010.

[5] DSRL (2011), New Low Level Waste Facilities - Annual Groundwater and Surface Water Monitoring Review 2010. DSRL report NLLWF/3/REP/GLD/0697/IS/01, December 2011.

[6] DSRL (2012), New Low Level Waste Facilities - Annual Groundwater and Surface Water Monitoring Review 2011. DSRL report NLLWF/3/REP/GLD/0858/IS/01, March 2012.

[7] SEPA (2011), Position Statement WAT-PS-10-01, Assigning Groundwater Assessment Criteria for Pollutant Inputs. Version 2.1, released June 2011. Scottish Environment Protection Agency.

[8] SEPA (2005), Hydrogeological Risk Assessment for Landfills and the Derivation of Control and Trigger Levels, SEPA Technical Guidance Note, Version 2.12, April 2005. Scottish Environment Protection Agency.

C.5 Session S5: Theme 2: Monitoring – The wider perspective: Regulatory and stakeholder viewpoints

The Draft Safety Guide on Monitoring and Surveillance of Disposal Facilities

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Summary

The Draft of the Safety Guide Monitoring and Surveillance of Disposal Facilities (DS357) will be presented to the Waste Safety Standard Committee (WASSC) in November 2012. The objective of this Safety Guide is to provide guidance for monitoring and surveillance of radioactive waste disposal facilities during their entire lifetime.

It places emphasis on an approach to monitoring and surveillance that provides data needed for the development of the safety case. A characteristic of the safety case is that its content necessarily evolves with time and with the decision steps taken during the facility lifecycle. Technical details on monitoring and surveillance methodologies are beyond the scope of this Safety Guide.

In general, the monitoring and surveillance programmes should be driven by, and inform the safety case. Even if long term safety should not rely on monitoring and surveillance, the results of such a programme should be used to strengthen the safety case and build confidence in safety.

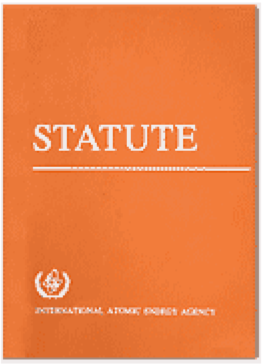
The document is structured in nine sections.

- Section 1 explains the background and the objectives of the document.
- Section 2 provides an overview of monitoring and surveillance for radioactive waste disposal facilities, and describes overall objectives for a monitoring and surveillance programme.
- Section 3 addresses roles and responsibilities of the regulatory body and the implementing organizations with regard to monitoring and surveillance.
- Section 4 addresses the design of a monitoring programme and includes some consideration of strategic issues for monitoring.
- Section 5 provides guidance on monitoring according to the type of disposal facility
- Section 6 addresses monitoring according to the stage of facility development. Section 7 provides specific guidance for surveillance activities only.
- Section 8 is concerned with the use of monitoring and surveillance information in regard to compliance aspects and constant development and improvement of the safety case and
- Section 9 provides a brief discussion of the salient issues pertaining to the management system for a disposal facility.

1. Background and history

The development of the Safety Guide Monitoring and Surveillance of Disposal Facilities (DS357) was approved in 2007. The standard was to cover the monitoring and surveillance activities in the preoperational, operational and post-closure phases and address all types of disposal facilities.

The Draft version of the Standard was posted for comments by Member States in 2011. More than 600 comments of the Member States where incorporated and the document will be presented to the Waste Safety Standard Committee (WASSC) in November 2012.



The Statute of the IAEA was approved on 23 October 1956 by the Conference on the Statute of the International Atomic Energy Agency, which was held at the Headquarters of the United Nations. It came into force on 29 July 1957.

According to its Statute the IAEA is authorized

"… To establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property (including such standards for labour conditions), and to provide for the application of these standards to its own operation as well as to the operations making use of materials, services, equipment, facilities, and information made available by the Agency or at its request or under its control or supervision; and to provide for the application of these standards, at the request of the parties, to operations under any bilateral or multilateral arrangements, or, at the request of a State, to any of that State's activities in the field of atomic energy;"

The IAEA Safety Standards are one of IAEA's Medium Term Strategy priorities.

The latest IAEA Medium Term Strategy covers the period 2012 to 2017. It has been developed through a process of interaction between the Secretariat and an open-ended Working Group established for this purpose by the Board of Governors.

It states: "(…) the Agency will enhance the global nuclear safety and security framework and assist national efforts to ensure appropriate levels of safety and security for all type of facilities and activities by continuing to: (a) establish standards and guidance; (…)"

The Safety Standards are structured in Fundamentals, Requirements and Guides.

The Fundamental Safety Principles establishes the fundamental safety objective and principles of protection and safety.

Safety Requirements publications establish the requirements that must be met to ensure the protection of people and the environment, both now and in the future. If they are not met, measures must be taken to reach or restore the required level of safety.

Safety Guides provide recommendations and guidance on how to comply with the requirements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures).

In 2008 a new, long-term structure for the safety standards was adopted. The Safety Fundamentals (SF-1), the General Safety Requirements (GSR) in seven parts and the General Safety Guides (GSG) are applicable to all facilities and activities. These are complemented by Specific Safety Requirements (SSR) and Specific Safety Guides (SSG), which are applicable to specified facilities and activities.

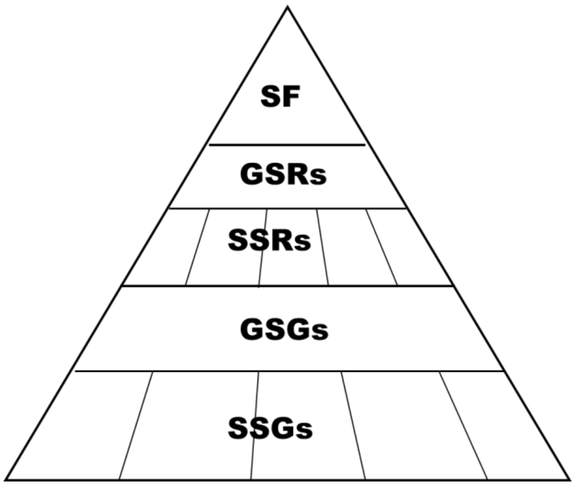
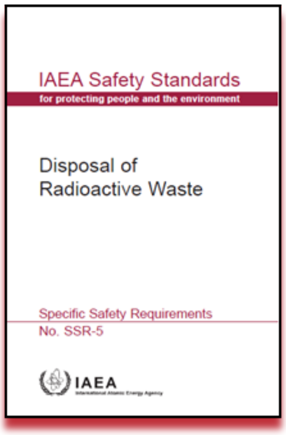


Figure 1: Hierarchy of Safety Standards

2. Relevant Requirements

In the field of disposal of radioactive waste the relevant safety requirements publication is SSR-5, Safety Requirements on Disposal Radioactive Waste. The objective of this Safety Requirements publication is to set out the safety objective and criteria for the disposal of all types of radioactive waste and to establish the requirements that must be satisfied in the disposal of radioactive waste. It applies to the disposal of radioactive waste of all types by means of emplacement in designed disposal facilities, subject to the necessary limitations and controls being placed on the disposal of the waste and on the development, operation and closure of facilities.



Requirement 21 of the Safety Requirements on the Disposal of Radioactive Waste [4] states that “A programme of monitoring shall be carried out prior to, and during, the construction and operation of a disposal facility, and after its closure, if this is part of the safety case. This programme shall be designed to collect and update information necessary for the purposes of protection and safety. Information shall be obtained to confirm the conditions necessary for the safety of workers and members of the public and protection of the environment during the period of operation of the facility. Monitoring shall also be carried out to confirm the absence of any conditions that could affect the safety of the facility after closure”.

In addition Requirement 10 indicates that “An appropriate level of surveillance and control shall be applied to protect and preserve the passive safety features, to the extent that this is necessary, so that they can fulfil the functions that they are assigned in the safety case for safety after closure”.

3. Content of the Safety Standard

The document is structured in 9 sections. The following pertains to a short summary of each of the sections.

Section 1: Introduction

The objective of this Safety Guide is to provide guidance for monitoring and surveillance of radioactive waste disposal facilities during their entire lifetime. It considers the monitoring and surveillance of:

- Near surface disposal facilities;
- Geological disposal facilities;
- Disposal facilities for uranium and thorium mine waste.

It places emphasis on an approach to monitoring and surveillance that provides data needed for the development of the safety case. Technical details on monitoring and surveillance methodologies are beyond the scope of this Safety Guide.

Section 2: Overview of monitoring and surveillance

Section 2 defines monitoring context of this Safety Guide, as continuous or periodic observations and measurements of environmental, engineering, or radiological parameters to help evaluate the behaviour of the components of the waste disposal system, or of and the impacts of the waste disposal system and its operation on the public and the environment. Most specifically this covers radiological, environmental and engineering parameters.

In the context of this Safety Guide the term surveillance refers to the physical inspection of a waste disposal facility in order to verify its integrity to protect and preserve the safety barriers.

In general, the monitoring and surveillance programmes should be driven by, and inform the safety case. Even if safety should not rely on monitoring and surveillance, the results of such a programme should be used to strengthen the safety case and build confidence in safety.

Section 3: Responsibilities of the operator and regulatory body

With regard to responsibilities related to monitoring and surveillance, the operator should design and perform the monitoring and surveillance programme that meets the requirements established by national regulatory bodies. If the programme is a part of the safety case, it should be designed throughout the pre-operational, operational and post-closure periods of the facility;

The regulatory body should provide the necessary requirements on the programme and implementation of the monitoring and surveillance for the disposal facility and should be responsible for implementing the following items:

- Periodically review the regulation in force for monitoring and surveillance,
- Review the monitoring and surveillance data provided by operators against established requirements;
- Provide evidence that waste disposal facility is being appropriately monitored and controlled

Section 4: Design of a monitoring program

The monitoring programme for a disposal facility should be defined to respond to the objectives stated in Section 2. It should include source and environmental monitoring programmes, to assess public exposure and impact on the environment as well as to assess potential release pathways.

The safety case should be used to establish the monitoring programme for confirmation of the performance of the disposal facility. The monitoring programme should also assess the functioning of the disposal system with respect to operational and long term safety.

Key technical factors that influence the design of a monitoring programme are:

- Waste characteristics;
- Facility type and design;
- Site characteristics;
- The stage of development of the facility.

Section 5: Monitoring by type of disposal facility

Near Surface Disposal:

This disposal option is suitable for waste that contains such an amount of radioactive material that robust containment and isolation for limited periods of time, typically up to a few hundred years, are required. Monitoring activity associated with near surface disposal facilities containing these types of waste will thus focus on the construction, operation and closure of the facility, providing confidence in the function of the system for hundreds of years, as well as monitoring radionuclides in groundwater or in the surrounding environment.

Geological Disposal:

In this case monitoring is focused on the construction, operation and closure of the disposal facility to provide confidence in the containment systems. Monitoring after closure of the facility, if any, may focus on the presence of radionuclides in the environment. As early releases to the environment are highly unlikely, this kind of monitoring is rather for the purpose of social reassurance than for ensuring the performance of the disposal system.

Mining Residue Disposal:

Mining residues can vary greatly with respect to their radiological hazards**.** The disposal systems are not designed to provide absolute containment at all times and the strategy is to control any release of radionuclides to the environment such that an unacceptable dose does not occur.

Monitoring will consider the construction; operation and closure of the facility but will have greater emphasis on the presence in the surrounding environment of radionuclides and associated chemicals that indicate how well the system is functioning.

The programme of monitoring of a disposal facility for naturally occurring radioactive material would be similar to that of a disposal facility for uranium or thorium mine waste.

Section 6: Monitoring in the different periods of a facility lifetime

Through its lifetime (see Figure 1) the repository is monitored for different purposes i.e. to:

- Establish a baseline;
- Monitor the behaviour of and changes to the disposal system barriers e.g:
    - waste packages

- near field chemical and physical disturbances induced by the construction of the disposal facility and the interactions between introduced materials, groundwater and host rock;
- chemical and physical changes to the surrounding geosphere and in the atmosphere;
- buffer and sealant materials;

- radionuclide transport and release detection to the biosphere
- Record of information in an environmental database

Baseline monitoring – for collection of data to support the site evaluation process and for identification of important features, events and processes for the first iteration of the safety assessment.

Monitoring of the as built facility – for evaluation of compliance with regulatory requirements, to support operational activities, and to support the development of the safety case for subsequent licensing steps. Additional measurements may be introduced at this step.

Monitoring of the operating facility – for evaluation of compliance with regulatory requirements and to support development of the safety case for subsequent licensing steps.

Monitoring for closure – for evaluation of compliance with regulatory requirements, to support closure activities, and subsequent post-closure monitoring. Additional measurements may be introduced at this step, while others will be discontinued

Monitoring of the post-closure performance of the disposal facility (if applicable) – for evaluation of compliance with regulatory requirements and to support subsequent decisions (e.g. scaling down of monitoring activities, release of the site from regulatory control).

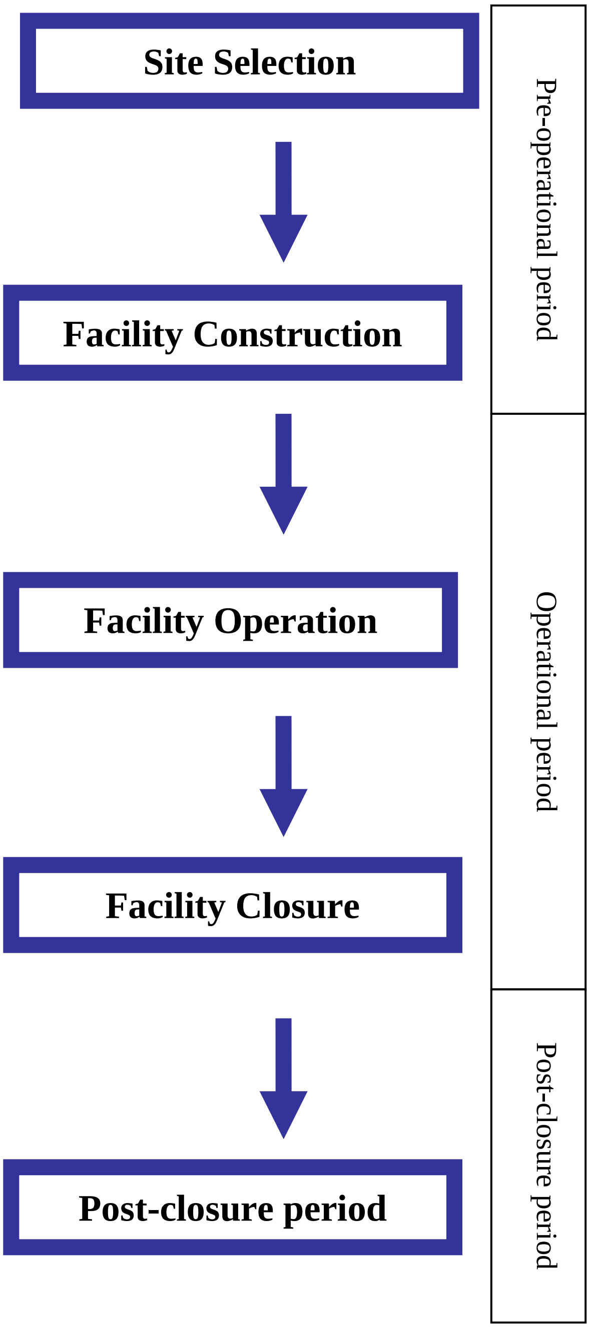


Figure 2: Monitoring in the lifetime of a disposal facility for radioactive waste (taken from DS 357).

Section 7: Development and implementation of a surveillance programme

The purpose of the surveillance programme is to provide for the oversight of a waste disposal facility to verify its integrity to protect and preserve the passive safety barriers, and the prompt identification of conditions that may lead to a migration or release of radioactive and other contaminants to the environment.

A site-specific surveillance plan and implementation procedures should be developed early in the facility lifetime, and should be periodically updated. The plan should include:

(a) Description of the site and adjacent area;
(b) Description of components of the waste management system and environmental setting;
(c) Type and frequency of inspections;
(d) Inspection procedures;
(e) Contingency or maintenance actions;
(f) Reporting requirements for inspections;
(g) Management system.

Section 8: Use of monitoring and surveillance information

At the minimum, monitoring and surveillance results should contribute to demonstrate compliance with the regulatory constraints and licence conditions. However, regulatory compliance for performance-based criteria such as dose will require monitoring to provide insights into features, events and processes (FEPs) and system performance which give information to support the safety case and safety assessment.

Since approaches for achieving this type of regulatory requirement do not follow strict rules, there should be good and early communication between regulator, operator, and other interested parties like NGO's and non-professional stakeholders.

The monitoring and surveillance data collected during the pre-operational period should include retrospective data from comparable types of facilities, if possible. The purpose of such data is to provide confidence in the general approach for disposal being proposed. As the facility moves into the operational period, monitoring and surveillance should continue to provide information about operating performance, which can be used to update the safety case. Before the final closure of the disposal facility, monitoring and surveillance data may be collected to confirm the continuing presence of safety functions as identified in the safety case.

Unexpected results do not necessarily indicate that disposal system safety has been compromised. The safety case should be updated to reflect the new knowledge. When unexpected results occur, they may raise questions with the regulator, and may influence interested parties confidence. In this regard, proper communication, transparency, and honesty should be emphasized to maintaining credibility.

A graded approach should be taken in responding to unexpected results, Response may vary from no action at all, to increased sampling frequency for identification, and/or confirmation of spatial and temporal trends, through to changes in design or procedures, all the way to significant remedial action or even retrieval of emplaced waste.. Actions, such as waste retrieval, should only be undertaken after very careful study and justification, including consideration of risks associated with the remedial activity.

Section 9: Management System

Elements of the management programme that should receive particular attention with regard to monitoring and surveillance are:

- Ensure the continuity of resources over long time periods;
- Establish processes leading to qualification of the monitoring and surveillance programmes and data derived from it in the regulatory process;
- Control of records over the duration of the project.

4. Conclusion

The Safety Guide will provide guidance to the member states of the IAEA about how to plan and perform a monitoring and surveillance program for disposal facilities for all kinds of disposal facilities. It further gives guidance on how to use the results of monitoring and surveillance and on how to integrate them in a safety case. This contributes to the use of monitoring programs in a way that they contribute to the safety of humans and the environment.

MoDeRn – Regulatory View on Monitoring of Spent Fuel Geological Disposal in Finland

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Summary

This paper provides an overview of the role of monitoring in the performance confirmation of a deep geologic repository in Finland. It has been written from the perspective of a safety authority.

The Finnish regulation specify how monitoring shall be used to gather information and to follow the facility safety and evolution of the site and near-field properties. Typically monitoring is used in nuclear facilities for radiation protection of the workers, monitoring of radioactivity and dose rates, radiation monitoring in the environment of the nuclear facility and meteorological monitoring. For geologic repository regulation requires monitoring of safety relevant bedrock properties and disturbances and also monitoring of engineered barrier system (EBS) during the operational period. As a regulator the Radiation and Nuclear Safety Authority (STUK) will ensure that proposed monitoring programme is adequate and carries out the necessary oversight.

In Finland Posiva and STUK have concrete experience on the site characterization and monitoring of the effect of construction of the ONKALO Underground rock characterization facility (URCF). Posiva has carried out monitoring during ONKALO construction period and STUK has reviewed, assessed and inspected the implemented programme. STUK's overall conclusion at this point is that Posiva's programme has been comprehensive and supported the maintenance of favourable site properties.

A key element regarding performance confirmation and related monitoring is development of monitoring strategy and understanding what needs to and what can be achieved by monitoring during the operational period in relation to long lasting evolution of the barriers.

1. Introduction - Spent nuclear fuel disposal in Finland

Finland is one of the foremost countries in the world in developing the disposal of spent fuel. The Construction License application for the Olkiluoto spent fuel disposal facility was submitted to the authorities at the end of 2012 and the facility is expected to start operation around 2020.

This has been a long-term project with over 30 years of parallel development of the repository project and the regulatory approach to spent fuel management.

In 1983 the Government made a strategy decision on the objectives and target time schedule for the research, development and technical planning of nuclear waste management. While an export and international disposal solution was still the preferred option, this decision required the licensees without this possibility to prepare for disposal in Finland and it also gave the timeline for the milestones on the way to an operating disposal facility by 2020.

The first step in the licensing process was reached at the end of 1999 when Posiva Ltd, the current implementer of the disposal programme, submitted the application for a Decision-in-Principle (DiP) [1] for a spent fuel disposal facility in Olkiluoto. The DiP was made by the government in late 2000, approved by the host municipality and ratified by the parliament in early 2001. It gave Posiva the authorization to start to construct an underground rock characterization facility, to the depth of actual planned disposal, as required by regulation.

The excavation of the underground rock characterization facility, ONKALO, is now nearing completion at Olkiluoto. Unlike the generic underground rock laboratories the ONKALO is being constructed at the actual repository site, and this means that the construction and operation of this facility should not cause major disturbances to the properties of bedrock that are important for the post-closure safety. Another difference between generic URL is that Posiva aims to use ONKALO later as access route to the repository. According to Posiva's preliminary plans the operating time of Olkiluoto disposal could be slightly over hundred years depending on the amount of spent fuel to be generated in future. This means that ONKALO design life is over 120 years. The current status of the construction of ONKALO is shown (dark grey) in Figure 1. As ONKALO is foreseen to become a part of the disposal facility, it has been constructed under the regulatory oversight of STUK.

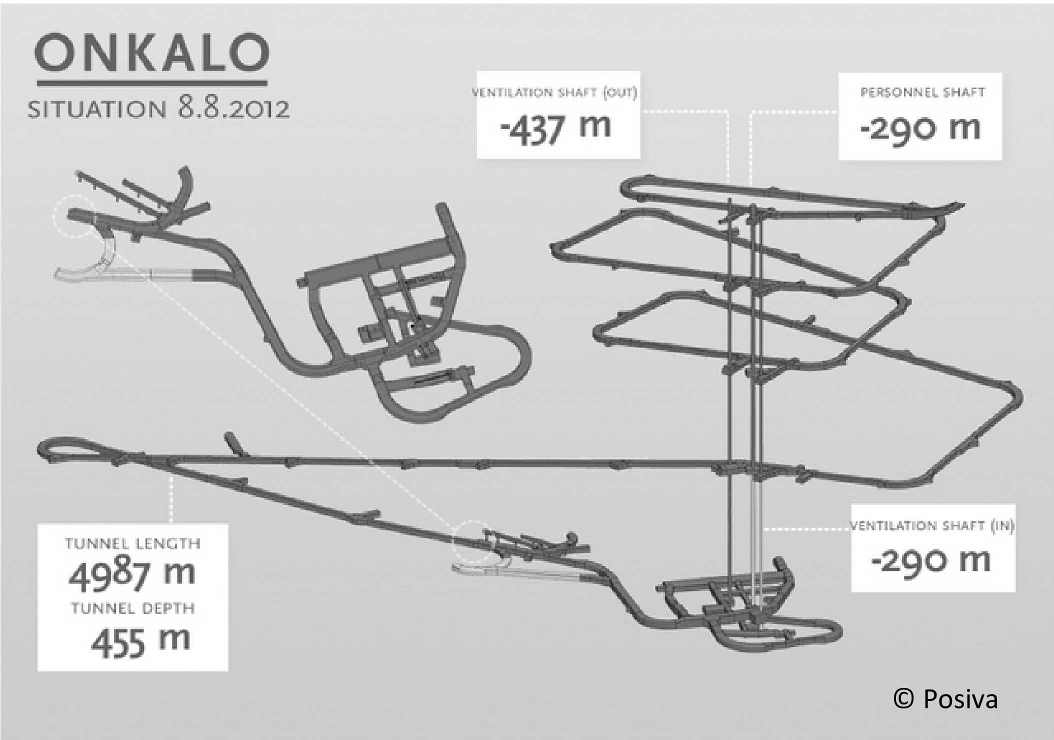

Figure 1: Construction situation on Underground rock characterization facility ONKALO. Access tunnel length 4987 m (www.posiva.fi).

2. General aspects of the role of monitoring

The roles of monitoring are related to specific phases of disposal facility lifecycle. For some phases the aims and also implementation is quite clear (for example site baseline monitoring). However for some other purposes the monitoring strategy or use of monitoring information is not as straightforward.

During pre-construction period the role of monitoring is to establish knowledge of site baseline and natural evolution. During construction phase, monitoring has the role to follow the effects that construction has compared to baseline or expected disturbance. In case of continued construction during the operational phase the same monitoring role for observing disturbances is continued. These monitoring roles are related to site and are quite easily understood and agreed among different parties.

During the operational phase some kind of barrier system evolution monitoring is required. In this area the strategy and implementation is not as well agreed and there exist more diverging opinions. There are alternative routes to acquire more information related to engineered barriers performance. For example implementer may choose to use one or several of the following alternatives: Monitor near field site properties, monitor in-active demonstrations of engineered barrier performance, monitor of defined active waste packages or use future wireless technology for monitoring all canister locations.

For every selected route it would be important to develop monitoring strategy that defines what kind of information is expected to be gained, and how it is connected to operational and post-closure safety. It is also important to address the possible mitigating or corrective actions that can be taken based on monitoring results. Key question is to address the level of confidence that can be achieved through monitoring and reliability of information that can be gained through long-term monitoring.

3. Legislation and regulation in relation to monitoring

The Finnish regulation and regulatory decisions specify how monitoring shall be used to gather information and follow the nuclear facility safety and evolution of the site and near-field properties. Typical areas where traditional monitoring is used in nuclear facilities are radiation protection of the workers, monitoring of radioactivity and dose rates, radiation monitoring in the environment of the nuclear facility and meteorological monitoring. In an underground disposal facility monitoring shall also be used to follow that favourable host rock properties are maintained during the construction and operation and for monitoring or performance confirmation of safety barrier performance.

STUK has given requirements for dealing with monitoring in nuclear facilities, especially for radiation and environmental monitoring, for all phases of a facility life span; licensing, design, operation and decommissioning. The Government Decree 736/2008 [2] for the disposal of spent fuel gives the requirements covering the performance related monitoring. These requirements are also given in more detail in STUK’s YVL Guides.

The Government Decree identifies the need of using investigations and monitoring for ensuring post-closure safety. The Decree also has requirements concerning favourable site properties that shall be observed via a research and monitoring programme. Concerning barrier performance it is required that ”*The long-term performance of* *barriers shall be confirmed by establishing an investigation and monitoring programme, to be implemented during the operational period of the final disposal facility.*"

Forthcoming, updated STUK YVL Guide D.5 [3] part "Construction, operation and closure of the disposal facility" gives more detailed requirements for monitoring:

> "*510. During the construction and operation of the disposal facility, an investigation, testing and monitoring program shall be executed to ensure the suitability for disposal of the rock to be excavated, to determine safety relevant characteristics of the host rock and to ensure long-term performance of barriers. This program shall include at least*
> - *characterization of the rock volumes intended to be excavated*
> - *monitoring of rock stresses, movements and deformations in rock surrounding the waste emplacement rooms*
> - *hydrogeological monitoring of rock surrounding the waste emplacement rooms*
> - *monitoring of groundwater chemistry at the disposal site*
> - *monitoring of the behaviour of engineered barriers.*"

Monitoring is also related to basic principle of continuous improvement of safety. STUK guide YVL D.5 requires licensee to have operating experience feedback programme where monitoring programme is one source of information. Based on these programmes, possibilities for safety enhancement shall be considered and any improvements found justified shall be implemented.

4. Monitoring in different phases of repository lifecycle

The Finnish regulations require the implementer to develop a safety concept including the safety functions and performance targets for different barriers. The regulation also includes general requirements for monitoring. The requirements have evolved during the development of the deep geologic repository. It is the implementer's responsibility to identify which geological or other parameters the monitoring programme should include. As a regulator STUK ensures that proposed monitoring programme has adequate coverage, it is carried out and information is collected and recorded. STUK reviews all monitoring results dealing with the facilities under construction and during operational period regularly. Monitoring is considered as a necessary tool to assist in estimating the safety of the repository in the stepwise licensing approach.

The lifecycle of repository can be divided for example in to the following phases; site selection, construction, operational, closure and post-closure. The monitoring may be related to these phases for example by following tasks:
- Monitoring before the site selection (for the Environmental Impact Assessment, EIA)
- Baseline or basic monitoring of site properties (bedrock, environment, bedrock, several areas of monitoring) during the detailed site investigation
- Monitoring the effect of construction (URCF or disposal facility)
- Monitoring or compilation of nuclear facility baseline before the start of the disposal operation (after the construction period of first part of the disposal)
- Monitoring related to demonstrations for technical feasibility of the concept (research phase dealing with EBS-components) and performance confirmation of barriers
- Monitoring the effect of operation and continued construction
- Monitoring the performance of closure structures

- Post-closure monitoring (institutional control)

In the following some parts and aspects of these task are addressed.

Monitoring before construction

The safety of the Olkiluoto disposal facility is based on ensuring the long-term engineered containment of the disposed waste. For long term safety it is vital that such chemical and mechanical conditions are maintained in the bedrock that the safety functions of the repository are not jeopardized over a long period of time in a variety of normal and abnormal circumstances.

During the safety strategy and concept development it is important to determine safety functions for barrier system and identify performance targets for these safety functions. Regarding the host rock, natural barrier, the role of site characterization and baseline monitoring is to characterize and verify the existence of the favourable site properties that are needed for the safety concept and to identify the status of undisturbed properties. This process can be part of identification of undisturbed host rock properties that form baseline for construction monitoring. In Finland this is a part where Posiva and STUK have concrete experience since the site characterization and monitoring of the site prior to ONKALO URCF construction has been realized.

After the site selection and DiP was finalized STUK made decision informing Posiva about the coming regulatory oversight and also informed about the content of information to be submitted before construction works start. According to STUK request, Posiva prepared a set of URCF documentation that focused on the construction of the facility and on post-closure safety issues. The documentation consisted of (see www.posiva.fi):
- Baseline Conditions at Olkiluoto (POSIVA 2003-02)
- ONKALO Underground Rock Characterisation Facility - Main Drawings Stage (Posiva WR 2003-26)
- Assessment of Disturbances Caused by Construction and Operation of ONKALO (POSIVA 2003-06)
- Programme of Monitoring at Olkiluoto During Construction and Operation of the ONKALO (POSIVA 2003-05)
- ONKALO Underground Characterisation and Research Programme (UCRP) (POSIVA 2003-03)

STUK made a review of the documentation during year 2003 using as support reviews of four international expert groups. STUK assessed Posiva’s understanding and plans against regulatory requirements and against the state-of-the-art understanding of post-closure safety. STUK submitted review findings to Posiva in early 2004. STUK’s key findings related to planned monitoring were that
- Posiva’s programme comprehensively covers the monitoring of disturbances in surrounding bedrock, surface water and groundwater and in surface environment.
- Overall impression was that monitoring plan is in principle adequate for URCF phase, but when entering to construction of actual disposal rooms or to disposal operations the coverage of monitoring programme should be re-evaluated.
- STUK noticed that Posiva should establish a seismic monitoring network to Olkiluoto and surrounding area.

- STUK emphasized the importance of non-proliferation regulation and monitoring activities needed for this and integration of safety and safeguards relevant monitoring activities.

Posiva's monitoring programme was based on assessment of post-closure safety relevant site properties and possible disturbances affected by construction. Posiva classified the effects based on post-closure safety relevance and developed quality assurance procedures that aimed for assuring that favourable site properties could be maintained. The key safety relevant areas and STUK oversight is described later in this paper.

Regulatory oversight of construction monitoring

The implementer, Posiva Ltd is currently finalizing the construction of an underground rock characterisation facility, ONKALO. During the construction, Posiva has carried out an extensive monitoring programme to follow for construction effects. This programme has included several monitoring areas, such as surface environment, hydrology, hydrogeochemistry, rock mechanics and foreign materials. STUK has followed the work done and reviewed the documentation. The information that the programme has provided will be utilized in the construction license application review process. STUK expects that a similar and extended monitoring programme is used later during the construction and operating periods of the disposal.

Construction of ONKALO until the planned disposal depth (c.a. –430m) disturbs the geological environment and conditions in a variety of ways. The purpose of STUK's regulatory control of ONKALO construction is primarily to ensure that the design, adaption and construction are carried out in such a manner that the geo-environment maintains its favourable characteristics and conditions needed for the safety functions. In particular, this implies the minimization of:

- Host rock responses to excavation, excavation disturbed areas and zones,
- Groundwater leakages to the ONKALO tunnels and shafts, and
- Introduction of foreign, potentially harmful substances to ONKALO during construction (cement and other grouting materials, reinforcement materials, explosives etc.).
- Pathways from surface to disposal rooms

Long-term effects of ONKALO construction are being observed by Posiva in the Olkiluoto Monitoring Programme (OMO; Posiva 2003-05 [4]). The programme includes monitoring of rock mechanical, hydrological, hydrogeochemical and environmental processes in the vicinity of the ONKALO. Particular attention is given to changes in characteristics that may have implications for post-closure safety, for instance, changes in groundwater salinity at repository depth. The monitoring programme has been updated for the construction licence application.

STUK has had a comprehensive regulatory approach for review and assessment and inspection of ONKALO construction activities. STUK has reviewed the updates to Posiva's monitoring plan during ONKALO construction and also Posiva's yearly reporting of monitoring findings in areas of rock mechanics, geochemical disturbance, geohydrological disturbance and biosphere.

During the construction STUK has reviewed Posiva's procedures for excavation, injection grouting and rock reinforcement where also the aspect of disturbance and monitoring is assessed. STUK has made inspections to management of ONKALO monitoring programme and has also focused to specific monitoring activities (procedures, resources, competence, quality of results, equipment, uncertainties). These inspections and regulatory findings are documented in inspection protocols.

Monitoring of operational safety

The programme developed for monitoring the effect of construction is continued during operational phase since the continuous construction and keeping the facility open may have effect on bedrock properties. For operational phase the licensee however has to expand the programme to cover also other monitoring requirements common for all nuclear facilities. These are described for example in Radiation Act [6], Nuclear Energy Act [5] and in specific YVL guides. These requirements are related to workers dose monitoring, environmental monitoring of discharges and monitoring or surveillance of nuclear material and security issues.

Barrier system performance confirmation

STUK's updated, soon to be published regulatory guide (YVL D.5) includes requirement for engineered barrier system (EBS) monitoring also during the operational period. The monitoring of EBS might include monitoring of relevant near field parameters, monitoring of long duration tests or in some cases monitoring of actual barrier evolution. However, the general safety requirement is that monitoring shall not impair post-closure safety. There are no explicit requirements identifying specifically the concept of performance confirmation. STUK considers it useful if licensee would have a strategy and systematic procedure to carry out testing and demonstration activities to show performance confirmation during the R&D, commissioning and operational period. Emphasis should be put on connecting the individual tests to the safety related properties of individual barriers.

The research and monitoring programme required by the Finnish regulation (GD 736/2008, 9§, 10§) contain the requirements to carry out research to follow up and develop the disposal process (concept, process, technology) during operational period. This can include various tests and demonstrations inherently including monitoring activities. Monitoring should be systematic and representative both in space and time and linked to the research programme. This research and monitoring programme can be considered as a part of performance confirmation process, which measures and evaluates whether the disposal functions behave as expected and within the safety envelope. Both monitored test results and analysis are required for the performance confirmation process. This type of an activity can also include a task to follow up the development of science and technology in the areas relevant to the monitoring of radioactive waste. The information produced and collected within these programmes can be used for experience feedback and shall be analyzed as part of periodic safety review.

As said, the Finnish disposal concept relies on long-term containment of waste. The performance of barriers and fulfilment of safety functions are assumed to be valid if the initial state is achieved and the evolution onwards follows the base scenario. Feasibility of the initial state can partly be assured by controlling and monitoring the activities connected to waste inventory, the canister and buffer and backfill components and their emplacement. The monitoring of EBS is carried out to follow the evolution of different engineered barriers in the disposal in contact with the bedrock. One important task is to identify the sources of uncertainties and determine the effects of uncertainties on the behaviour/performance of various barriers and the safety of the whole concept. This work is partly long-term scientific R&D work and partly performance confirmation.

There are no direct ways to ensure that the evolution of a repository follows the assumed normal evolution during the life-time, up to 1 Ma, of the repository. It is also doubtful if the disposal as a whole shall evolve to a quasi static, saturated state during the operational period. In some cases it is yet possible to follow up the evolution starting from the initial state during the operational period through carefully planned and executed research and monitoring programme. The current monitoring instruments have a limited lifetime when compared to planned operational period of the disposal facility and barrier evolution and thus confirmation of post-closure performance can not rely on monitoring. Some assumptions concerning the future evolution of these barriers may be verified and, as a part of performance confirmation, full scale instrumented and monitored demonstration tests (prototype repository) with proper dismantling phase can be useful in verifying some basic assumptions already during the operating period. Results can be used for confidence building for the system and managing and minimizing uncertainties in the information used in the safety analyses for periodically updated safety cases.

Monitoring during the institutional control phase

According to Nuclear Energy Act (YEL) (7h§, 3rd para: "*The disposal of nuclear waste in a manner intended as permanent shall be planned giving priority to safety and so that ensuring long-term safety does not require the surveillance of the final disposal site*.") the repository concept must be based on a passive solution not requiring active control, monitoring or surveillance. This means that no active monitoring or measures are required to maintain the safety of the repository after the closure.

In Finland the responsibility of the repository (also monitoring and surveillance) will be transferred to the State after the successful and approved closure of the disposal (YEL 32§).

In case the State considers it necessary, a monitoring system may be used and the estimated life time cost will be charged in advance form the implementer before the approval of the closure (YEL 34§, 2^{nd} para).

This monitoring is mainly used for confidence building of various stakeholders. It is doubtful that the repository would have any radiological environmental impacts during the expected monitoring period. However monitoring and collection of information of possible environmental impacts (releases) may reassure the local population. Monitoring is most probably carried out on the surface and possibly in the bedrock at shallow depth and could also include observation of site properties evolution after repository closure.

In excess to this performance and safety related monitoring there may be some monitoring and surveillance activities for the safeguards and security measures.

5. The role of demonstrations regarding monitoring

Monitoring is an essential and usually necessary part of all kinds of short or long-term demonstrations or research activities carried out in laboratories, URLs and repositories. It is also possible to build up demonstrations to present the monitoring possibilities and technology and to show the long term durability of instruments and data acquisition.

For the short time demonstrations (few years) the technology and expertise together with experience is available and the cost is reasonable. The main problems are the stability and robustness of the commercially available instrumentation in hostile environmental conditions (temperature, pressure, chemical conditions, radiation).

Serious consideration of the targets of these short term demonstration tests (i.e. test design) should be carried out to identify the processes and results of scientific and/or safety interests in the performance confirmation process of the disposal system. This requirement is even more important for the long term monitoring activities.

For the long term demonstrations the technology and expertise are not always commercially or at all available and the cost of custom maid instrumentation is high. Also experience of successful long term instrumentation and monitoring test or demonstrations are sparse. The necessary technology may still be available in future during the operational period, up to and over hundred years, of a disposal.

Meanwhile, with these long term processes, a strategy to follow could be a combination of a robust instrumentation and a periodic dismantling of structures and EBS components and carrying out very detailed laboratory characterization of possible changes in properties (in comparison to initial state) to estimate the performance evolution.

6. Conclusions

In Finland Posiva and STUK has experience in implementing and regulating the monitoring of first phases of repository lifecycle. Posiva has developed monitoring programme for site characteristics baseline and construction effect monitoring. STUK has reviewed, assessed and inspected the implemented programme. STUK’s overall conclusion at this point is that Posiva’s programme has been comprehensive and supported the maintenance of favourable site properties. Based on STUK regulatory experiences it is important that implementer addresses carefully the safety relevant properties, the parameters selected for monitoring and the management system to take actions based on monitoring findings.

One near future item to develop further is to address in more detail the requirement for EBS monitoring and how this can be related to performance confirmation. The new YVL regulation is seen to be sufficient for construction phase and need for update is evaluated when approaching to operational phase.

STUK noted that Posiva submitted an updated monitoring programme as part of construction license application. This programme is expected to follow the same lines as the previous programme for ONKALO and STUK reviews and assesses the adequacy of programme. It seems to be accepted that performance confirmation can start already from the site selection and extend up to, but not beyond, the time of final license approval for permanent closure of the waste repository. This means that the process can last decades or even over a hundred years in some disposal facilities.

Monitoring of the site, bedrock and EBS components during the construction, operation and pre-closure period could assist in performance confirmation of a deep geologic disposal. An important item to acknowledge is the conflict of slow, long lasting, evolution of barrier system and fairly short expected lifetime of current monitoring equipment. The expected outcome from these activities is at least the early evolution of EBS components and bedrock conditions, possibly justifying the base scenario, from the initial state in the monitored areas during the selected monitoring period. Representativeness of the acquired results is limited to certain point and time. The monitoring strategy must consider how these few point measurements are analyzed and uncertainties assessed and how they represent the overall status of the disposal system.

References

[1] Decision in Principle, DiP. Valtioneuvoston periaatepäätös 21 päivänä joulukuuta 2000 Posiva Oy:n hakemukseen Suomessa tuotetun käytetyn ydinpolttoaineen loppusijoituslaitoksen rakentamisesta, Helsinki 2000. In Finnish.

[2] Government Decree on the safety of disposal of nuclear waste, (GD 736/2008), 27th November 2008, Helsinki.

[3] STUK Guide YVL D.5 Disposal of Nuclear Waste (Draft)

[4] Programme for monitoring at Olkiluoto during construction and operation of the ONKALO, Posiva 2003-05, Posiva, Eurajoki.

[5] Nuclear Energy Act, (990/1987), 11th December 1987, Helsinki.

[6] Radiation Act, (592/1991), 27th March 1991, Helsinki

Monitoring requirements in the Swiss regulatory framework

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1. Introduction

The Swiss expert advisory group (EKRA) concluded in its study in 2000[1] that, based on the current knowledge, passively safe geological disposal is the only method for isolating radioactive waste which meets the requirement for long-term safety over geological time scales (i.e. for high-level waste up to more than 100'000 years). The disposal concept shall be based on a combination of engineered and natural safety barriers which ensure long-term isolation of the waste. In order to take into account societal demands from the public for controllability and retrievability of the waste, EKRA has developed the concept of monitored long-term geological disposal, which combines passive safety with a period of monitoring and the possibility of retrievability without undue effort during the emplacement phase and monitoring phase until final closure of the repository.

2. Repository concept and regulatory framework

According to the concept of monitored long-term geological disposal, the deep geological repository system comprises the following three elements (see figure 1): a) *main facility* for the emplacement of the radioactive waste, b) *pilot facility* for monitoring repository system behaviour and for demonstrating compliance with safety requirements, c) *test areas* (underground rock laboratory with several test areas) for investigating safety-relevant properties of the host rock or the engineered barriers to support the safety case or for demonstrating the correct functioning of required technologies (e.g. for emplacing the backfill material, for retrieving waste packages and for sealing of caverns and tunnels).

The proposed EKRA concept of monitored long-term geological disposal was included in the Nuclear Energy Act of 2003[2]. The Nuclear Energy Act, the Nuclear Energy Ordinance[3] and the guideline (ENSI-G03)[4] specify in more detail the requirements for monitored geological disposal.

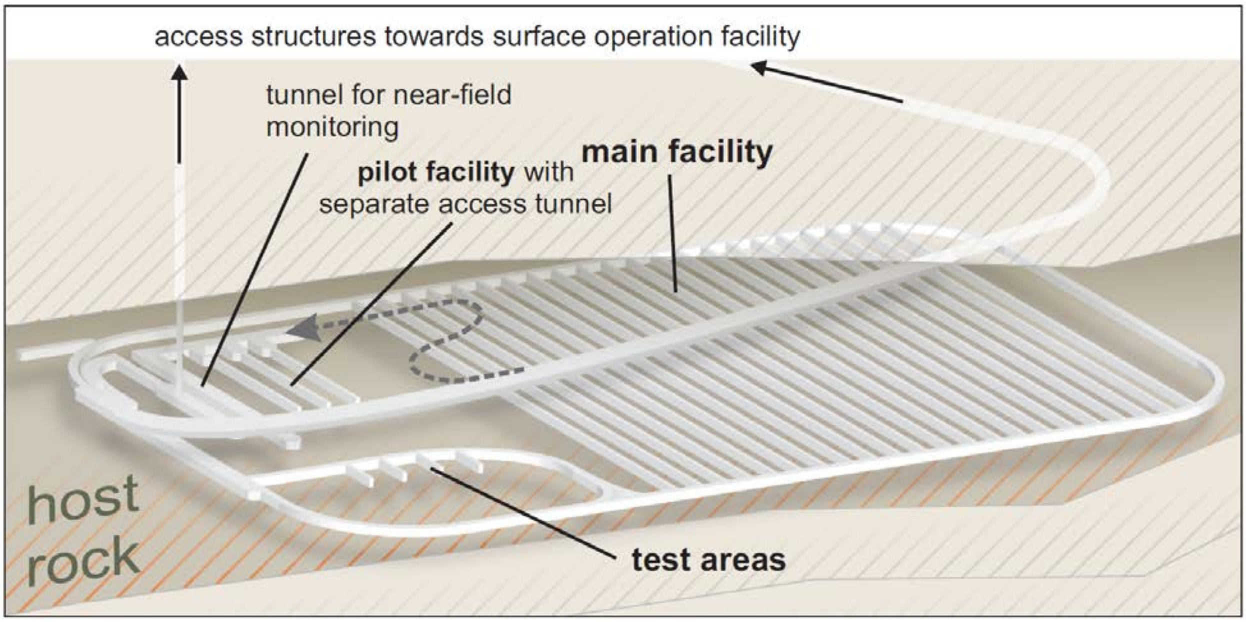

Figure 1: System elements of a monitored geological repository: main facility, test areas and pilot facility.

According to the regulatory framework the *test areas* are self-contained parts of the geological repository, where the safety-relevant properties of the host rock or the engineered barriers as well as the degradation behaviour of materials can be investigated in detail in order to support the safety case, or where required technologies (e.g. for emplacing the backfill material, for retrieving waste packages and for sealing of caverns, tunnels and shafts) can be developed, tested and their correct functioning be demonstrated.

The *pilot facility* is a self-contained part of a deep geological repository that is separated from the main facility and is used to monitor the behaviour of the entire barrier system up to the end of the monitoring phase. The main purpose of the monitoring programme of the pilot facility is to provide information on the conditions, processes and effectiveness of the installed barrier system, to confirm compliance with the safety requirements and to allow for early identification of any unexpected developments.

3. Phases of repository implementation

According to the Swiss Nuclear Energy Act and the Nuclear Energy Ordinance, implementation of a geological disposal facility is a stepwise process over several decades which include the following phases (estimated time needed for each phase of the implementation of a deep geological repository for high-level waste (HLW) is indicated in parentheses)[5]):

1. Site selection process based on the sectoral plan for deep geological repositories[6] and general licence application for the selected site (~15 years)

2. Pre-construction environmental monitoring phase (baseline conditions) (4 years)

3. Underground exploration phase (rock laboratory for site characterisation) including test areas (20 years)

4. Repository construction including pilot facility (6 years)

5. Operation of the disposal facility (first pilot facility / second main facility) (15 years)

6. Monitoring phase (post-emplacement/pre-closure observation phase) (50 years)

7. Final closure of the repository (5 years)

8. Post-closure environmental monitoring phase (optional, can be ordered by the government)

The duration of the post-emplacement/pre-closure monitoring phase (7) is not legally fixed yet and will be specified in due time by the competent Swiss Federal Department. To estimate the costs for the Swiss waste management programme, 50 years have been assumed.

The phased implementation process for the geological HLW repository is illustrated in figure 2.

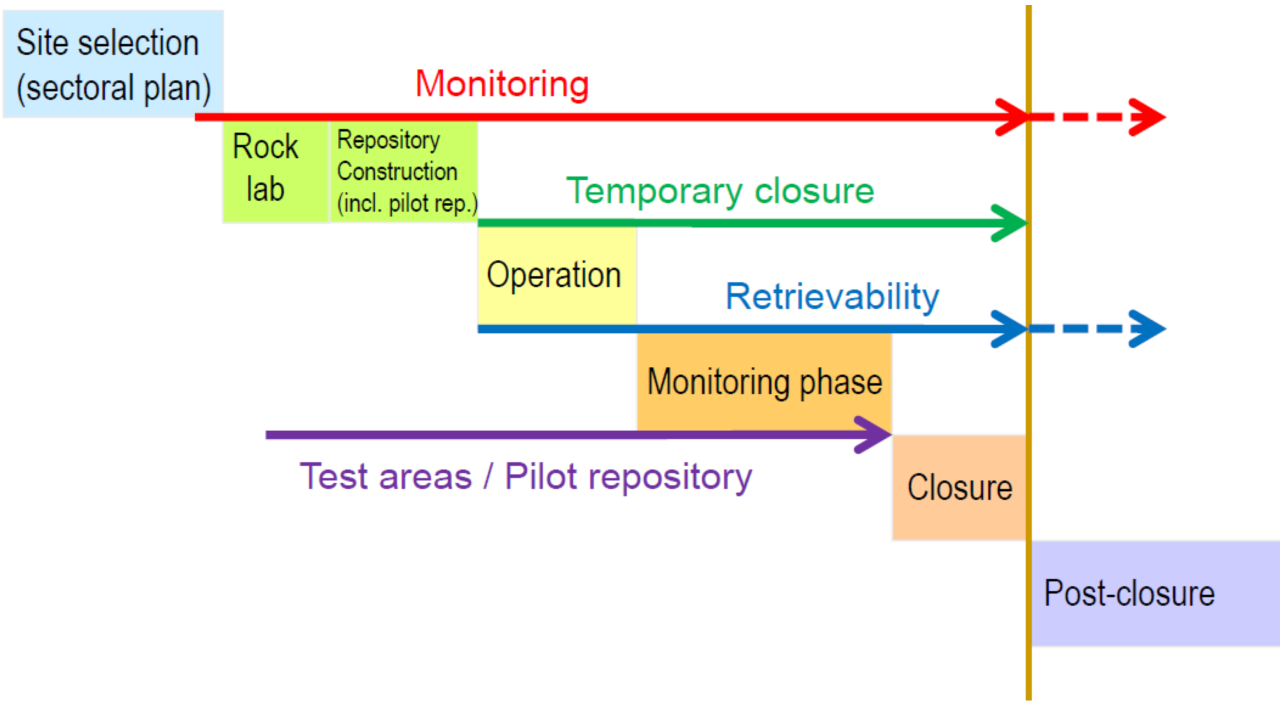

Figure 2: Schematic overview of the phased implementation of a geological HLW repository in Switzerland. For all phases a total duration of >100 years is anticipated up to closure.

4. Requirements for the pilot facility

In the pilot facility, the behaviour of waste, backfill material and host rock must be monitored up to the end of the monitoring phase. During monitoring, data are to be collected to support the safety case with view to repository closure. They form the basis for the decision on final closure of the repository. The following principles must be considered for the design of the pilot facility:

- The geological and hydro-geological conditions must be comparable to those of the main facility.

- The pilot facility must be spatially and hydraulically separated from the main facility.

- The construction of the pilot facility and the emplacement procedure of waste and backfill material must correspond to those of the main facility.

- The pilot facility must contain a small but representative quantity of waste.

- The pilot facility has to be operated and sealed before the start of waste emplacement in the main facility.

The pilot facility has to be operated in such a way that

- the barrier system of the main facility is adequately reproduced and

- the selection of waste packages is representative of the inventory of the main facility.

5. Requirements for monitoring

The monitoring programme for the pilot facility is destined to investigate the time-development of the pilot facility and its geological environment in such a way as to provide information

- on safety-relevant conditions and processes in the pilot facility and its geological environment
- for early recognition of unexpected developments
- on the effectiveness of the barrier system
- to support the confirmation of the safety assessment.

The information must be transferable to the situation in the main facility and its geological environment.

Complementary to the monitoring in connection with the pilot facility and test areas, the Swiss regulatory framework requires further monitoring elements for a deep geological repository:

- The environmental monitoring of a geological repository must be initiated sufficiently early before the start of underground construction to allow reliable data to be collected for the purpose of establishing the baseline of the environmental conditions. Monitoring must continue until the facility is released from the provisions of the nuclear energy legislation. It includes monitoring the radioactivity of springs and groundwater, soils, water bodies and the atmosphere in the area potentially influenced by the repository. The delivery and chemical composition of spring waters also have to be investigated for the purpose of preservation of evidence.

- As a continuation of underground site characterisation, monitoring of the geological environment surrounding the underground structures has to be carried out up to closure. Monitoring has to include, in particular, the hydrogeological conditions, water composition, rock parameters that are relevant for safety and the geometry of excavations. This supplements the geological and hydrogeological databases used for evaluating the long-term evolution of the repository.

- For the operation of a geological repository and its surface facilities, suitable radiological monitoring measures have to demonstrate compliance with the safety requirements. Radiological monitoring has to continue until the facilities are released from the provisions of the nuclear energy legislation.

As a basic requirement, monitoring shall not compromise the passive safety barriers. The suitability of the monitoring programmes has to be checked periodically. The monitoring programmes and their results are to be submitted periodically to the regulatory body for review.

6. Regulatory research project

In autumn 2011, the Swiss regulator has started a project to discuss and investigate issues concerning the pilot facility in more detail. These include

- processes and parameters which can be monitored over decades in a pilot facility
- possible concepts for the design of a pilot facility
- expectations of the public on the monitoring programme of a pilot facility.

The first phase of the project consists of expert hearings on specific questions with respect to a pilot facility. A second step will be scoping calculations of safety relevant processes. In order to evaluate specific requirements for the monitoring of a pilot facility, ENSI will also rely on the results generated by the EU project MoDeRn.

6. References

[1] EKRA (2000), Entsorgungskonzepte für radioaktive Abfälle: Schlussbericht, UVEK, Bern, Schweiz, Januar 2000.

[2] Nuclear Energy Act (2003), Switzerland, March 2003

[3] Nuclear Energy Ordinance (2004), Switzerland, December 2004

[4] ENSI-G03 (2009), Specific design principles for deep geological repositories and requirements for the safety case, Swiss Federal Nuclear Safety Inspectorate ENSI, Würenlingen, Switzerland, April 2009

[5] Nagra (2008), Entsorgungsprogramm 2008 der Entsorgungspflichtigen, Nationale Genossenschaft für die Lagerung radioaktiver Abfälle, Nagra Technischer Bericht NTB 08-01, Wettingen, 2008.

[6] SFOE (2008), Sectoral Plan for Deep Geological Repositories Conceptual Part, Swiss Federal Office of Energy SFOE, Bern, Switzerland, April 2008.

C.6 Session S6D: Theme 3: Monitoring technologies: Feasibility and limitations (focusing on monitoring barrier and repository component demonstrators)

State of art of monitoring technology for repositories: instrumentation performance obtained from long duration experiments

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Summary
The successful implementation of a repository programme relies on both the technical aspects of a sound safety strategy, comprising scientific and engineering excellence, as well as on social aspects such as public acceptance. Monitoring has the potential to contribute on both aspects and thus has an important role to play as national radioactive waste disposal programmes move forward towards a successful conclusion, i.e. safe and accepted implementation of geological disposal. The FP7 MoDeRn Project "Monitoring Developments for Safe Repository Operation and Staged Closure" aims to further develop the understanding of the role of monitoring in staged implementation of geological disposal to a level of description that is closer to the actual implementation of monitoring.

One relevant part of the MoDeRn project aims to establish the state-of-the -art of applicable monitoring technologies that could be applied to monitoring programmes. Such state-of-the -art was developed upon the experience in comparable monitoring environments, including URLs, ILW repositories and long term storage experiences, as well as relevant industrial experience in other fields as for instance nuclear power plants, mining operations, subsurface infrastructures, hydrocarbon exploration or CO2 sequestration exploration.

The monitoring technologies have been structured in the following sections:

- Repository-based monitoring,
- Borehole-based monitoring,
- Surfaced-based monitoring and
- Aerial monitoring systems

As the main interest of MoDeRn project is the monitoring to be carried out during the operational phase, the state-of-the -art report pays more attention to those techniques that are more suitable for that period, which are the repository and borehole based ones. In this sense all experiences and results obtained from long duration experiments developed in European URLs are very valuable because they are very close to the conditions expected at the Repository.

The review carried out provides not only the required technical information on the different techniques but evaluates the maturity and applicability of the described technologies. This study allows highlighting gaps in knowledge or application of monitoring techniques that still need to be addressed.

1. Introduction

Spent nuclear fuel and long-lived radioactive waste must be contained and isolated for very long periods, and current schemes for their long-term management involve disposal in deep geologic repositories. The successful implementation of a repository program for radioactive waste relies on both the technical aspects of a sound safety strategy and scientific and engineering excellence as well as on societal aspects such as stakeholder acceptance and confidence. Monitoring is considered key in serving both ends. It underpins the technical safety strategy and quality of the engineering, and can be an important tool for public communication, contributing to public understanding of and confidence in repository behaviour.

The increased interest in monitoring the repository prior to closure is consistent with a general consensus that future work is required after receipt of a license to construct and operate. It is expected to contribute to a transparent disposal process acceptable to stakeholders and to provide further basis supporting a future decision to close the repository. This is consistent with socio-political feedback received on earlier disposal program developments, many of which have effectively halted further progress towards implementing a repository, irrespective of their demonstrated technical and scientific soundness. From these, a consensus appears to have emerged, that an informed, stepwise approach provides an acceptable basis permitting progress from a licensing stage through progressive construction, operation and ultimately closure of a repository

To further build upon these prior and parallel developments, the European Commission has decided to include the Topic *Strategies and technologies for repository monitoring* in its 7th Framework Program to request corresponding proposals. A Grant (Agreement n°232598) was awarded to the collaborative MoDeRn project, whose main goal is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during the staged approach of the disposal process.

Up to 18 partners representing 12 countries and including 8 Waste Management Organisations joined their efforts since 2009, and aim at developing a “roadmap to repository monitoring” by 2013, which addresses these issues. The partners represent organisations responsible for radioactive waste management in the EU, Switzerland, the US and Japan as well as organisations having relevant monitoring expertise. Other partners offer substantial experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organizations, industry) in highly technical issues.

MoDeRn partners stated that for the development of the repository monitoring several key issues must be addressed, and that after identifying relevant monitoring objectives, as a result of implementer’s requirements and stakeholder expectations, the capacity to provide some information to meet those objectives should be determined. Therefore, to evaluate the present technical capability for the monitoring activities development and the need of future research in this matter an assessment of the state-of-the-art of relevant technology responding to these requirements was required.

2. Objectives and approach

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

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

Emphasis was placed on sensors, signal transmission, local energy sources and signal diagnosis tools and techniques, which will be relevant for monitoring in repositories. Special attention was paid to innovative approaches and a dedicated workshop was organised with representatives of related research projects [1]. Furthermore, the results of few RTD activities focused on promising monitoring technologies, identified at the very beginning and developed within the MoDeRn project, have been incorporated as well:

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

3. The state-of-the-art report

The state-of-the-art report is structured in five sections:

- Section 1 describes the background to the MoDeRn project and the objectives and structure of the report.
- Section 2 provides a high-level summary of repository monitoring.
- Section 3 summarises the state-of-the-art gathered on monitoring technologies.
- Section 4 provides an evaluation of the monitoring techniques presented and highlights the main areas for improvement in existing technologies.
- Section 5 presents the conclusions from the study.

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 the stakeholder expectations.

An example of processes in different parts of a repository that a repository monitoring programme might cover is provided hereafter, based on a generic conceptual design for the engineered barrier system of a high-level waste (HLW) repository illustrated in Figure 1.

- Waste disposal packages:
    - Containment of waste.
    - Mechanical and chemical stability of waste packages.
- Other engineered components (buffers, backfills, seals and structural components):

- Containment of waste in repository – resistance to groundwater flow and transport through the repository.
- The consistency of thermal, hydro, mechanical and chemical (THMC) conditions with the assumptions made in the safety case.

- Natural environment (near-field geological environment):
    - Minimise perturbation of host rock.
    - 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.

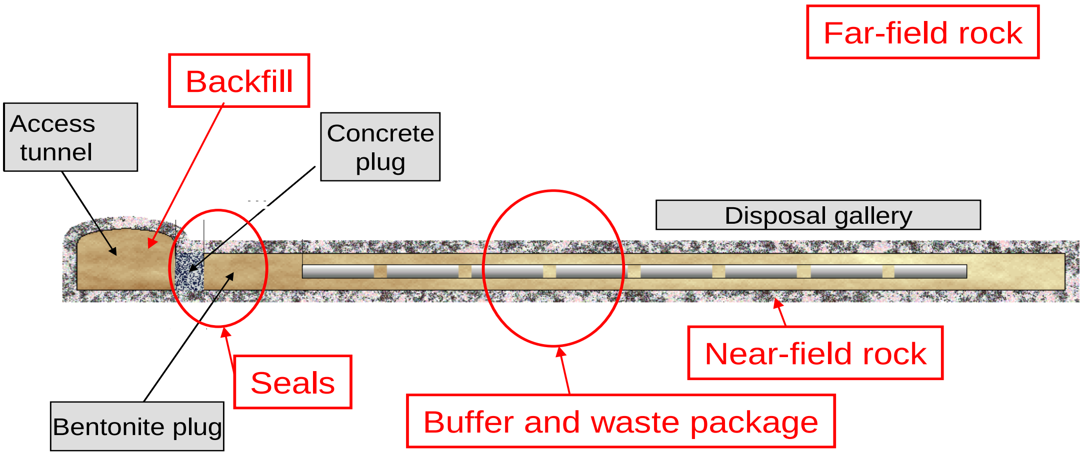

Figure 3:
engineered barrier system of a HLW repository.

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 relay upon monitoring but that monitoring systems provide for the operator, the regulator and the public a means, in the short term, of monitoring 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 should be considered. Other aerial monitoring systems such as satellite based techniques could also be used to provide monitoring information.

In consequence the applicable monitoring technologies (Section 2) have been structured in the following sections:

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

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

4. Discussion

A preliminary list of parameters of interest for most repository monitoring programs[24] was identified and compiled:

- 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

As an example of the information provided in the document, a summary of the chapter corresponding to the measure of water content and humidity at repository level is included hereafter (not all the available techniques are considered here due to the length limitation of this paper).

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

[24] 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.

In a very simplified manner, the construction of a Nuclear Waste Repository involves the excavation of a rock and the later emplacement in the vaults of the waste that 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 with the amount of water contained in the pores.

In this sense the <u>water content</u> 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 <u>humidity</u> 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 the 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 invested to extract water. This is especially interesting for modelling purposes.

Techniques and signal characteristics

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

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

I. 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.

Figure 4: Neutron moderation: equipment: probe versions and readout

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 conceived to remain inserted in the material and surface probes, both usually applied to silos of bulk material.

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 4 - 16 in. 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 16 in. 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 out due to 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 is 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 content in organic matter require specific attention and specialised calibration as organic compounds contain significant hydrogen.

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

II. Volumetric methods: Dielectric techniques.

They estimate water content by measuring the bulk permittivity (or dielectric constant), which determines the velocity of an electromagnetic wave or pulse through the measured material. 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 require of 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 automated continuous readings.

- *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: $Ka_b = (c/v)^2 = [(c \times t)/(2 \times L)]^2$ (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 5: 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 analysed). In highly saline materials, the use of epoxy-coated probe rods may solve the problem. However, this implies loss of sensitivity and change in calibration. In addition to travel time, 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 1.2 inch radius around length of waveguides).

III. 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 be measured, 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 start reading sufficient time must be allowed after field installation so that the device and the material can equilibrate.

- *Relative humidity sensors*

Under vapour equilibrium conditions, water potential of a porous material is directly related to the vapour 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 [2].

- *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 these 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 6*). 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 [3].

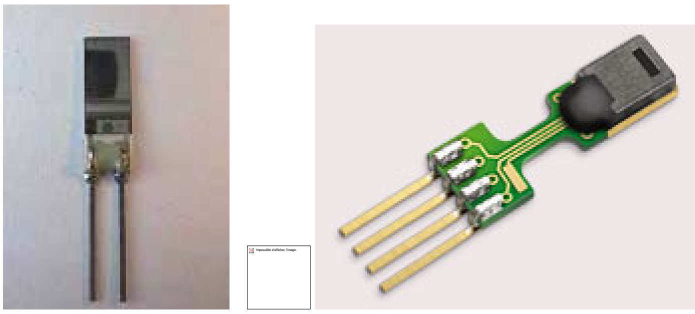

Figure 6: Capacitive probe

Capacitive sensors are characterised by low temperature coefficient, ability to operate at high temperatures (up to 200° C), full recovery from condensation and reasonable resistance to chemical vapours. The sensors show a good long-term performance. Although generally specified for a measurement range form 0 to 100 % relative humidity capacitive sensors lost their accuracy when they become saturated [4].

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 key 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 selection of techniques and sensors for a Nuclear Waste Repository can depend on many different factors and 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 [5]. 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.

TDR sensors use to be very large in comparison with capacitive hygrometers. 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, 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.

5. Conclusions

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

For instance some areas for further improvement in existing technologies have been identified by the partner organisations:

- Adequate corrosion sensors are required
- The available sensor should be tested and if required, shielded against radiation
- Long-term duration of sensors should be evaluated or improved
- Additional research is needed regarding long term power supply
- Combined solution for wireless data transmission should be established

6. Acknowledgements

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

References

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

[2] Campbell, G.S. and Gardner, W.H. (1971): Psychrometric measurement of soil water potential: temperature and bulk density effects. Soil Sci. Soc. Am. Proc. 35: 8-12

[3] Platineanu, I.C., Starr, J.L. (1997): Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. Soil Science society of America Journal, 61, 1576-1585

[4] Alonso, E.E., Springman, S.M. & Ng, C.W.W. (2008): Monitoring Large-Scale Test for Nuclear Waste Disposal. Geotech. Geol. Eng. 26, 817-826. doi: 10.1007/s10706-008-9195-2

[5] García-Siñeriz, J.L., Bárcena, I., Fernández, P.A. & Sanz, F.J. (2004): Instrument analysis report. Project deliverable D14, Aitemin internal report, Madrid. Project NO.70-AIT-L-6-9, 79 pp

MoDeRn - Design and development of a large-scale in situ monitoring test in the French URL at the Centre Meuse / Haute-Marne

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Andra, France

Summary

A large-scale experiment on monitoring of intermediate-level long-lived waste (ILLW) disposal cells has been set up in Andra's Meuse / Haute Marne underground laboratory (URL) between April and December 2011. The experiment has validated the installation procedures including redundancy and performance of sensors in a one-to-one scale mock-up. Over three hundred measurement points provided by various sensors types fill every 30 minutes a database in order to determine the thermo-hydro-mechanical (THM) behaviour of the host rock and the concrete liner.

The instrumentation was installed in a circular cross-section 3.6 m long and 5 m in diameter, with the aim of being representative of a possible monitoring system for ILLW disposal cells. Several types of sensor were tested in this section within the framework of Andra's R&D program (see. Fig.1).

18 months after installation, a very good sensor survival rate has been confirmed. Also, measurements using different technologies showed a good correlation. The monitoring test will be analysed over several years in order to obtain information on sensor aging, accuracy, possible drift and robustness. Measurements will also be compared with results from different non-destructive measurement methods in order to confirm the required level of reliable performance.

Finally, such long-term measurements will help to create a database of event signatures.

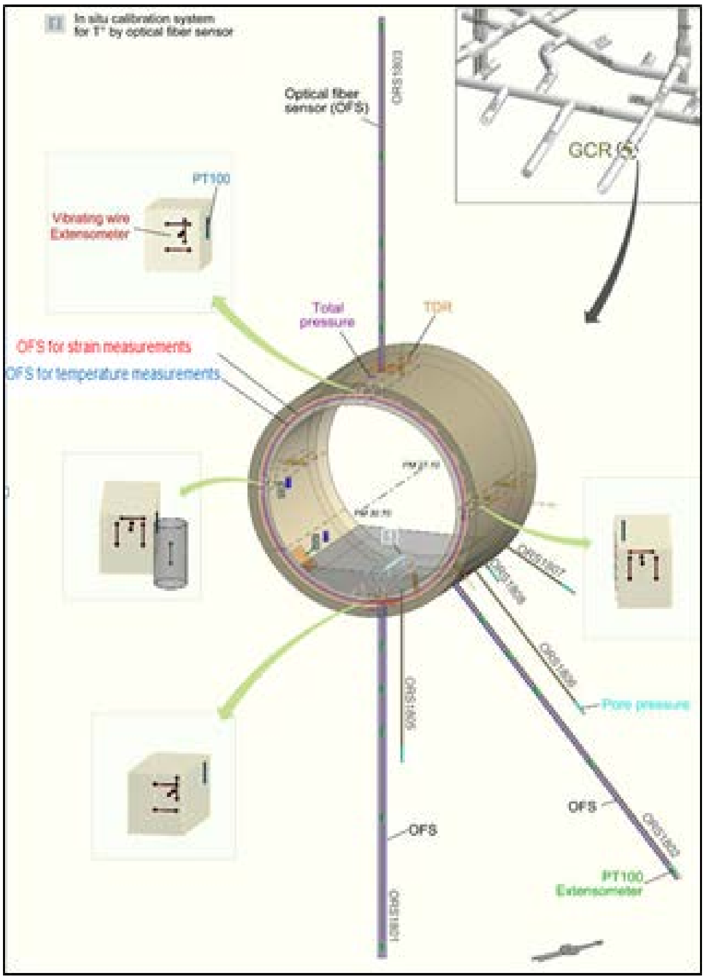


Figure 18: Monitoring section instrumentation

1. Introduction

The underground installations of Cigéo (the planned French Industrial Centre for Geological Disposal) will be constructed stagewise and operated over a period in the order of a century in an area close to the location of the underground laboratory. Within the framework of this project, monitoring of the environment and the repository installations, which in Andra's project is termed "Observation and Surveillance", should provide the required information for safe operation of the facility and reversible management. The monitoring system should provide input for the safety analyses during repository operation and after closure, highlight developments that provide information on flexibility for future decision-making and on the environmental conditions for implementing such decisions. Finally, monitoring can also provide input for improving the design procedures for future waste disposal cells (see Stephane Buschaert & al. paper, this meeting).

The monitoring system envisages a combination of in-situ instrumentation and non-destructive measurement methods that will be used to obtain reliable data. To optimise sensor implementation, both consistent disposal cell design and homogeneity of the rock properties are taken into account.

Andra's overall monitoring strategy for all phases of the disposal process is basis and acts as guideline for the development and implementation of the different monitoring approaches. This paper highlights the monitoring approach for the ILLW disposal cells of a geological repository and provides detailed consideration of thermo-hydro-mechanical parameters.

2. Monitoring of intermediate-level long-lived waste (ILLW) disposal cells

Monitoring system specifications

In the underground repository, the adverse environmental conditions have consequences for all types of devices and systems. The main component of the monitoring system will be installed during the construction phase, run during the operational period and could be used for decades to centuries for post-closure observation.

The requirements and specifications for long-term safety, operational safety and reversibility, in addition to the adverse environment for sensors, require the sensors to be elementary (no on-board electronics), non-invasive, reliable and robust with a known ageing behaviour. Sensor reliability is a key issue in meeting the requirements on long-term monitoring where the interpretation of measurements may involve significant uncertainties. The combination of instrumentation to provide redundancy would extend the period over which the instrumentation continues to provide usable data. For Andra, the monitoring program includes a qualification process that is used to make an evaluation and develop sensors for specific applications.

In order to select and qualify an adequate monitoring system, Andra's R&D program has identified potentially adequate sensors for the monitoring system for the ILLW cells of Cigéo. Sensors that are qualified under well-known and controlled conditions in laboratory are also tested in parallel in the *in situ* environment and hardened to radiation. The paper focuses on a large *in situ* test performed in the Andra Underground Research Laboratory (URL).

Design of the monitoring system

The design of the monitoring system for the ILLW cells (Fig. 2) has to ensure the reliable operation of the measurement system for a period of at least 100 years, without any maintenance. It is therefore essential that the long-term stability of the sensors be assessed.

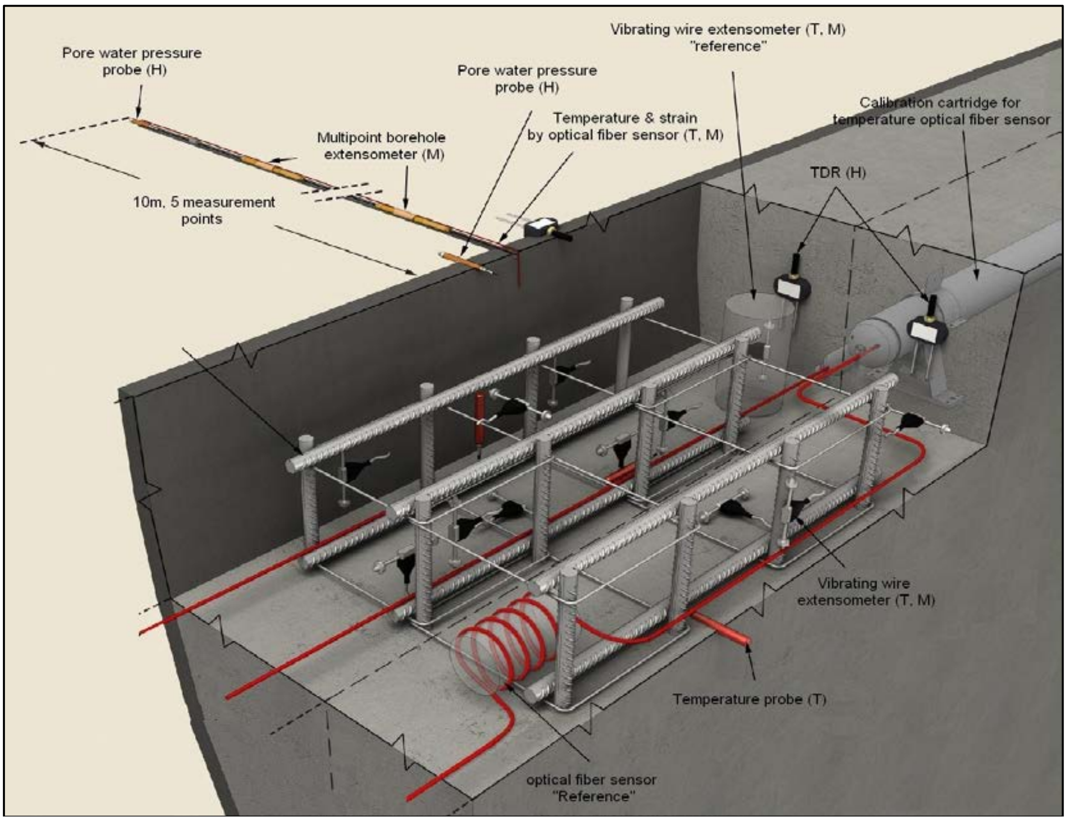


Figure 8: Monitoring system design for ILLW disposal cells.

Various strategies are envisaged on site for this purpose, including periodical calibration wherever possible, the development of self-calibrating devices and redundant measurements using different sensor technologies. As an example, distributed measurements by OFS provide temperatures and/or deformations at all points over the entire length of the installed sensor. These can be compared to point measurements obtained using sensors such as Pt100 or vibrating wire extensometers (VWE).

In order to interpret the results, the measurements delivered by the sensors have to be decorrelated for influences such as thermal effects, in order to obtain the physical value for the target parameter. More specifically, the VWE includes a thermometer (coil resistance) and is juxtaposed with a Pt100 probe to determine thermal effects; in addition, VWE sensors are placed in samples (cylinders of 16 x 32 cm with the same concrete used for the gallery) in the area to be able to decorrelate the effects of shrinkage and creep of concrete.

3. Large-scale experiment

The monitoring section experiment was carried out as part of a global test in Andra's URL under the name ORS (observation of the gallery concrete liner). The monitoring section experiment started in 2011 and was conducted in the rigid liner gallery named GCR (Fig. 3).

3.1. Monitoring section experiment

As part of the global ORS experiment in Andra's URL, a representative sensor system for monitoring ILLW cells has been implemented, with the following goals:

- Testing implementation procedures for sensors, particularly for innovative technologies
- In-situ testing of different complementary sensor technologies for the THM characterisation
- Obtaining representative feedback on the durability and robustness of sensors
- Testing field calibration of temperature devices in order to obtain traceable measurements.

In order to measure THM parameters, several sensors (see Fig. 1) were installed in the GCR tunnel inside a circular cross-section 3.6 m long and in boreholes excavated in the surrounding rock. This section contains 129 localized measurement sensors and 11 optical fiber lines providing 182 relevant measurement points.

Many challenges were faced in the implementation of the sensors. For example, to measure the water content in the Callovo-Oxfordian rock, a Time Domain Reflectometry (TDR) probe was selected for its robustness. This sensor is composed of two metallic rods, a specific head probe and a coaxial cable. It is generally used for soil water measurement (soft ground) where it can be easily implemented. The TDR was adapted for the argillite and installed in the stiff rock by excavating two holes with a diameter slightly greater than the antenna hole. To avoid the presence of air around the rods, a special grout was applied (see images in Fig. 3) in the gap between the rods and the host rock. Similarly, to remove any possible bias originating from air gap, before installation, the visible part of the host rock which will be in contact with the TDR was surfaced in order to make it as flat as possible.

Figure 9: Images of the TDR installation.

Also modifications to the installation procedures were developed in order to measure pore water pressure in the Callovo-Oxfordian rock (Fig. 4). Several difficulties had to be overcome. Firstly, the pore water pressure in the rock after disturbance (excavation) is very low in the first 5 m. It reaches the non-disturbed values from approximately 15 m. Sensors have to be installed at depth, distant from the gallery, in order to record the expected pressure. This test will indicate whether the pressure increases faster in the rock if it is supported by a stiff concrete ring.

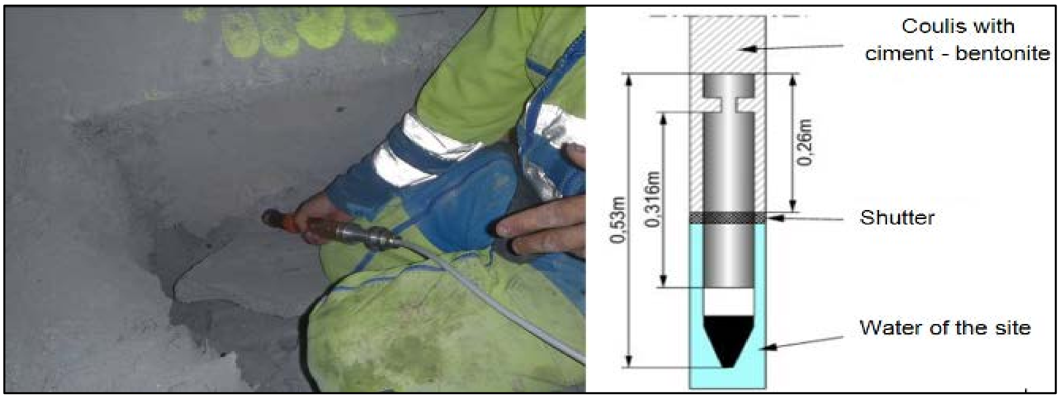


Figure 10: Picture of installation of a pressure cells

The second challenge was the sealing of the boreholes. Sealing has to ensure a permeability value as low as possible, in order to approximate the Callovo-Oxfordian rock permeability. The OFS cables were installed in three boreholes for temperature measurement and inside the concrete liner for both temperature and strain measurements. In the borehole, the OFS cables were attached to an extensometer, while the OFS cables in the liner form two circles and are attached to a wire mesh (Fig. 5). A key issue with this installation was the pressure induced in the cables because of clamping. This may cause propagation losses and a decrease in the intensity of optical signal.

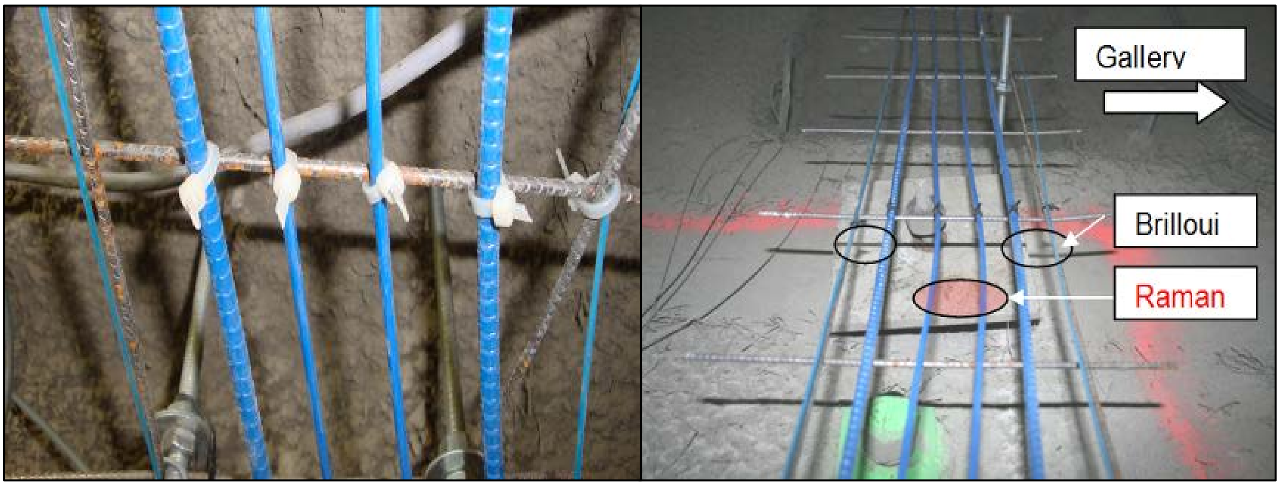


Figure 11: OFS fixed on a wire mesh, zoom (left) & types (right)

Distributed strain and temperature measurements provided by the OFS cables were placed in redundancy with individual sensors. Two different types of OFS for measuring strain were installed and one for temperature, in order to assess installation protocol, robustness and measurement performance. For this, temperature was measured by Raman scattering in the OFS and compared to platinum probes (Pt100). Similarly, the strain was obtained by distributed Brillouin scattering with the OFS and compared to VWE.

Figure 12: Cables in the concrete ring (west)

One difficulty was the significant number of cables in the section. Figure 6 shows the number of cables in the west part of the concrete ring. The cables had to be fed in and out of the concrete liner in two specific locations. Due the construction process, cables were moved three times during implementation. One cable was damaged during these manipulations.

3.2. Results

Many parameters have been monitored since April 2011 in both the argillite and the concrete liner: temperature, strain, water content and pore pressure.

3.2.1. Water content sensing by TDR

TDR reflectogram provides the travel time of an electromagnetic pulse along the sensing chain (Fig. 7): in our case, 2 metallic rods inserted into the host material (Fig. 3) (Fig. 7).

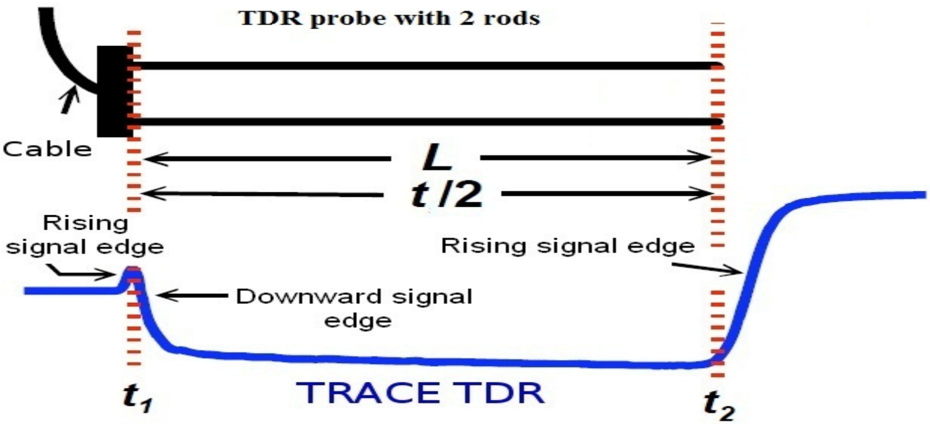


Figure 13: Reflectogram of TDR

This time is dependent on the dielectric constant ε_c of the material:

$$V_p = \frac{2L}{t} = \frac{C_0}{\sqrt{\varepsilon_c}} \qquad [\text{m ns}^{-1}]$$

where:

V_p = propagation velocity of a voltage pulse [m ns^{-1}]

L = length of the transmission line or probe

[m]

t = travel time of a voltage pulse back and forth the transmission line [ns]

C_0 = velocity of light in vacuum (0.2998) [m ns^{-1}]

ε_c = composite dielectric number of test medium [-]

Volumetric water content θ can be obtained after calibration of the sensors in the host material and the relationship determined between water content and travel time. Such laboratory calibration tests have been launched a year ago. Clay samples are not equilibrated yet. Presently, results are limited to raw data, namely time of flight. Orders of magnitudes or dielectric properties are 80 for water and 10 for soil; thus travel time increases with water content.

The curves (Fig. 8) show the evolution of the travel time for the TDR installed in the argillite (bottom of the gallery) and in the intrados and extrados of the concrete (east part of the liner) in the gallery.

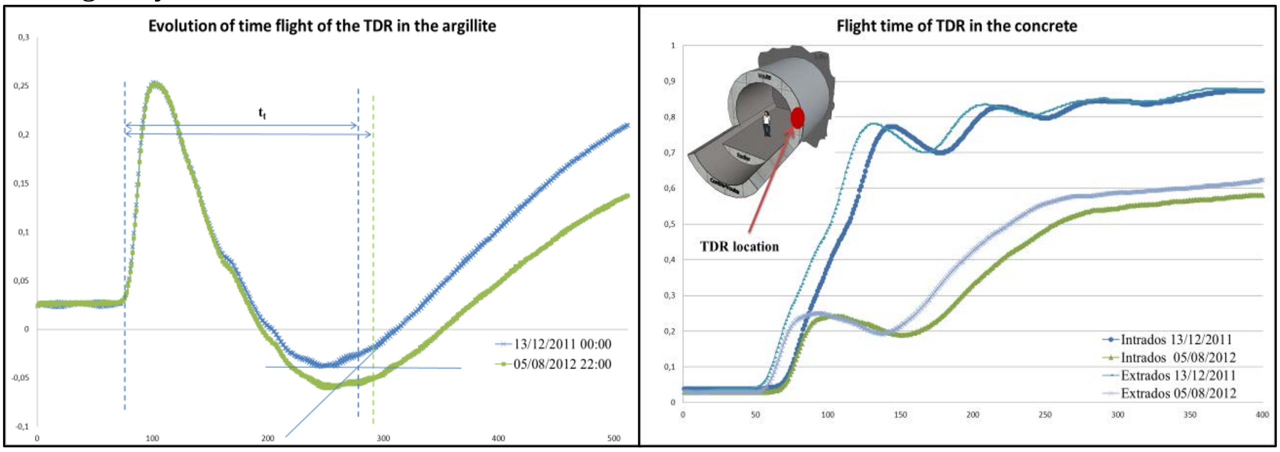


Figure 14: Evolution of the TDR travel time in the argillite (left) and concrete (right)

The evolution of the travel time between December 2011 and August 2012 indicates an increase in the water content in the rock around the gallery and the drying of the concrete over a period of 8 months, consistently with expected construction and ventilation influence. The calibration process in laboratory is currently in progress and will allow travel time to be converted to water content.

3.2.2. Pore water pressure sensors

The pore pressure sensor (PPS) is based on a vibrating wire and a porous filter. The key aspect of the system is the sealing of the measurement chamber. In order to evaluate the performance of the sensor chain, an additional parameter has to be taken into account. The pore pressure in the host rock follows an exponential, meaning that the full-scale test, in accordance with the design of the monitoring system, involves the installation of the PPS in the first metres of the rock where the pore pressure is very low (Fig. 9).

To assess the system qualification, a test has been performed in another URL gallery (GRD) with a specified sealing element (packer) in order to assess the sensor adaptability. The pressure delivered by the sensors increased rapidly (Fig. 9) for the first PPS installed in a chamber full of water at 15 m from the gallery.

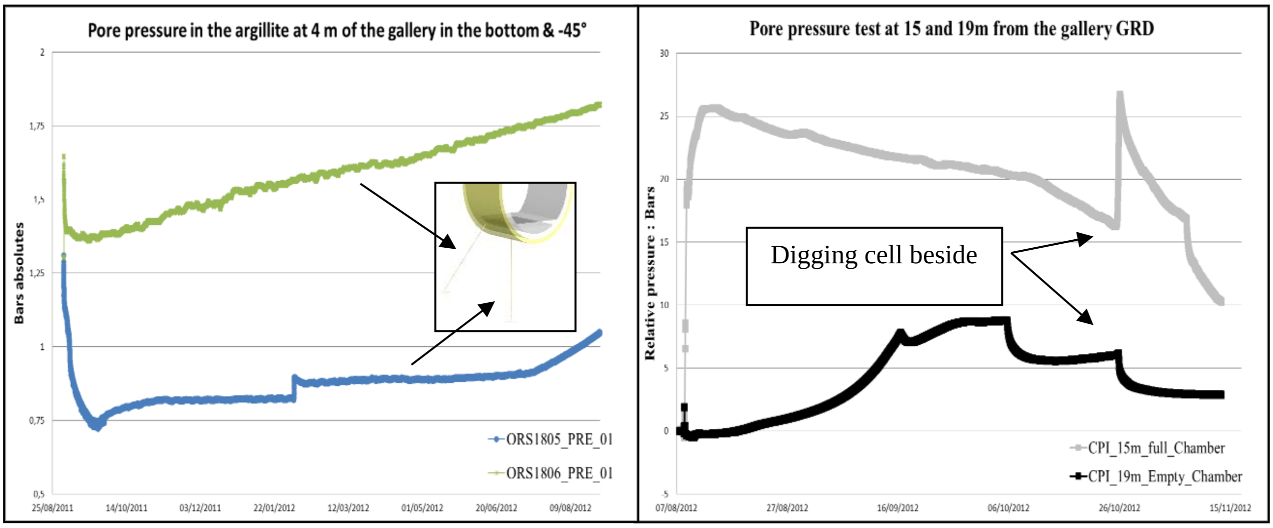


Figure 15: Pore pressure at 4 m depth from the GCR gallery (left) & at 15 to 19 m depth in the boreholes from the GRD gallery (right)

The pressure of the next PPS, installed at 18 m from the gallery in an empty chamber, increases slowly as water flows very slowly due to the low permeability of the argillite. The decrease in pressure is due to the excavation of the adjacent cell.

3.2.3. Temperature and strain sensing using OFS

Distributed measurements by optical fiber sensors were remotely performed every 15 minutes using commercially available instruments: a Brillouin-OTDA (Optical Time Domain Analyser) and a Raman Distributed Temperature Sensor (DTS). The first make the temperature measurement only on multimode optical fibers. The second make temperature and/ or strain measurement on single-mode cables. Both multimode and single mode cables were collocated in the concrete in order to compensate strains measured by Brillouin scattering with temperatures measured by Raman scattering. The instruments were located in the underground laboratory. The full sensor line is approximately 500m long, with only 20 m embedded inside the concrete liner. Spatial resolution of both instruments is 1 m.

$$\Delta\nu = C_\varepsilon\, \varepsilon + C_T\, \Delta T$$

Where,

$\Delta\nu_c$ = frequency shift induced by the strain/temperature changes [MHz]

C_ε = Brillouin strain-frequency coefficients [MHz/ µm/m]

C_T = Brillouin temperature-frequency coefficients [MHz/°C]

Both C_T and C_ε coefficients are fibre-type dependent and for this experiment, they values are: $C_T = 1$ and $C_\varepsilon = 0.05$.

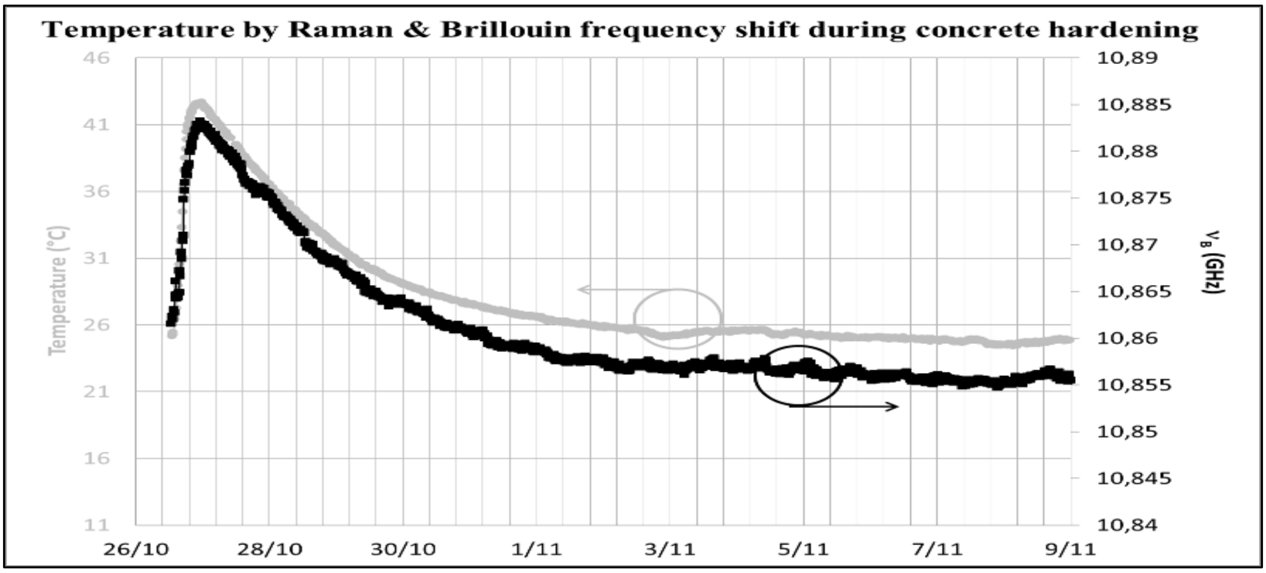


Figure 16: Raman temperature sensing & raw Brllouin frequency shift after concreting

During concrete hardening, an exothermal chemical reaction takes place. Consequently, temperature increases and the Brillouin frequency shifts. Thermal expansion of the concrete induces strain on the OFS cable, which also increases the Brillouin frequency (see Fig. 10, where temperature measurement acquired by Raman sensing lines (left y axis) and raw Brillouin frequency (right y axis) are illustrated).

To provide useful information, concrete thermal expansion ε_{therm} must be differentiated from the parameters of interest: stress, creep, shrinkage, noted ε_{comp}. If $\alpha_{concrete}$ is the concrete thermal expansion coefficient, strain can be obtained using the following equation:

$$\varepsilon_{comp} = \frac{\Delta \nu_B}{C_\varepsilon} - \frac{(C_T + \alpha_{concrete} C_\varepsilon).\Delta T}{C_\varepsilon}$$

Embedded and instrumented concrete samples [1] allow in-situ measurement of $\alpha_{concrete}$. As a first approximation [2], assuming $\alpha_{concrete}$=10 µε/°C, C_T=1 MHz/°C and Cε=0.05 MHz/µε, the compensated strain measurements were obtained (Fig. 11). OFS cables were co-located with VWE and Pt100.

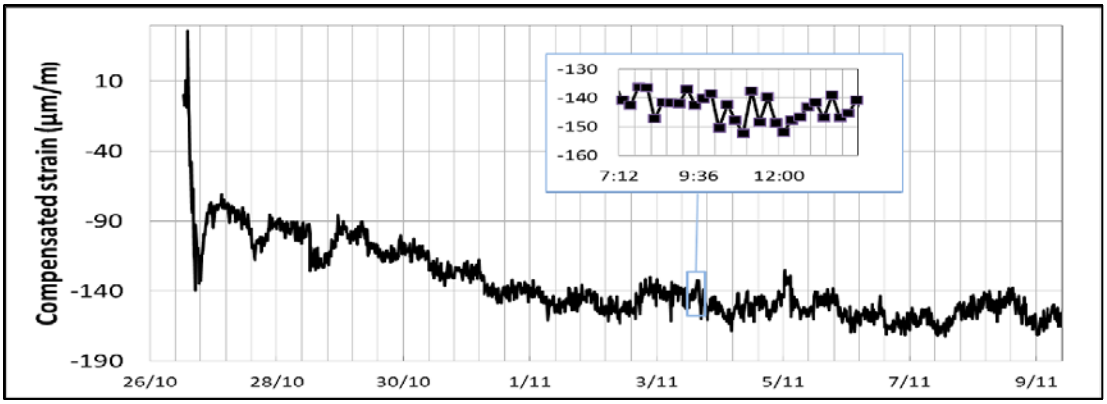


Figure 17: Temperature compensated strain during concrete pouring

The 150 µm/m compressive strain measured is the consequence of the early-age shrinkage of concrete. This value is fully consistent with the one measured by the VWE placed near the OFS (Fig. 11). The figure shows that the resulting strain measurement repeatability is about 30 µm/m while temperature measurement repeatability is less than 0.2°C in the Raman sensing line. It's an interesting result because previous experiments on Raman temperature compensated Brillouin strain measurements showed results of 3.6 °C and 80 µm/m repeatability with 5 m resolution [3].

Temperature variation was greater on VWE sensors measurements than for the OFS during concrete pouring of next section. Actually, VWE sensors have been installed closer to the next concrete ring (at 60cm) than the OFS (1.20 m). Average deformations observed by OFS vary between intrados and extrados VWE values. This method also allows long-term monitoring. Concrete liner strain evolution was measured during all the construction steps; measurements will continue in the coming years to acquire as much information as possible before repository construction.

An advantage of the distributed measurements provided by the OFS is illustrated in Figure 12. In this gallery, the concrete liner is not reinforced. Tensile strain zones were identified and precisely located by distributed measurements, at locations where there was no electronic sensor.

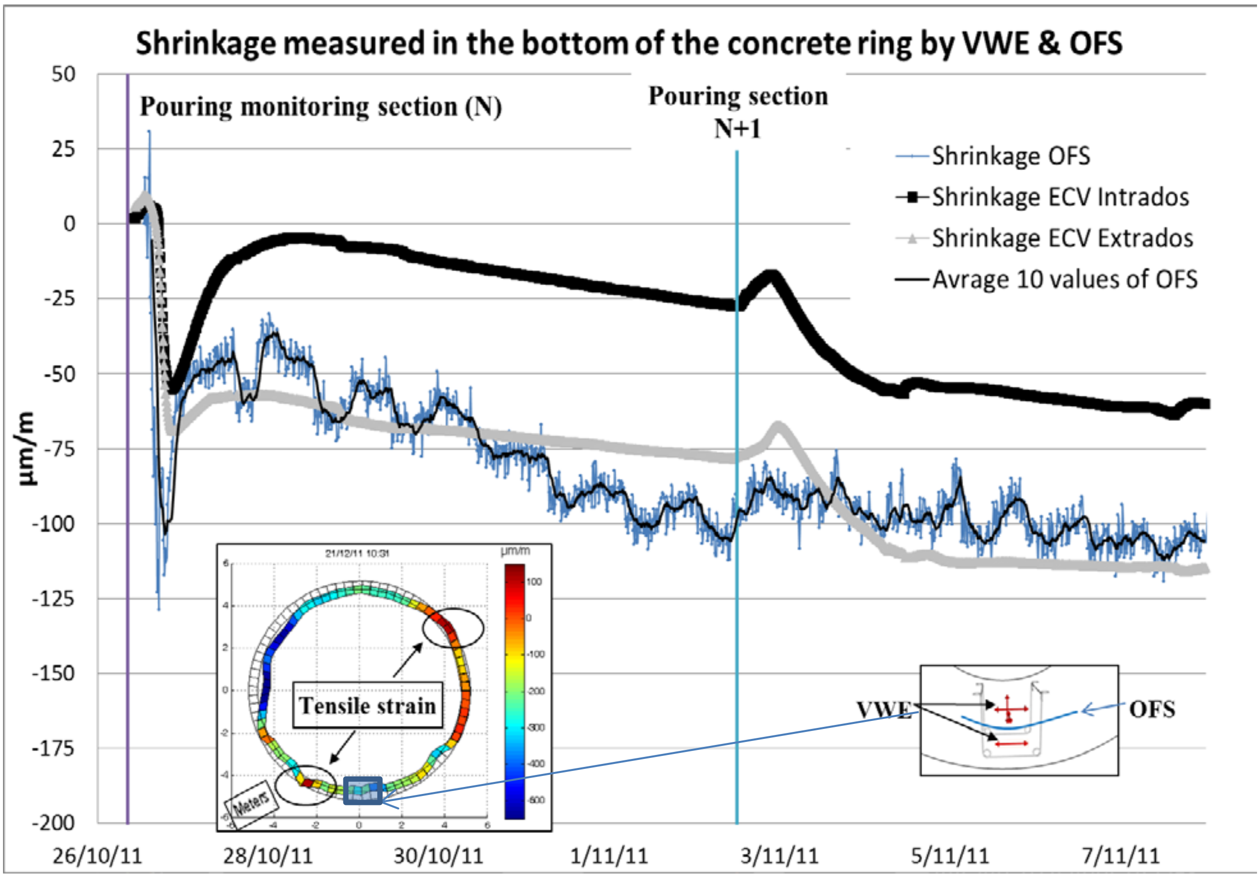
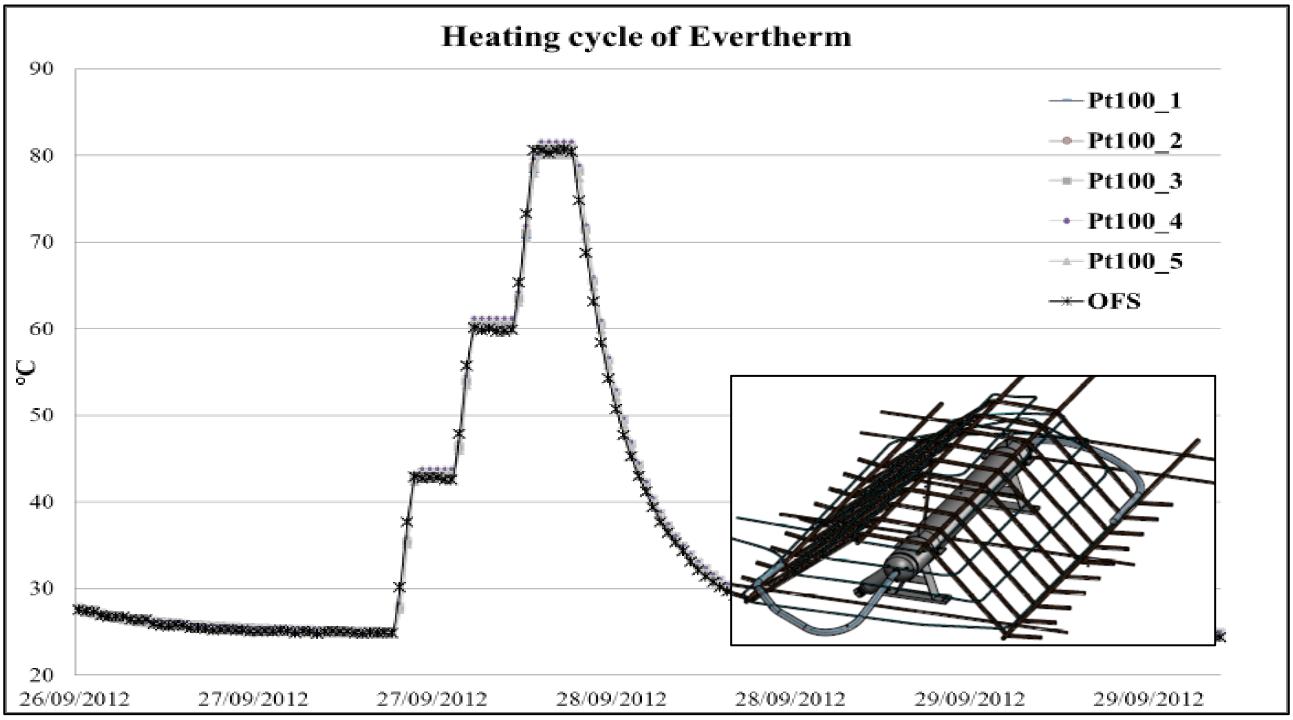


Figure 18: Concrete shrinkage by VWE & OFS (Strain in the GCR concrete ring by OFS in the top right, 8 days after concreting).

3.2.4. Field calibration device

Application of RAMAN DTS for long-term monitoring requires good knowledge of the metrological performance of this new technology. Periodical checks of the temperature readings will also be required on site, in zones that will no longer be accessible after installation. A novel, in-situ thermal cartridge was developed in order to calibrate and



periodically check such measuring systems.

Figure 19: T° measured during a heating cycle

The device (Evertherm) is a cartridge that relies on the combination and adaptation of various sub-elements to control (by well-known thermal measurements standards) and measure the temperature and its distribution over a length of fiber optic to monitor long-term drift and allow use in various environments. The fiber optic is inserted into a central tube, which is positioned in the middle of a thermally conductive block. The conductive block is equipped with heating elements connected to an external temperature controller by means of a waterproof connector. The block is equipped with three temperature probes distributed in order to evaluate its thermal stability and homogeneity. The thermal cartridge is 1.20 metres long, maintaining a fiber cable portion of 1 metre long at a uniform temperature on the timescale of the DTS measurement. Three highly robust mini-crucibles containing re-usable metallic alloys have been developed for this specific application. The device has been successfully installed in the slab of the monitoring section.

Temperatures measured by the OFS in the Evertherm tube are perfectly correlated with expected temperatures, as can be observed in Figure 19.

4. Conclusions and perspectives

The first results of this monitoring qualification test showed well correlated measurements between the different technologies employed and a very good survival rate. In December 2012, the survival rate was around 95% of the sensors (including 182 m or 13 lines of OFS). The survival rate without OFS is around 98% for the 129 other sensors and 69% for OFS. Damage to sensors occurred mainly on the part of cable located at the concrete/ gallery interface and in the upper part of the concrete ring. Failure of sensors occurred in the first months after installation and during construction work or repositioning of the cables.

This monitoring test will be studied for several years in order to obtain information about ageing, accuracy, possible drift and robustness of the sensors. In addition, measurements will be compared with different non-destructive methods to determine the required level of reliable performance. The feedback obtained for implementation of sensors will guide future choices with a view to increasing sensor reliability and decreasing failure during the construction process. The results will also allow an assessment of these innovative technologies (OFS, TDR, etc.) compared with other conventional sensors used in the same section or in adjacent ones.

As an example, the sensing scheme combining RAMAN and BRILLOUIN instruments with multiple sensing cables is a promising solution for performing simultaneous temperature and strain monitoring. This real-scale experiment shows that RAMAN-BRILLOUIN temperature and strain sensing are well suited for underground tunnel monitoring. It also appears that the optical fiber cables chosen were sufficiently robust to tolerate construction conditions. When dealing with distributed data, a major difficulty is accurate event localisation. This was solved by (i) creating artificial events as thermal excitation during the construction step to provide an accurate map or (ii) inserting reference points such as the thermal reference cartridge along the sensing lines. Another difficulty faced was repeated optical fiber breaks.

As a perspective, data mining will be performed in order to analyse and correlate data originating from the different types of sensors. A study of data fusion has been initiated in order to make the first steps towards monitoring data management. What is more, measurements will be compared with models in order to improve the latter.

References

[1] Lamour V., Haouas A., Dubois J.-Ph. & Poisson R. (2009): Long term monitoring of large massive concrete structures: cumulative effects of thermal gradients. - NDTCE’09, Non-Destructive Testing in Civil Engineering Nantes, France, June 30th – July 3rd, 2009.

[2] Delepine-Lesoille S., Phéron X., Bertrand J., Pilorget, G., Hermand G., Farhoud R., Ouerdane Y., Boukenter A., Girard S., Lablonde L., Sporea D., and Lanticq V. (2012): Industrial qualification process for optical fibers distributed strain and temperature sensing in nuclear waste repositories. - Journal of sensors, Article 369375.

[3] Alahbabi, M. N., Cho, Y. T. & Newson, T. P. (2005): Simultaneous temperature and strain measurement with combined spontaneous Raman and Brillouin scattering. - Opt. Lett. 30.11 (2005), pp. 1276-1278.

Monitoring THM effects in a full scale EBS/host rock system – first experiences of the FE-Experiment in the Mont Terri URL during construction and ventilation phase

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Summary

The Full-Scale Emplacement (FE) Experiment at the Mont Terri underground research laboratory (URL) is a full-scale heater test in a clay-rich formation. Based on the Swiss disposal concept it simulates the construction, emplacement, backfilling, and post-closure thermo-hydro-mechanical (THM) evolution of a spent fuel / vitrified high-level waste (SF / HLW) repository tunnel in a realistic manner. The aim of this experiment is to investigate SF / HLW repository-induced THM coupled effects mainly in the host rock but also in the engineered barrier system (EBS). A further aim is to gather experience with full-scale tunnel construction as well as canister and buffer emplacement.

The entire experiment implementation (in a 50 m long gallery with approx. 3 m diameter) as well as the post-closure THM evolution will be monitored using a network of several hundred sensors, a part of which has already been installed and is currently generating data. These are distributed in the host rock in the near- and far-field, the tunnel lining, the EBS, and on the heaters. The experimental conditions such as temperatures up to 130°C in the EBS and up to 60°C in the host rock, salinity of about 25 mS/cm and long experiment duration of at least 10-15 years require a sound instrumentation strategy and careful selection of sensors and materials. Therefore, the monitoring set-up consists of various state-of-the-art sensors and measurement systems covering adapted standard systems as well as fiber-optic sensors. All sensors are connected to a data acquisition system.

The results and experiences of the FE-Experiment will provide important input for developing the monitoring strategy of full-scale heater tests at the future URL and the pilot repository at the future Swiss repository site. We present the instrumentation concept and rationale as well as the first monitoring results of the construction and ventilation phase. In addition, the challenges in connection with design, installation, data storage as well as data analysis and interpretation will be discussed.

1. Introduction

Temperature-related effects on rocks of SF / HLW repositories under non-isothermal conditions are subject of many R&D programs for radioactive waste disposal worldwide. The effects of heating are well known on local and laboratory scale. However, the experimental investigation of impacts on the rock as a result of transient large-scale heating and the behavior of a combined heater, backfill and rock system at large scale are topics of recent research projects to improve the understanding of THM effects in a full-scale EBS/rock system. Fundamental part of large scale heater tests in URLs is a sound monitoring strategy and instrumentation to understand the processes occurring in the EBS/rock system and to provide reliable data for analysis and validation of numerical models. In addition, the technical aspects and long-term performance of the monitoring equipment will provide valuable experiences for the monitoring of future full-scale heater tests and the pilot repository.

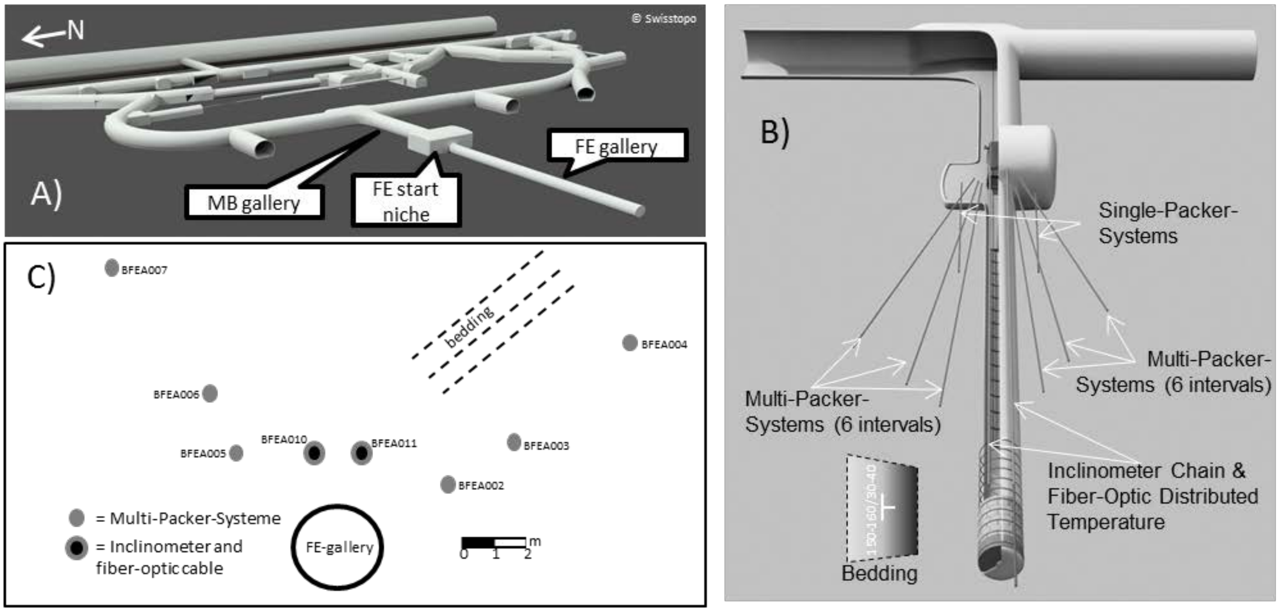

Figure 1: A) Perspective view of the URL Mont Terri incl. the approx. 50m long FE gallery. B) Perspective view of the FE gallery and far-field instrumentation. C) Spatial distribution of the boreholes for far-field instrumentation in a cross-section at gallery meter = 20 m, viewing direction is towards gallery end.

In this paper we present the monitoring strategy and instrumentation design of the FE-Experiment at the Mont Terri URL (Switzerland). The FE-Experiment is a full-scale heater test in a clay-rich formation. It simulates the construction, waste emplacement, backfilling, and post-closure THM evolution of a spent fuel SF / HLW repository tunnel based on the Swiss disposal concept at 1:1 scale. The main aim of this experiment is to investigate HLW repository-induced THM coupled effects in a full-scale EBS/host rock system. Further objectives are the validation of the design basis for tunnel construction as well as canister and buffer emplacement at full scale with all relevant components. The entire experiment implementation as well as the post-closure THM evolution will be monitored using a network of several hundred sensors. These are distributed in the near- and far-field of the host rock around the gallery, the tunnel lining, the engineered barrier system and on the heaters. The construction of the test gallery is completed, the ventilation phase is now ongoing, the heating phase, however, has not started yet. In this paper, we present preliminary results of the construction and ventilation phases.

1.1 Location and geological setting of the FE-Experiment

The FE-Experiment is located at the end of the former MB test tunnel in the northwestern part of the Mont Terri URL (Canton Jura, Switzerland). The URL lies completely in the Opalinus Clay formation, in the southern limb of the Mont Terri anticline [1]. The around 175 million years old (Aalenian) Opalinus Clay is basically a claystone with differing proportions of sand and carbonates. The URL is 275 m underground. It can be accessed via the security gallery of the A16 Mont Terri motorway tunnel. The FE gallery is located in the centre of the shaly facies of Opalinus Clay, far outside of the existing laboratory tunnels and experiments (Fig. 1A). The FE gallery is driven parallel to the strike of the bedding approx. towards SW (Fig. 1B). The bedding planes in this area are dipping about 30-40° from horizontal to the southeast.

1.2 Experimental Layout

The FE-Experiment is based on the Swiss disposal concept for SF / HLW. The 50 m long test gallery was excavated with a diameter of approx. 3 m by means of a hydraulic hammer and a road-header. The gallery was constructed with different support types resulting in approx. 2.6 m inner diameter. The first 9 m section, which serves as access gallery, is supported with steel arches and shotcrete, the central part from 9-37.8 m is supported with a shotcrete lining and rock bolts and at the end of the gallery only steel arches are used (Fig. 2). In the central part of the experiment gallery three heaters with dimensions similar to those of waste canisters will be emplaced. The remaining space will be backfilled with compacted bentonite pellets, including the end of the gallery where no shotcrete is used and bentonite pellets will have direct contact to the host rock representing an interjacent sealing section according to the Swiss disposal concept. The entire experimental section will be sealed towards the start niche with a concrete plug holding the buffer in place and reducing air and water fluxes.

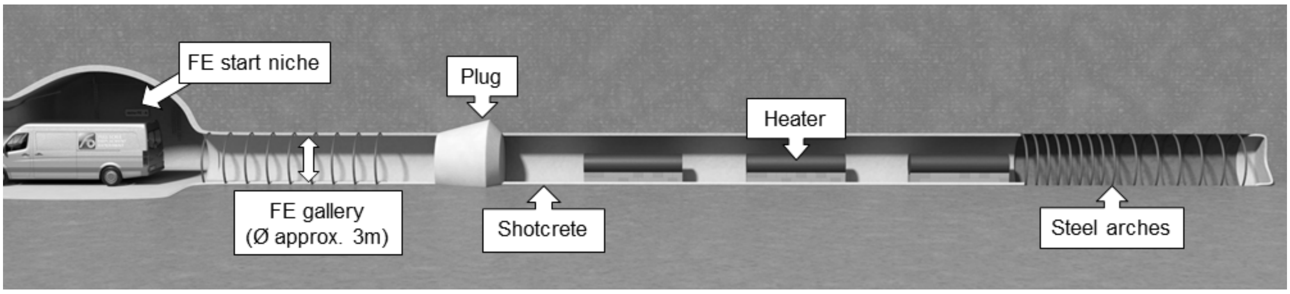

Figure 2: Perspective view of the final set-up of the future FE experiment shown without bentonite pellet backfill, without rock bolts and without sensors (drawing not to scale).

The FE project started with the excavation of the so-called FE start niche (Fig. 1), which was completed in May 2011. In winter-spring 2012 the instrumentation of the far-field rock (Fig. 1C), was completed. During summer 2012 the FE gallery was constructed followed by the ventilation period. Next steps are the near-field rock instrumentation as well as heater and EBS emplacement and instrumentation. According to the current plan, the heating and monitoring phase of the FE-Experiment is envisaged for at least 10 years.

2. Instrumentation and monitoring strategy

The instrumentation is divided in three main phases. The instrumentation of the far-field rock (from approx. 1.5 to 20 m distance to the gallery wall) is installed in boreholes drilled from the FE start niche (Fig. 1B). The instrumentation of the near-field rock is and will be installed by means of radial boreholes from the gallery. Finally the concrete lining, EBS and heater will also be equipped with sensors. Taking the anisotropic properties of Opalinus Clay into account, most measurement positions in the rock are orientated parallel and perpendicular to the bedding (Fig. 1C). The measurement points in the rock and the EBS aim to monitor the induced THM-coupled parameters such as:

- Temperature

- Pore-water pressure (only in rock)
- Total pressure (at the rock-concrete interface, at the concrete-bentonite interface, and on the heater surfaces)
- Strain and displacement (in the rock and of the heaters)
- Water content and suction (in the concrete lining, EBS and rock close to the gallery).

The design and layout of the monitoring system and material choice are crucial for its life time. Depending on the location, the instrumentation has to withstand different conditions, e.g. in the EBS the temperature will be high and swelling pressures of the bentonite backfill might occur within the life time of the experiment, whereas in the far-field rock the temperatures are lower and varying pore-water pressures will occur. Due to the long test period, elevated temperatures, salinity of Opalinus Clay pore water, and trapped oxygen, corrosion is an issue for appropriate material choice. In addition, the instrumentation set-up has to ensure a sufficient redundancy against sensor failures/malfunctions. These boundary conditions require a sound instrumentation strategy and careful selection of sensors and materials. Therefore, the FE monitoring set-up consists of various state-of-the-art sensors and measurement systems covering adapted standard systems as well as new fiber-optic sensors.

In this paper we will focus on the monitoring systems and results of temperature, pore-water pressure and water content. For measuring pore-water pressure and temperature in the far-field and near-rock we use multi-packer-systems (MPS) and single packer systems. Stainless steel type is adapted to the salinity and expected temperatures and PT1000 sensors are used for temperature measurements. Pressure sensors are replaceable as installed at the surface and connected by lines to the intervals. In addition to the point temperature measurements we use Raman spectra fiber-optic distributed temperature sensing (DTS). The fiber-optic cable, which is the temperature sensor, is attached in two boreholes to an inclinometer casing. The fiber-optic cable is connected to a light-reading unit which sends laser pulses into the optical fiber and analyses the backscattered light [2]. The two-way travel time gives the location of backscatter and the Stokes/Anti-Stokes ratio the temperature at the backscatter location resulting in distributed temperature measurement for 1m intervals along a several kilometre long cable [3]. The advantages of this sensor type are its resistance to heat and corrosion as well as no electronic parts involved in the sensor. In the FE gallery, the fiber-optic cable runs twice in and out of the borehole to ensure redundancy and spare cable sections at the borehole mouth allow splicing in case of failure.

Measurements of water content, saturation and suction in partially saturated clay-rich rock with a deformable grain skeleton are a known challenge, because water content, saturation and suction are not directly correlated and a proper sensor contact to the rock is essential. Additionally discontinuities in the excavation zone (EDZ) have to be taken into account as well as chemical effects. In that context the choice of sensor type and installation procedure is crucial. Therefore, we started with an evaluation and test installation of different sensor types and different installation techniques. For desaturated rock in the gallery near-field we test capacitive RH/T sensors, for intermediately and varyingly desaturated rock we evaluate time domain reflectometry (TDR) and frequency domain reflectometry (FDR). For nearly to fully saturated rock equitensiometers as well as normal pore pressure sensors are used. In addition the sensor-contact to the rock, which is crucial for reliable measurement values and interpretation, is evaluated using different borehole diameters and different annulus fillings.

All sensors are connected to a data acquisition system and data are stored in a database. By means of a web interface real-time data view is possible. Alarm levels are defined and alert emails will be sent in case predefined values are exceeded.

Finally, the measurement locations need to be reasonably distributed in space to capture the spatiotemporal variations of the relevant parameters while minimizing the disturbance of the instrumentation on the experiment. For our planning of the instrumentation design and layout we used scoping THM simulations. The simulation results were valuable to determine the measurement locations for estimated changes and gradients of pore-water pressure, water content, and temperature and to evaluate the disturbance of the instrumentation equipment on the experiment. Results of a geomechanical model were used to ensure that the measurement positions provide sound monitoring during the construction phase, too.

3. Results

We present only selected time series of pore-water pressure and temperature that are representative for the monitoring performance. The test installations and evaluation for water content and suction sensors are currently on-going. Thus, no data are shown for these parameters.

3.1 Pore-water pressure evolution during construction

The excavation of the FE gallery caused a coupled hydraulic-mechanic response in the intervals of the MPS. Figure 3 shows the pressure time series of the intervals in borehole BFEA003 (orientated parallel to the bedding planes) and Figure 4 of the intervals in borehole BFEA006 (orientated perpendicular to the bedding planes). The intervals have different distance to the gallery and are located at different locations above the gallery (Table 1). The pore pressure shows a step wise increase with approaching tunnel face and a step wise decrease follow by a recovery phase when the tunnel face passed by. Although magnitudes are slightly different, all MPS intervals in both directions, parallel and perpendicular to the bedding, show similar shapes of pore- water pressure evolution during the construction and ventilation phases. All intervals, minimum distance of 2 m to the gallery wall, are fully saturated after excavation and no interval is in suction. A detailed analysis of the pore pressure time series including convergence-, extensometer-, and inclinometer-data is currently in progress.

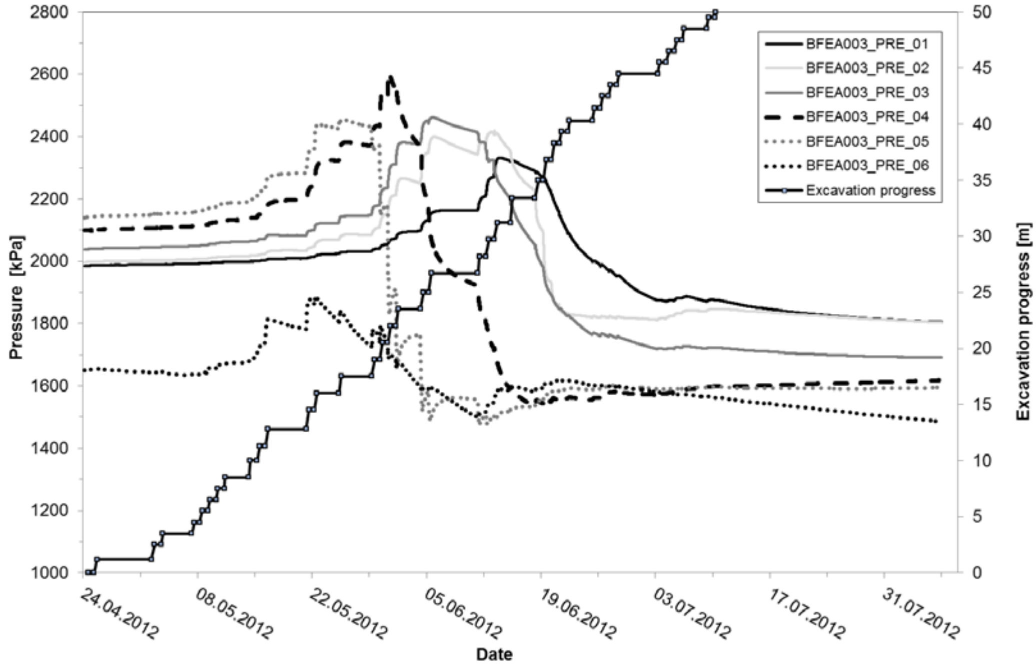

Figure 3: Pressure time series of MPS intervals in borehole BFEA003. Interval 01 is the deepest and interval 06 the shallowest. The black step-curve shows the progress of the gallery excavation.

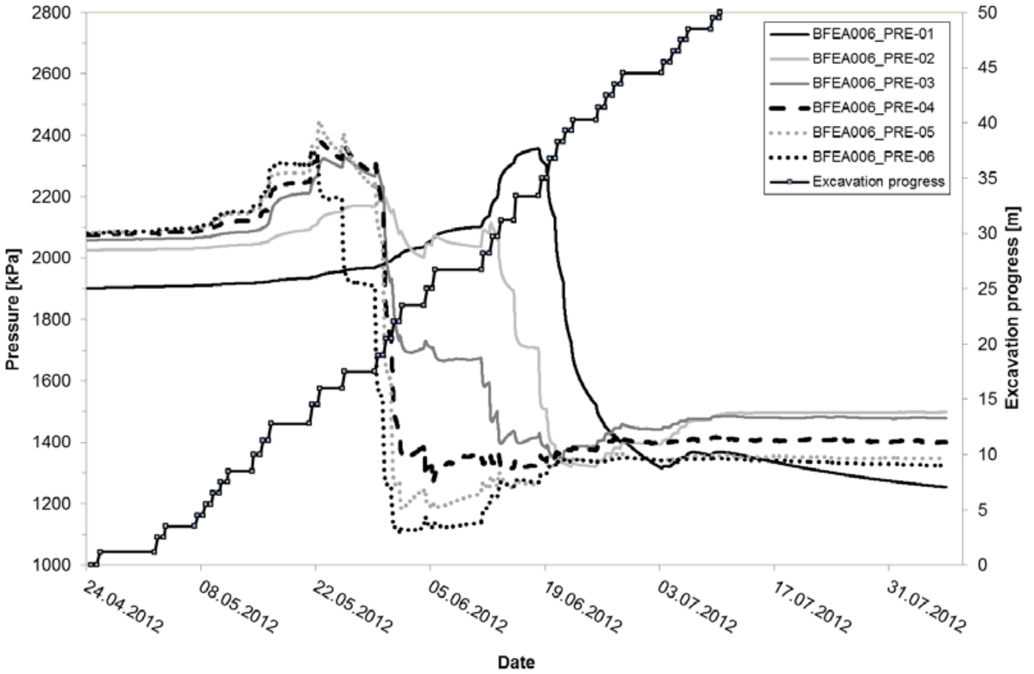

Figure 4: Pressure time series of MPS intervals in borehole BFEA006. Interval 01 is the deepest and interval 06 the shallowest. The black step-curve shows the progress of the gallery excavation.

Table 1: Locations of the mid-points of the MPS intervals in borehole BFEA003 and BFEA006. BFEA003 is orientated parallel and BFEA006 perpendicular to the bedding planes.

BFEA003 and BFEA006	Gallery meter [m]	Radial distance to gallery wall [m]
Interval 6	16.6	4.7
Interval 5	20.3	5.2
Interval 4	24.1	6.0
Interval 3	27.8	6.7
Interval 2	31.5	7.4
Interval 1	35.7	8.1

3.2 Temperature evolution during construction

Although the heating phase of the experiment has not started yet, the temperature sensors could be tested during the construction phase, because the heat generated by the construction works propagated into the first meters of rock. Figure 5 shows the spatiotemporal varying temperature distribution along the fiber-optic cable in the borehole BFEA011. At depth 0 m the temperature fluctuations reflect the air temperature of the FE start niche. The resolution of the temperature measurement is 0.015°C and the accuracy is ±1°C for our set-up.

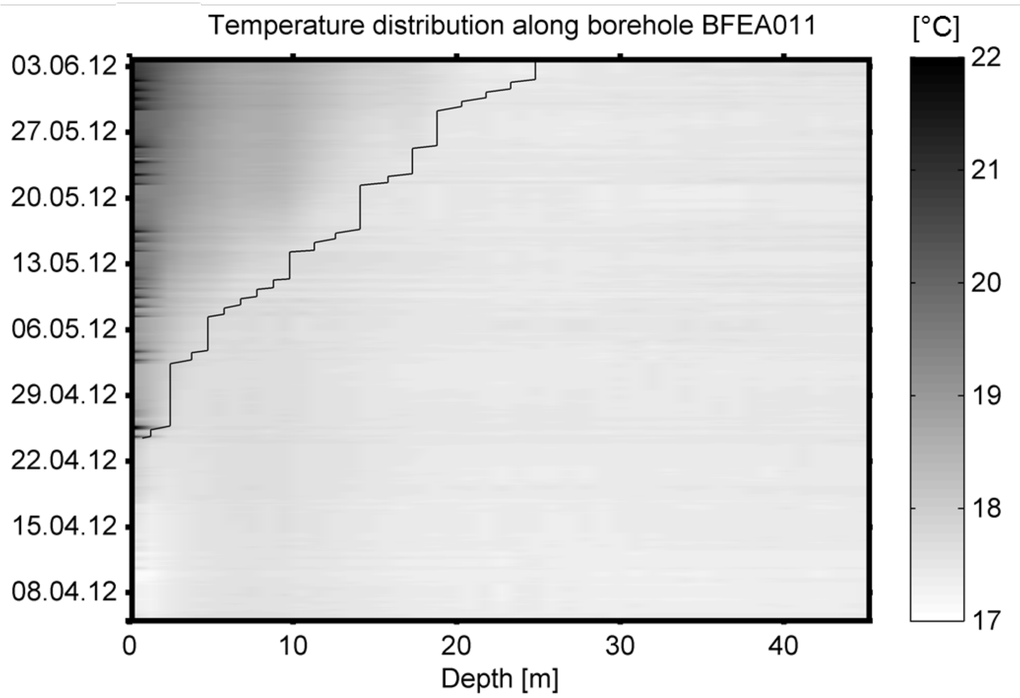

Figure 5: Temperature distribution along the fiber-optic cable in the borehole BFEA011, which runs subparallel to the gallery axis. The black solid line shows the progress of the gallery excavation with respect to the borehole depths.

4. Discussion and Conclusions

For planning the instrumentation and monitoring of the FE-Experiment scoping simulations and experiences from previous and on-going heater experiments turned out to be very valuable to estimate the spatiotemporal variations of parameters like temperature, pore-water pressure, and water content as well as the expected conditions that the equipment has to withstand during the experiment period. After defining the set-up and before installation we recommend a comprehensive quality assurance of the equipment off- and on-site including tests for water and gas tightness done by the contractor who is responsible for installation. In addition, checking the sensors accuracy and calibration before installation is essential. Although sensors might be delivered calibrated, the connection to a different data logger causes an offset in the measurement value. Moreover, we recommend, if possible, a periodic calibration during operation of accessible sensors. Although a sound quality control before and during installation is crucial, sensors and equipment might fail during installation or after exceeding their life time under harsh experimental conditions. Therefore, enough redundancy of sensors and measurement locations is recommended. At this stage of the FE-Experiment only one sensor (PT1000) out the approx. 700 measurement points failed due to improper handling during installation.

The far-field instrumentation provided valuable "Mine-By" data during the construction of the FE gallery, even if the main objective of the sensor network is the THM monitoring during heating. At this stage of analysis, the pore-water pressure response can be explained by coupled hydraulic-mechanical processes caused by the gallery excavation.

The fiber-optic DTS system produces good quality data. Resolution and accuracy are satisfactory and in the same range as standard point temperature sensors. The distributed temperature measurements along the fiber-optic cable reveal detailed insights into the spatiotemporal varying temperature field in the rock around the gallery. However, we will evaluate the long term accuracy of the DTS system through performing calibration and performance checks regularly.

As the test installations and evaluation for water content and suction sensors are not finished yet, no discussion is done here. Nevertheless, we recommend checking the following aspects before installation of water content and suction sensors in borehole within a clay rich rock:

- Check the sensors' rating as to salinity and temperature, if possible, long-term usage.
- Ensure contact of sensor to rock.
- Check pore water salinity, which is important for electrode design using TDR or FDR technology.
- Define calibration procedure (rock specific, salinity specific, temperature specific, sensor specific if needed).
- Check water tightness under longer experiment duration.
- Check sampling volume for proper design of the position of sensors.
- Check measurement principles (e.g., equitensiometer require contact to air to work)

In addition to the monitoring data, the experiences of long-term performance and technical aspects of the instrumentation will provide important input for developing the monitoring strategy of full-scale heater tests at the future URL and the pilot repository at the future Swiss repository site.

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(Germany) and BGR (Germany) are participating in the FE-Experiment. The engineering and demonstration components of the FE-Experiment are also part of NAGRA's participation in the EC co-funded 'Large Underground COncept EXperiments' (LUCOEX) project and therefore receive funding from the European Atomic Energy Community's Seventh Framework Programme (FP7) under grant agreement n269905.

References

[1] Thury M., P. Bossart (1999): The Mont Terri rock laboratory, a new international research project in a Mesozoic shale formation, in Switzerland. Engineering Geology, 52 (3-4), 347-359, DOI: 10.1016/S0013-7952(99)00015-0

[2] Tyler S.W., J.S. Selker, M. B. Hausner, C. E. Hatch, T. Torgersen, C. E. Thodal, G. Schladow (2009): Environmental Temperature Sensing using Raman Spectra DTS Fiber-Optic Methods. Water Resour. Res., DOI:10.1029/2008WR007052. 2009.

[3] Selker J.S., L. Thévenaz, H. Huwald, A. Mallet, W. Luxemburg, N. van de Giesen, M. Stejskal, J. Zeman, M. Westhoff, M.B. Parlange (2006): Distributed Fiber Optic Temperature Sensing for Hydrologic Systems. Water Resour. Res.,. DOI:10.1029/2006WR005326.

Monitoring of Sealing Dams
– Experiences from a Test Set-up at the Repository ERAM, Germany

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Summary
In the repository for radioactive waste at Morsleben in Germany (ERAM), low-level and medium-level waste with a volume of about 37,000 m³ is disposed of in different sites of the mine. The decommissioning concept intends to backfill the mine with a high degree of stabilising material. This leads to a system, where no brine inflow into the repository is expected, although no one can exclude totally this scenario. Therefore the sealings have to constrain possible infiltration of brine into the disposal chambers and, in the far future, the migration of radionuclides into the biosphere. In lack of generally accepted codes of practice there are many complex engineering performances necessary dealing with the dam materials, the behaviour of the host rock, the interaction between the dam and the excavation damaged zone. Due to the functions of the dams, the investigations cover the geomechanical behaviour of the host rock and dam materials as well as the hydromechanical behaviour. In consequence, the BfS (Federal Office for Radiation Protection) decided to construct an in-situ dam as an experimental set-up comparable to the future real dams. To get the necessary information, a comprehensive monitoring program was installed.

The geology of the salt structure leads to sealing locations in different formations of salt rock and anhydrite. The test set-up this paper is dealing with is located in salt rock. Based on the geomechanical and hydromechanical behaviour of the salt rock, the design of the dams has to fulfil various requirements. One of the main objectives is the impermeability of the system covering the dam, the excavation damaged zone and the host rock as well as the structural safety. Dams in salt rock profit by the creeping of the salt. So the dam material could have a small shrinkage if the short term function can be warranted by injections.

If an immediate effect of the dam stability is necessary in order to transfer a hydrostatic load, the radial stress in the interface between dam and host rock is relevant. To estimate the real stress-strain behaviour of the dam and the enclosed salt rock as well as the interaction between the elements of the system, measurements of the time-depending shrinkage, the internal stresses of the dam material, the radial stress etc. are carried out. Furthermore, the pore pressure is measured because the dam is pressurised by brine via a pressure chamber at the end of the dam. To determine all these parameters with an ensured quality, a comprehensive measurement program is required, while the functionality of the building must not be restricted.

Even with careful planning, constructing and monitoring of the measurement program for the in-situ test, many challenges arise in the analysis and interpretation of the measured values. This is to be expected for long-term monitoring programs.

1. Introduction

The radioactive waste repository Morsleben (ERAM) serves as a repository for low and intermediate-level radioactive waste. It is located in Saxony-Anhalt, Germany. Currently, the repository is in the phase of decommissioning. The mines have four main floors and several interim levels. The shafts Bartensleben and Marie were excavated at the beginning of the last century and are connected on the 1st and 3rd floor. Due to the former mining for the production of potash and rock salt, the excavation ratio is very high.

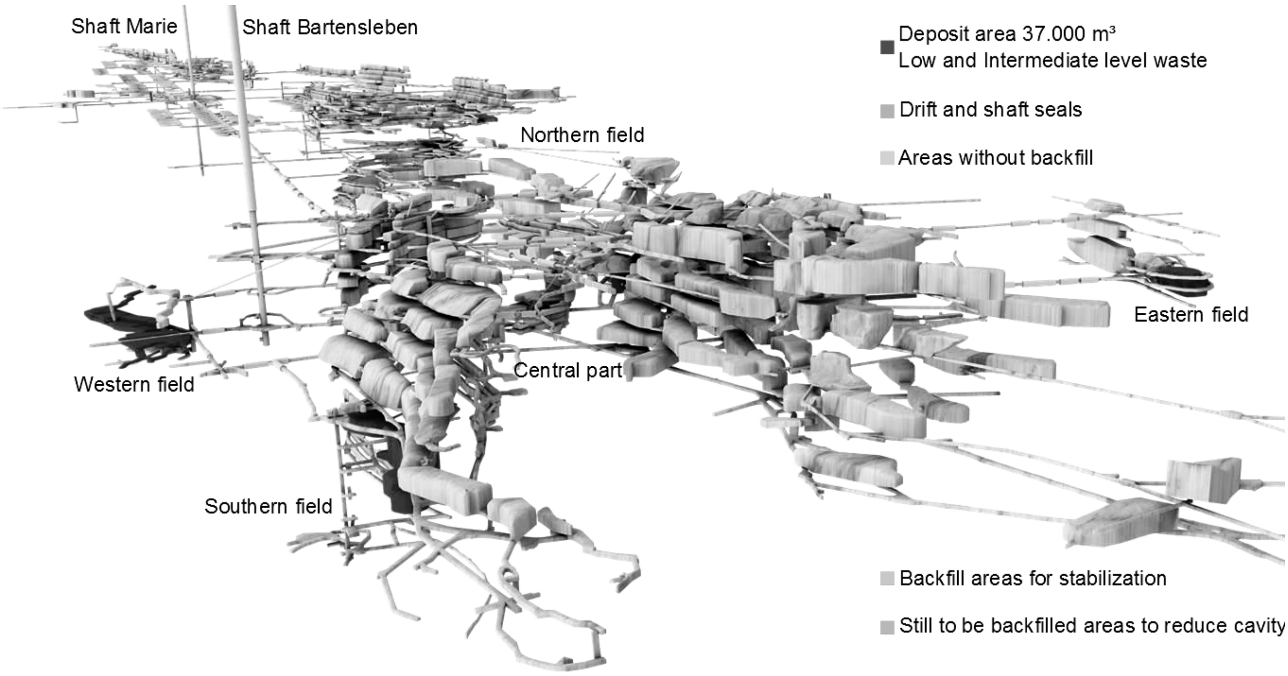

Figure 1-1: Mine fields of Bartensleben with deposit areas (in foreground) and Marie (in background)

Overall, in the period from 1971-1991 and from 1994-1998, 37,000 m³ radioactive waste were emplaced. The storage areas are in the mine Bartensleben in the northern, eastern, southern and western fields and also, in lower amounts, in the central part (Fig. 1-1).

Figure 1-2 shows a schematic geological east-west section through the Morsleben salt structure. The salt diapir was claimed tectonically and has a distinctive saddle and syncline structure. While the saddles are mainly the Staßfurt series and consist of rock salt and potash, the synclines comprise rock salt and main anhydrite of the Leine series. The main anhydrite exists because of the brittle material behaviour and the tectonic stress in blocks surrounded by salt. The caprock was formed, but it is possibly penetrated by the anhydrite. There is the possibility of solution inflows along the anhydrite.

For further stabilisation, mining excavations have to be backfilled. In addition, the storage areas in each field have to be protected against solution inflows with sealing dams. Similarly, the shafts have to be closed and sealed.

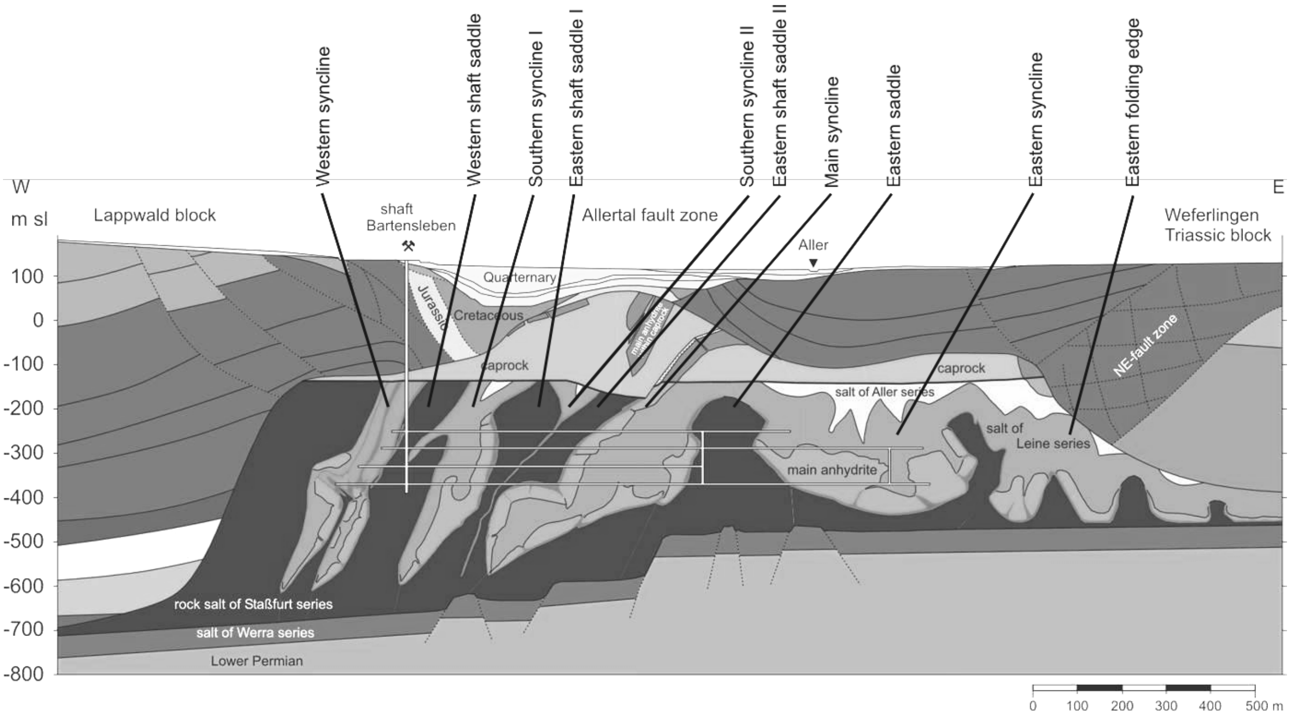

Figure 1-2: Geological structure of the salt dome repository (east-west cross-section) with overburden

2. Functions of Sealing Dams in a Repository

If solution enters the salt structure, the sealings have the function to delay the inflow of solution into the storage chambers. The following considerations relate to sealing structures in rock salt because a first in-situ experiment was carried out in this formation. To delay the solution inflow, the route has to be sealed. The integral permeability for the sealing structure, the contact zone and the excavation damaged zone (EDZ) has to be below a certain limit. The necessary permeability can be achieved with a dam composed of salt concrete. In this case, the autogenous shrinkage of the construction material has to be considered. The resulting joint between dam and contact zone must be injected with superfine cement for a strong and low permeable connection. The construction sequence shown below was designed to ensure compliance with the requirements of the sealing structures:

- Recut of the drift to remove EDZ (criterion: permeability $k \le 10^{-18}$ m²)
- Installation of the injection pipes for grouting the contact zone
- Concreting of the sealing structure composed of salt concrete
- Waiting time to allow for the alleviation of autogenous shrinkage of the salt concrete (criterion: $\dot{\varepsilon}_{\text{shrinkage}} \le \dot{\varepsilon}_{\text{creep rock salt}}$)
- Injection of the contact zone

Once the sealing structure has been completed, a stress state will occur, which is characterised by normal stresses and shear stresses in the contact zone. The normal stresses result from the creeping of the rock. The shear stresses are based on a single-sided fluid pressure after flooding the pit (Fig. 2-1).

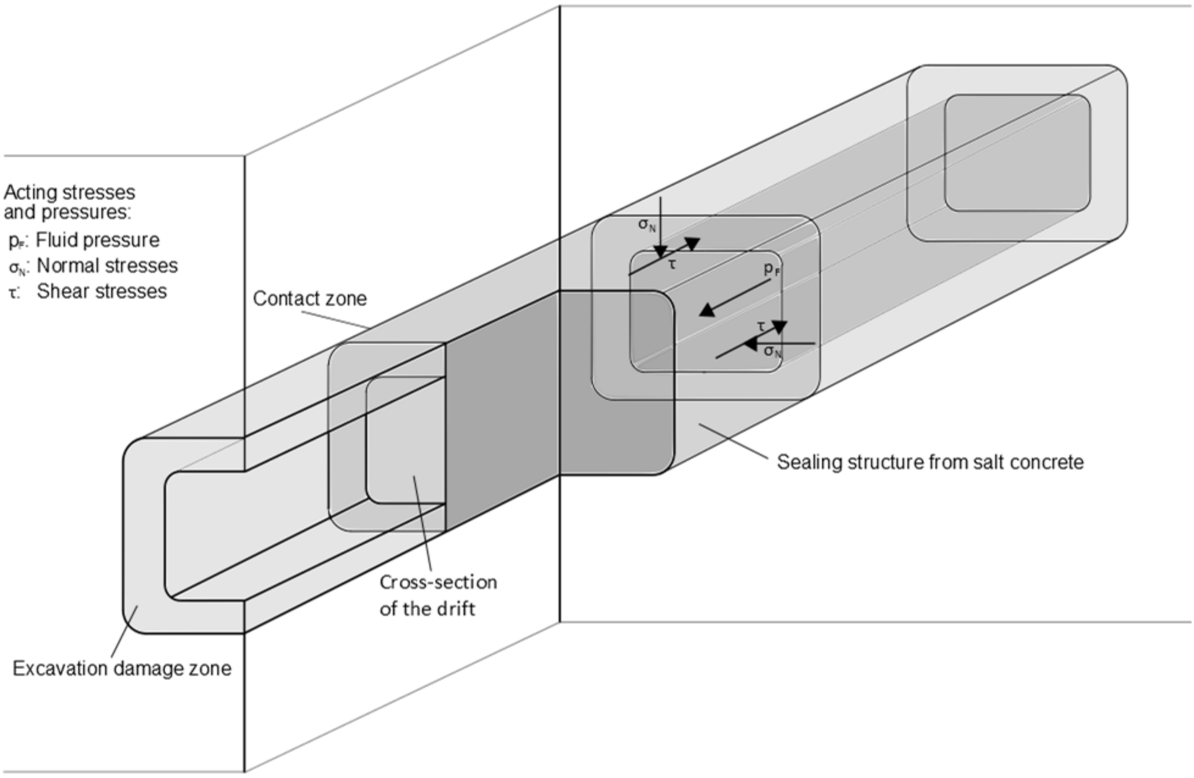

Figure 2-1: Schematic of a drift seal

3. In-situ Test of a Sealing Structure in Rock Salt

To detect the general function of the drift sealing, an in-situ test was built. This demonstration is required in the decommissioning of the ERAM. The in-situ test consists of a test and an accompanying drift. In Fig. 3-1, the experimental set-up is shown. The test drift consists of dam, pressure chamber, control chamber and four measuring cross sections and a measuring longitudinal section. The pressure chamber is made of porous sandstone and can be loaded from within the accompanying drift with fluid or gas pressure.

Through these experiments, the corresponding design values are determined. These values are permeability in the contact zone and in the structure on the one hand and the correct time of injection of the contact zone and the stability against displacement on the other hand. Figure 3-2 shows the necessary measurements in the measuring sections. The cables of the sensors run perpendicular to the longitudinal axis of the sealing structure to the accompanying drift. In order to test the plausibility of the measurement program and for a better understanding of the system, additional measurements were performed:

- Hydrofrac measurements
- Convergence measurements
- Permeability measurements in the host rock and in the contact zone

A detailed description of the design of the in-situ test is given in [1]. In [2] the running measurement program is described in detail. First results of the measurements were presented in [3].

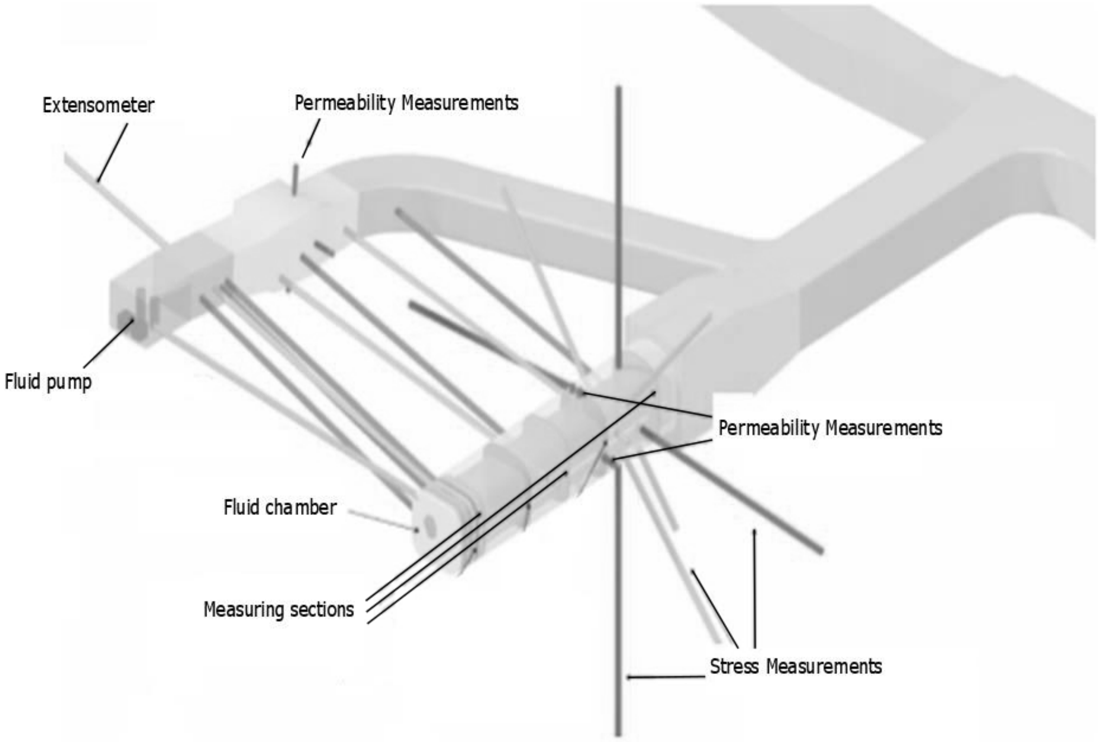

Figure 3-1: In-situ test (view from above with accompanying drift)

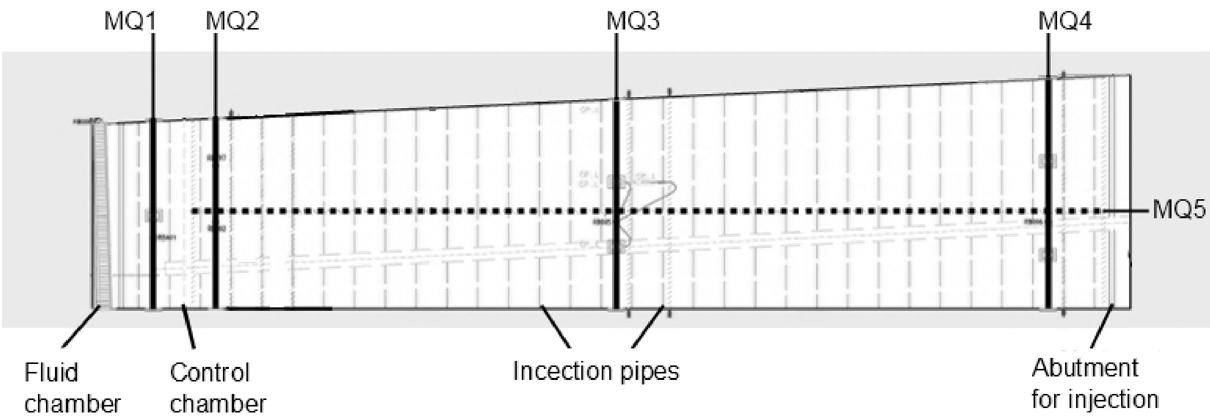

Figure 3-2: Lateral cut section with measuring sections: MQ1 Strain-, Temperature-, Pore-pressure-measuring; MQ2 Strain-, Deformation-, Temperature-, Pore-pressure-measuring; MQ3/4 Strain-, Deformation-, Temperature-measuring; MQ5 Deformation-, Temperature-measuring; Fluid-/Control-chamber Fluid-pressure-measuring

4. Experiences with a Measuring Program for the In-situ Test

Hereinafter, the fluid pressure and stress measurements are considered in more detail, as these are essential for monitoring programs.

Figure 4-1 shows the time profile of pressure in the pressure chamber, which has been measured at four points. Once the dam was completed, four pneumatic pre-tests were made. At the end of February 2011, the contact zone was injected. A hydraulic pre-test to check the function of the fluid pressure sensors was performed from February to early April 2012. The hydraulic main test began in early May 2012 and is still on going.

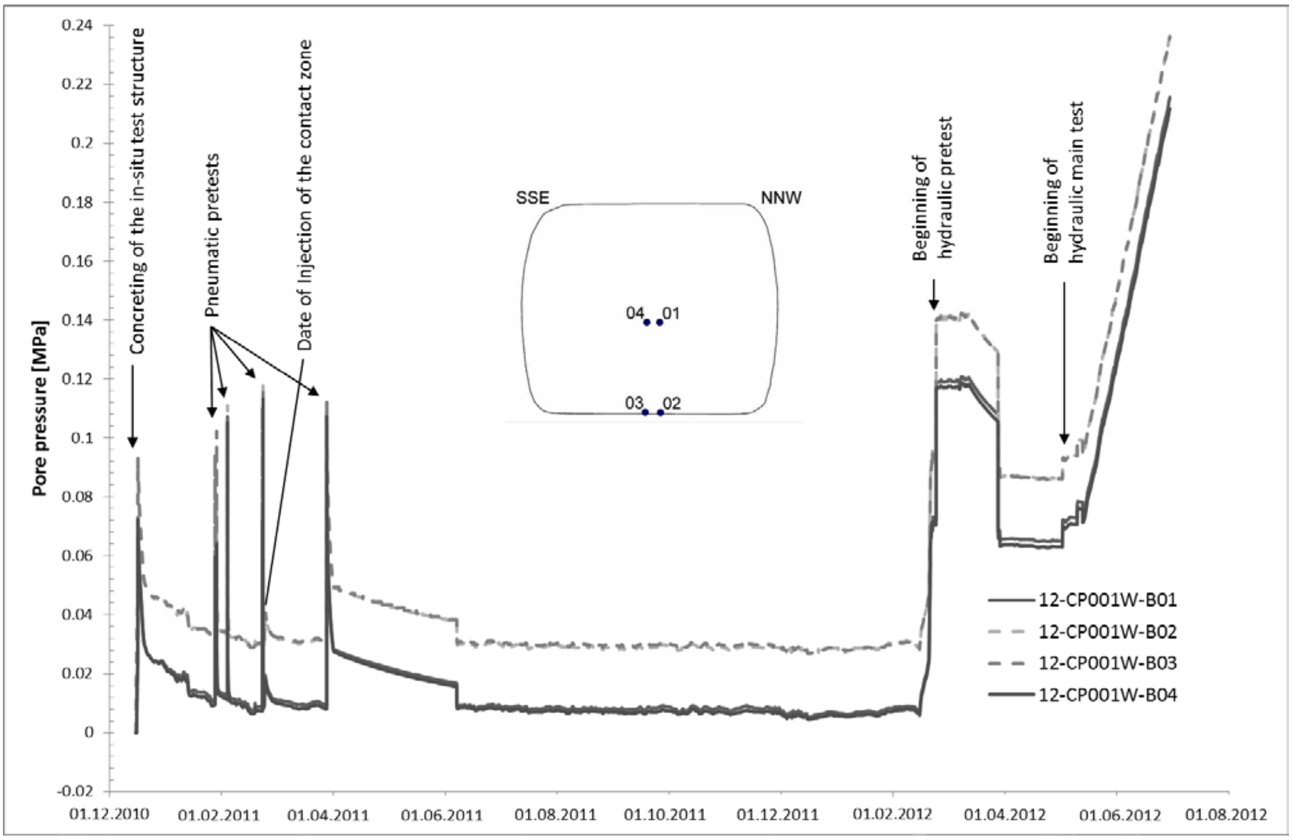

Figure 4-1: Development of the fluid pressure in the fluid chamber

The measurement results can be evaluated only approximately, since the inflow surface is not known and a two-phase flow is assumed. Figure 4-2 shows a comparison of the pore pressures at the beginning of the hydraulic pre-tests and the hydraulic main test for the measuring sections equipped with pore pressure sensors. The distance from the pressure chamber to MQ1 is about 1 m, to the control chamber about 1.6 m and to MQ2 about 2.5 m. The pressure on the roof of the pressure chamber has been extrapolated. The sensors in MQ1 react in a short time to the pressure increase in the pressure chamber. The contact zone is hydraulically active. In this area the course of the pressure curves, leads to the suggestion that there are inhomogeneous flow paths in the material. The response of the sensors in the control chamber shows as a possible interpretation that the hydraulically active joint in the contact zone in the faces and in the floor is greater than in the roof. This was not expected. In principle, the same observations have been made for the MQ2. The pressure-time curve from this cross section shows a further increase in the measured pressures, without an increase in the pressure in the pressure chamber. Pore pressure sensors in the concrete do not respond, so primarily flow occurring in the contact zone is observed.
After the hydraulic pre-test the pressure in the pressure chamber was decreased. Therefore the pressure at the sensors in the measuring cross-sections was also intended to fall. This was observed at two sensors only. The hydraulic pathways seem to downsize. Remarkable is the pressure on the floor of the control chamber which is higher than on the floor of the pressure chamber. This suggests that fluid inclusions get additional pressure caused by the rock behaviour.

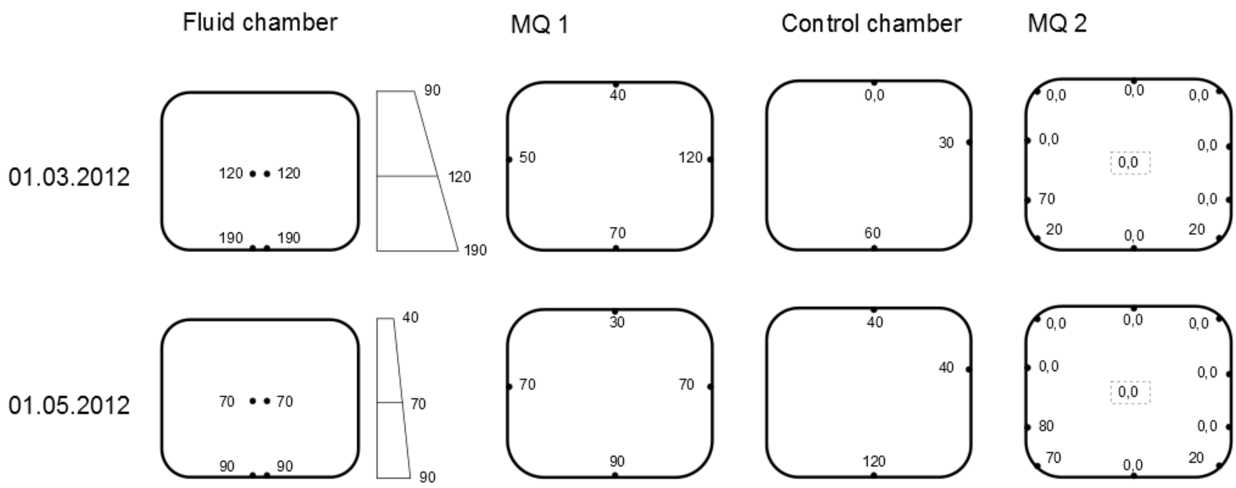

Figure 4-2: Pore pressures (in kPa) in the contact zone at the beginning of hydraulic pre-testing (March 01, 2012) and the hydraulic main test (May 01, 2012)

In the contact zone, the fluid flow develops on preferred pathways. In this case, sensors can be flown around. Fluid inclusions may also occur, showing an independent behaviour of the pressure chamber. Based on these measurements and the unknown two-phase flow due to the incomplete saturation, statements regarding the permeability can only be made with strong simplifying assumptions. The installation of the sensors was done very carefully to avoid improper connections.

Normal stress measurements have been performed in the measuring sections in the contact zone of the measuring sections MQ1 to MQ4. Additionally, horizontal and vertical stresses in the concrete structure have been recorded in the measuring sections MQ2 to MQ4. It was also possible to inject the encoders (pressure pads, stress monitoring stations) after installation in order to close possible gaps between sensor and concrete or rock. In Fig. 4-3 and 4-4, stress-time curves for MQ1 and MQ4 are exemplified.

During the concreting and hardening process the stress increase can be easily understood. The following stress rates based on the rock behaviour are too low. The measured stress state (absolute values) cannot be improved substantially by re-injection of the sensors on the right face and in the roof. Based on the measured stress distribution, an equilibrium state cannot be deduced (see also Fig. 4-5). Obviously, only relative changes in stress may be interpreted. The hydraulic pre-test leads to decreased stress in the roof and in the faces. The influence of fluid leads to an altered load transfer.

The MQ4 is located about 2.2 m from the air-side end face. Here the stress increase due to the concrete pouring and setting time can also be identified in the stress-time history. Afterwards, the stress increase based on the rock behaviour is too low as well. The pressure pad in the floor of MQ4 was re-injected. In May 2011, the contour line was recut on the air side to take samples from the contact zone. This leads to significantly greater stress rates, indicating re-activation of the primary creep. From the beginning of 2012, the stress rates in MQ4 have been approximately equal. The absolute values, however, are so far apart that even here no equilibrium state can be derived. The measured values in MQ4 can only be interpreted as relative changes in stress as well as in MQ1. An influence of the hydraulic pre-test is not visible, probably because no fluid advanced to MQ4. Moreover, the measurements in this cross section were affected by other activities. In this time, the jacket tube of the injection pipes was drilled to remove it.

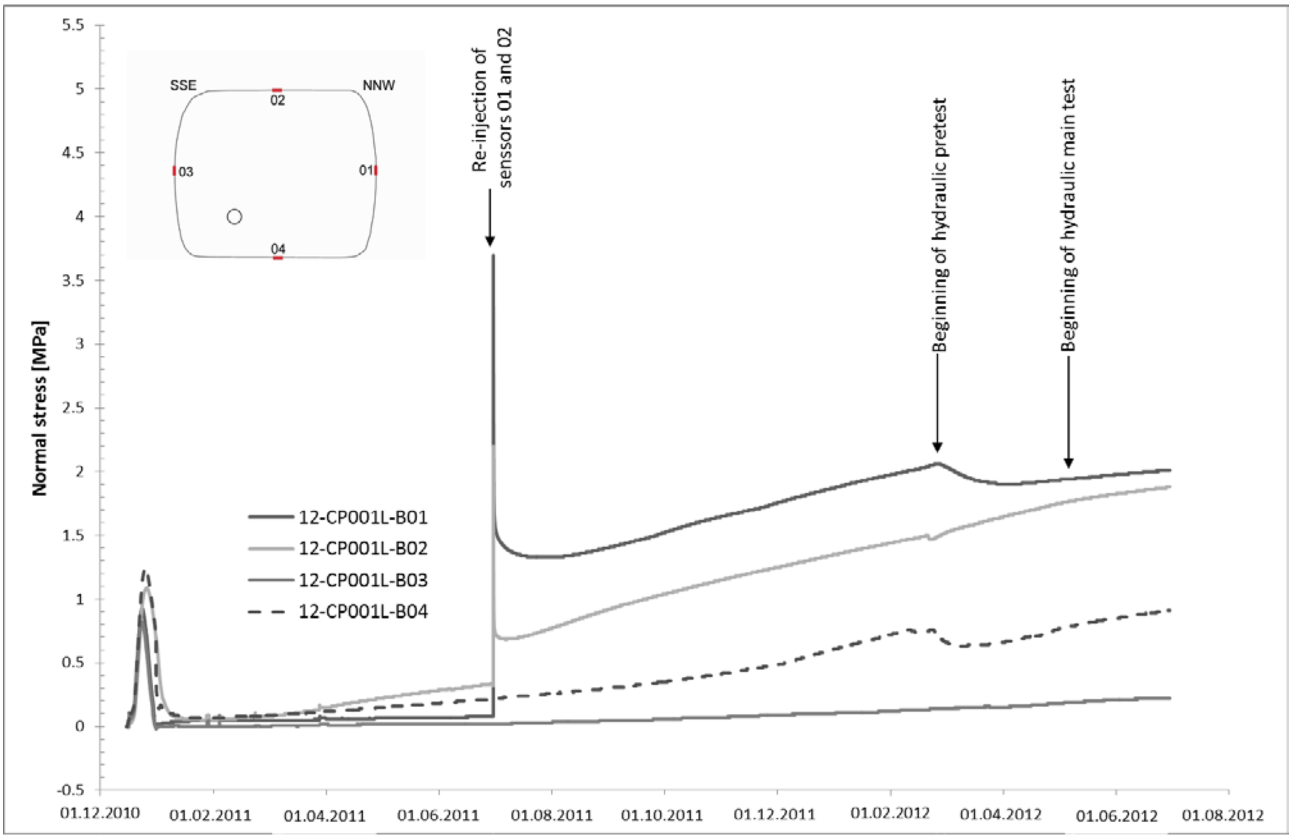

Figure 4-3: Development of normal stresses in the measuring section MQ1

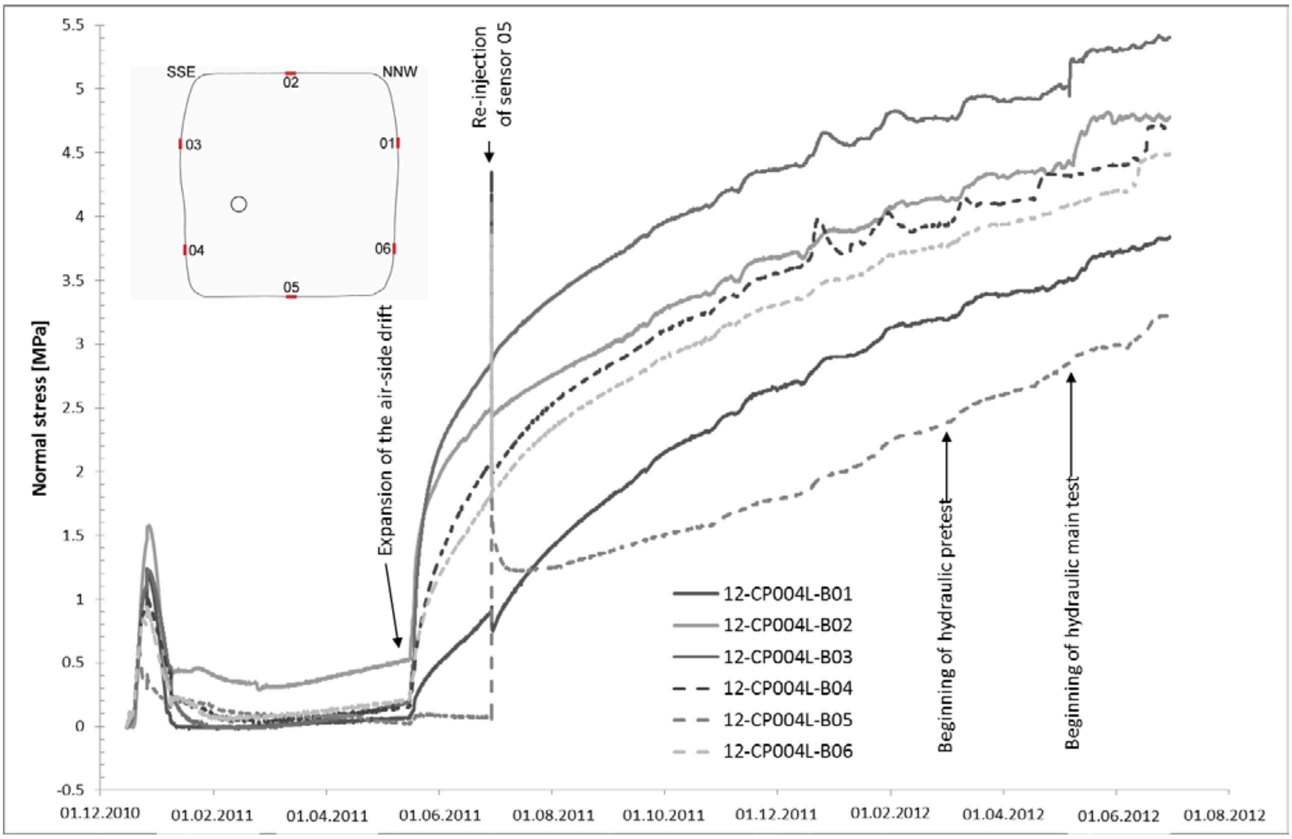

Fig. 4-4: Development of normal stresses in the measuring section MQ4

Figure 4-5 shows the normal stresses in the contact zone of the measured cross sections MQ1 to MQ4 and the horizontal and vertical stresses in the concrete for MQ2 to MQ4 for the beginning of the hydraulic pre-test and the start of the hydraulic main test. Generally an increase in stress can be observed between the observation time points. The values in each cross-section do not correspond to the equilibrium conditions. Also, the stresses in the concrete show no uniform picture and tend to appear too low. Occasionally, no significant changes can be identified through the observation period. An interpretive approach taking account of shear stresses or different cohesive compound cannot currently be justified based on the existing data. Therefore only the stress rates can currently be analysed descriptively.

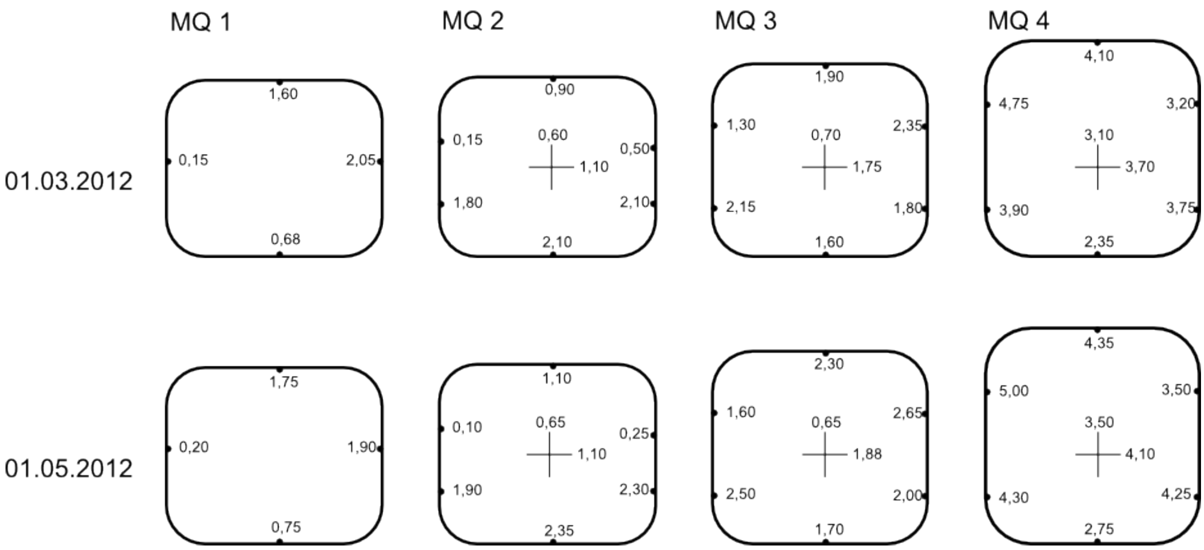

Figure 4-5: Normal stresses (in MPa) in the contact zone at the beginning of the hydraulic pre-test (March 01, 2012) and the hydraulic main test (May 01, 2012)

More results and interpretations of the measurements on the sealing structure can also be found in [4].

5. Conclusions for adapting to a Monitoring Program over a long period

Experience with a measurement program designed for a short period of time shows that certain issues need to be resolved for the long-term monitoring of geotechnical sealing structures in repositories. Ideal installation conditions for the structure and the sensors cannot be expected. The measured values are influenced by local conditions. Different flow paths and flow resistances in the contact zone are expected especially in the initial phase. The functionality will not be affected in the long term, because the creep of the rock salt leads to a homogenisation of the local states. This leads to a difficult evaluation of the measured fluid pressures. In a monitoring program it is taken into account that the fluid pressures will depend on the local conditions and that the fluid front is not progressing uniformly. Because of the discrete arrangement of the sensors, not necessarily all flow paths are detectable. The stress measurements show an even greater uncertainty. This can be attributed to the connection of the sensors to the rock. Also, the re-injection of stress sensors with defined injection quantities leads to unknown changes in transmitting stresses between host rock and structure. In addition, hard and soft inclusions are to be expected after the injection. The relative stress changes can be taken as reliable information. Exceeding of the material strength cannot be detected because no absolute values of the stresses are available. Further research and development work is still required for the in-situ stress measurements.

The use of wireless sensors for monitoring systems has many advantages. For example, no leadthroughs need to be planned and constructed in security-related components. However, other issues related to power supply and data transmission are not yet fully understood (see [5]). But new promising research approaches help solve these problems (see [6]). It was shown in the in-situ experiment that a cable routing perpendicular to the longitudinal axis of the structure does not adversely affect the functionality, at least for relatively short periods of time.

Even with careful planning, constructing and monitoring of the measurement program for the in-situ test, many challenges arise in the analysis and interpretation of the measured values. This is to be expected for long-term monitoring programs.

References

[1] Mauke, R.; Mohlfeld, M. (2010): In situ Versuch für ein Abdichtungsbauwerk im Steinsalz – Zielstellung, Versuchsprogramm, geotechnische Instrumentierung; Mitteillungen des Instituts für Grundbau und Bodenmechanik TU Braunschweig, Messen in der Geotechnik,, Braunschweig, Germany, 2010

[2] Stahlmann, J.; Mauke, R.; Mohlfeld, M.; Missal, C. (2011): Salt and Rock Mechanic Challenges at the Verification of Drift Seal Systems at the Morsleben Repository, Germany; 12th ISRM International Congress on Rock Mechanics - Harmonising Rock Engineering and the Environment, Edited by: Qian; Zhou, Beijing, China, 2012

[3] Manthee, F.; Fischle, W. R.; Paehge, W.; Rathke, C.; Mauke, R. (2011): Results of stress and strain measurements in a barrier made of salt concrete, 8th International Symposium on Field Measurements in GeoMechanics, Berlin, Germany, 2011

[4] Mauke, R.; Stahlmann, J.; Mohlfeld, M. (2012): In-situ verification of a drift seal system in rock salt – operating experience and preliminary results, 7th Conference on the Mechanical Behaviour of Salt, Edited by: Bérest, P.; Ghoryci, M.; Hadj-Hassen, F.; Tijani, M., Paris, France, 2012

[5] Jobmann, M.; Eilers, G.; Haverkamp, B. (2011): Überwachung eines Endlagers für hochradioaktive Abfälle in Deutschland – Grenzen und Möglichkeiten; atw – International Journal for Nuclear Power, 56. Jg Heft 11, Berlin, 2011

[6] Grafe, F.; Wilsnack, Th.; Rössel, A.; Mauke, R. (2013): Wireless data transfer in salt rock, MoDeRn - Monitoring in Geological Disposal of Radioactive Waste "Objectives, Strategies, Technologies and Public Involvement", International Conference and Workshop, Luxembourg, 2013 (this conference)

C.6 Session S6T: Theme 3: Monitoring technologies: Feasibility and limitations (focusing on monitoring technologies)

Monitoring High-level Radioactive Waste Repositories with Non-intrusive Seismic Methods

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Summary

It is widely accepted that high-level radioactive waste repositories need to be monitored during their operational phases and possibly after closure. To avoid disturbances of the repository seals, such monitoring needs to be performed in a non-invasive manner. We have investigated the possibilities and limitations of seismic tomography for such a monitoring task. Changes within a repository are expected to produce subtle but measurable variations of the seismic waveforms when a high-fidelity sparker source and firmly grouted multicomponent motion sensors are employed. Traveltime tomography is not expected to yield useful information at the resolution required, but appropriate full-waveform inversion techniques have the potential to detect and delineate significant changes in temperature, pressure and water content within a repository. Currently available waveform inversion algorithms usually employ an acoustic (P-waves only) approximation. Our tests have shown that such an approximation is not adequate for radioactive waste repository monitoring. In contrast, elastic full-waveform inversion schemes that include shear waves as well have the potential to provide the necessary information. We propose a monitoring strategy in which the host rock properties are determined prior to repository excavation using elastic full-waveform inversion of seismic crosshole data. Once the repository is established, it can be monitored with repeated seismic measurements involving sources in distant boreholes and triaxial receivers placed as close to the repository as regulators will allow.

1. Introduction

Disposal of high-level radioactive waste (HLW) is a challenging task, because the waste needs to be isolated from the biosphere for about 1 million years. There seems to be a consensus that only a deep geological repository may comply with the necessary safety standards. Once a HLW repository is built and operational, there is a societal demand to monitor its status and keep track of its immediate surroundings.

The monitoring targets include the (i) waste itself, (ii) containers in which the waste is placed, (iii) buffer material in which the waste is embedded (e.g., bentonite), (iv) excavation damage zone (EDZ) of the repository and (v) host rock surrounding the repository. These targets are expected to be exposed to several processes that may lead to significant changes of their physical properties:

1. Since a radioactive waste repository will be located well below the groundwater table, it is expected that the repository will be water saturated at some stage. This will cause swelling of the bentonite surrounding the waste canisters. The swelling pressure will cause changes of the elastic properties, that is, the seismic velocities and attenuation factors are expected to increase. Although not yet studied in detail, the electrical properties (electrical conductivity) are also expected to change by the infiltrating water.
2. High-level radioactive waste will produce substantial amounts of heat. Both elastic and electrical rock properties are temperature dependent. Therefore, it is expected that geophysical measurements could monitor thermal changes in the repository.
3. The decay of radioactive material and corrosion will produce gaseous phases that may increase the pressure within a repository. Additionally, and probably more importantly, the gaseous phases may substitute liquids. Replacement of liquids by gases will affect both the elastic and electrical rock properties.
4. Fluid migration and pressure and temperature variations within a repository together with external forces (isostatic or tectonic) may affect the amount of fracturing in the EDZ and the surrounding host rock. Like the processes described above, the amount of fracturing influences the elastic and electrical medium properties.

Monitoring of these processes needs to be performed in a non-invasive manner, since they should not affect the safety barriers protecting the HLW. Geophysical methods are appropriate for such non-invasive testing, but HLW monitoring is challenging. Subtle changes of the physical properties need to be detected and/or imaged. In the framework of two EC projects ESDRED (www.esdred.info) and MoDeRn (http://www.modern-fp7.eu), the possibilities and limitations of seismic tomography have been explored.

Here, we report the results of our investigations related to the applicability of seismic tomography for HLW monitoring. Using realistic scenarios based on two different test sites, we first inspect the requirements in terms of data accuracy and measurement repeatability. Then, we investigate the suitability of waveform inversion algorithms. More specifically, we test the validity of the commonly applied acoustic approximation. Finally, we propose a seismic-waveform-inversion-based monitoring strategy, with which small-scale changes within a repository and its surroundings can be imaged. Our investigations are largely based on synthetic data, but we also consider results from field measurements at the two test sites.

2. Test Sites

Field measurements were made within the clay-rich environment of the Mont Terri rock laboratory (FMT) and the granitic mass of the Grimsel Test Site (GTS). The experimental setup at FMT is shown in Fig. 2.1a. Two diverging observation boreholes were drilled perpendicular to a 1-m-diameter microtunnel, which mimicked a downscaled repository. The microtunnel was initially filled with dry sand and then progressively water saturated and finally slightly over pressurized. At various stages, crosshole seismic measurements were made by firing a sparker energy source in the lower borehole and detecting the resulting waves on a hydrophone chain in the upper borehole.

The GTS experiment is illustrated by the simplified sketch in Fig. 2.1b. At the end of a 3.5-m-diameter tunnel, a 1-m-thick layer of bentonite was emplaced and sealed with a

4-m-thick concrete plug. The bentonite layer was then successively water saturated. The associated swelling process was monitored by means of repeated crosshole seismic surveying using six observatory boreholes around the target.

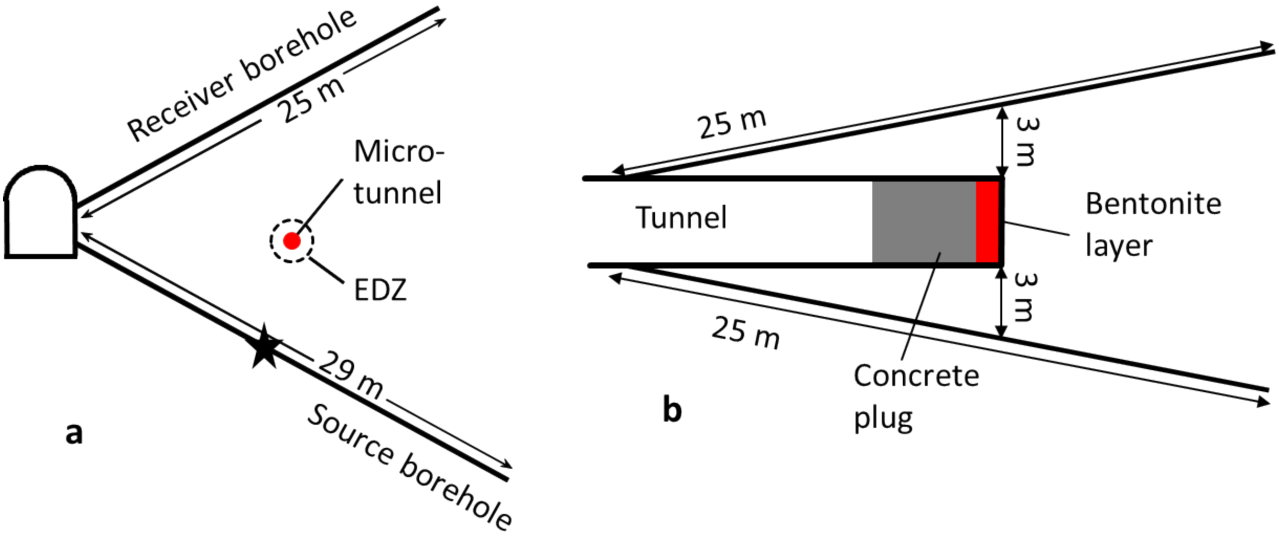

Figure 2.1: (a) Experimental setup at the Mont Terri (FMT) site. Black star indicates the shot position used to compute the seismograms in Fig. 3.1. (b) Experimental setup at the Grimsel test site (GTS). Note, that only two of the six observational boreholes at GTS are shown.

3. Modeling of Expected Waveform Changes

To assess the utility of seismic techniques for monitoring HLW repositories, it was necessary to first establish by means of numerical seismic modelling the likely changes in the seismograms due to the differential changes in the state of the repository. We computed synthetic seismograms for the same recording configuration as used at the FMT site. This entailed assuming a plausible background model for the clay-rich formation (including 30% anisotropy) and initially a dry sand-filled microtunnel with an associated dry EDZ. Pressure seismograms were generated using a modified version of the elastic finite-difference code described in [1]. For the next simulation, the microtunnel was assumed to be water saturated and the EDZ to be healed completely.

The resulting seismic sections for the two scenarios are displayed in Fig. 3.1. There is virtually no difference between the first-break arrival times in each case. Simple calculations confirm that the maximum traveltime variations caused by changes in the microtunnel and its EDZ do not exceed 0.1 ms, which is close to the first-break picking accuracy. Consequently, traveltime tomography is unable to detect the changed conditions. In contrast, subtle but significant changes in the waveforms are clearly seen, thereby indicating that a full-waveform inversion approach may yield useful information, assuming that sufficiently high-quality data can be acquired.

4. Repeatability of Waveforms

A key requirement for successful time-lapse imaging is that the experiments are highly repeatable. We have conducted extensive repeatability tests at FMT and GTS. Detailed results are described in [2]. It was found that the sparker source employed for these tests was highly repeatable and provided sufficiently high energy in the desired frequency range from a few hundred Hz up to several kHz. The hydrophone receivers, however, were afflicted by serious repeatability issues. To illustrate this phenomenon, we show the results of a re-insertion experiment in Fig. 4.1. The blue seismograms were obtained for a shot detonated at the cross in Fig. 2.1a. The red seismograms were obtained for the same source position, but after removing the hydrophone chain from the borehole and immediately placing it back in the hole at the same position. The substantial waveform differences are attributed to different coupling conditions between the two experiments caused by minor misplacements of the hydrophone positions and by slight variations in the seating of the hydrophone chain. The magnitudes of the waveform differences far exceed the effects to be monitored (compare Figs. 3.1 and 4.1).

An obvious solution is to replace the hydrophones by firmly grouted or rigidly affixed geophones or accelerometers. This would ensure consistent coupling conditions for each sensor, but there could still be variations along the borehole. Furthermore, it is still necessary to separate the effects of the constant, but unknown coupling effects from geological variations within the medium itself. Both of these problems can be addressed by simultaneously solving for unknown source function and receiver coupling factors while inverting for medium properties. We recently published a procedure for achieving this goal [3].

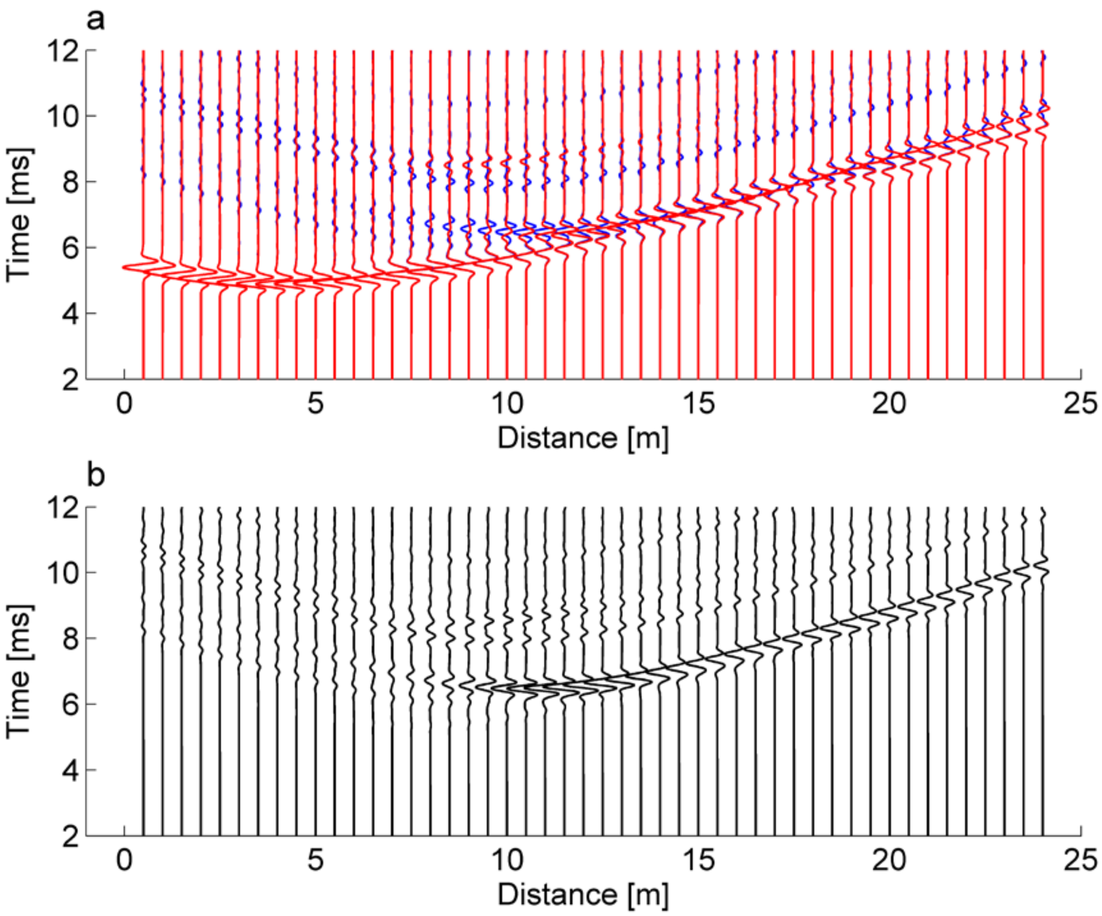

Figure 3.1: Synthetic seismic traces for a shot fired at the location indicated by the black star in Fig. 2.1a. Hydrophones were placed in the receiver borehole. (a) Blue traces are computed for a dry microtunnel with EDZ and the red traces are computed for a model

representing a water-saturated microtunnel and healed EDZ. (b) Resulting traces, when the blue seismograms are subtracted from the red seismograms shown in (a).

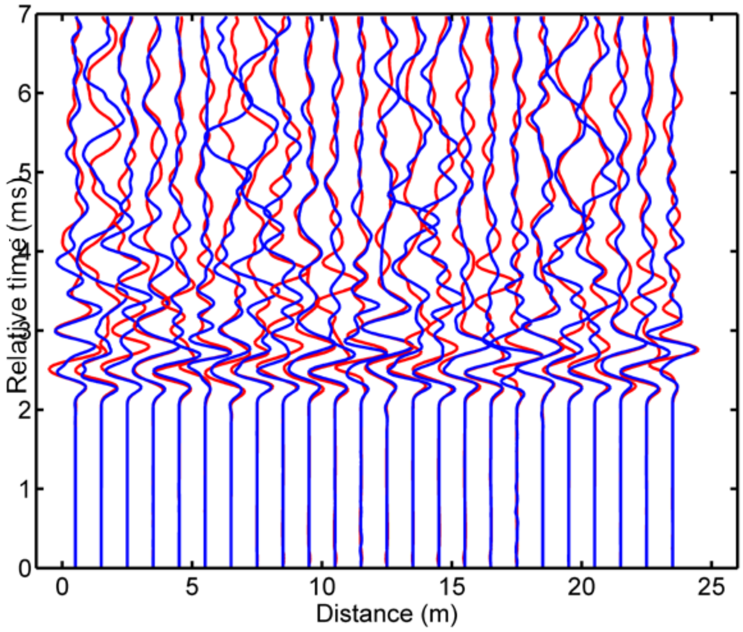

Figure 4.1: Results from a re-insertion experiment using a sparker source (black star in Fig. 2.1a) and a hydrophone chain. Source gather from the initial experiment - blue traces. Source gather after re-inserting the hydrophone chain - red traces. Distances are relative to the receiver borehole collar. Average source-receiver distances are 10-15 m. First breaks have been horizontally aligned for display purposes. For clarity, only every fourth trace is plotted.

5. Validity of the acoustic approximation

Although substantial efforts have been made over the past few years to develop full-waveform schemes that can be used to invert observed data, numerous issues and problems remain, such that elastic waveform inversions are far from being applied on a routine basis. A major concern is the massive computational resources required for 3D elastic wave experiments. A common approach to mitigate this problem is to make an acoustic approximation. Here, it is assumed that the material has no shear strength. Therefore, only compressional P waves can propagate and no shear waves and mode conversions can occur (e.g., [4]). We have shown in an extensive study that acoustic inversions of crosshole elastic data produce erroneous and misleading results when the medium of interest includes spatially extended discontinuities at which P-to-S conversions can occur, or if the offsets are large [5].

Since monitoring experiments are primarily concerned with differential changes within a medium of interest, we have investigated if such changes can be detected and mapped when image artefacts are present due to the acoustic approximation. For this purpose, we simulated a water-saturation experiment at GTS (Fig. 2.1b). The elastic properties of the host rock and concrete plug were held constant and only the velocities and densities of the bentonite layer were allowed to vary with changing water content. Acoustic as well as elastic waveforms were synthesised for different degrees of saturation. For computing the “acoustic data” the shear strength of the material was neglected, whereby a realistic shear strength was assumed for the "elastic data set". Both data sets were inverted using a purely acoustic waveform inversion code [6]. The average bentonite velocities obtained from the inversions are shown in Fig. 5.1 as a function of the true (simulated) values. The "acoustic data – acoustic inversion" results (Fig. 5.1a) demonstrate that such experiments can be successful; even though the true velocities are slightly underestimated, the general trend is correct. By comparison, results of acoustically inverting the "elastic data" fail to recover the true velocity structure. We conclude that true elastic full-waveform inversions are required for HLW monitoring experiments.

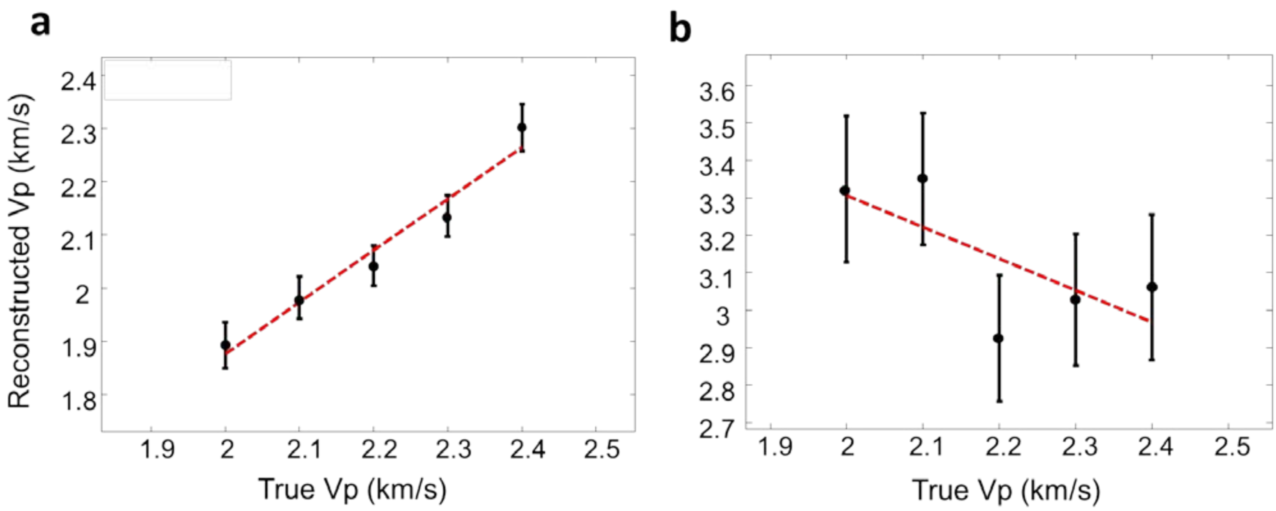

Figure 5.1: Acoustic inversion results for a water-saturation experiment simulated for the GTS setup (Fig. 2.1b). Black dots are average velocities for dry bentonite (true Vp = 2.0 km/s) and increasingly saturated bentonite layers (true Vp up to 2.4 km/s). Dashed red line is a least-squares linear fit through the data points, and black vertical bars represent the standard deviations from the linear regression analysis. (a) Results for "acoustic data – acoustic inversion" experiments. (b) Results for "elastic data – acoustic inversion" experiments.

6. A Possible Strategy for Monitoring HLW Repositories with Seismic Tomography

Having identified that traveltime and acoustic waveform inversions are not adequate for HLW repository monitoring, we propose a strategy that is based on elastic full-waveform inversions. As an example, we consider a scenario similar to the FMT setup (Fig. 2.1a). Figure 6.1a - 6.1c shows realistic elastic models (including compressional (*Vp*) and shear (*Vs*) wave velocities and density (ρ) variations) of the Opalinus clay found at Mont Terri.

Before excavating the repository, we suggest drilling two boreholes (solid black lines in Fig. 6.1a - 6.1c). To characterise the host rock between these two boreholes, crosshole tomography should be employed. Based on an experimental design study [7], we propose explosion-type sources (e.g., a seismic sparker) in one borehole and multicomponent geophones in the other borehole to detect the resulting waves. The geophones should be well coupled to the host rock, but they should be removable.

Here, a downscaled version of an excavated repository is modelled as a 1-m-diameter microtunnel perpendicular to the plane spanned by the two boreholes. Figure 6.1d - 6.1f shows enlarged portions of the tomographic planes in Fig. 6.1a - 6.1c with the addition of the microtunnel and an assoicated EDZ. They are seen as circular low-velocity / low density anomalies (Fig. 6.1d - 6.1f). For later monitoring experiments, we recommend placing additional multicomponent geophones as close to the repository as regulators will allow (e.g., open black dots in Fig. 6.1d - 6.1f).

Once the repository is water saturated, it is expected that seismic velocities within the microtunnel will have increased and that the EDZ will have healed, such that the elastic properties within the EDZ zone will return to approximately the original values prior to excavation. The *Vp*, *Vs* and □ models corresponding to the simulated water-saturated repository are shown in Fig. 6.1g - 6.1i.

Our simulated seismic monitoring experiment employs explosion-type sources detonated in the two boreholes and the eight firmly grouted receivers close to the microtunnel (Fig. 6.1). The key question is whether it would be possible to image the differences between Fig. 6.1d - 6.1f and Fig. 6.1g - 6.1i. To answer this question, we have simulated seismic waveforms using the two scenarios and subsequently inverted the data using an elastic full-waveform algorithm [7]. The resulting *Vp* tomograms in Fig. 7.1a and 7.1d closely mimic the true structures. The match of the *Vs* velocities in the tomograms of Fig. 7.1b and 7.1e is slightly inferior, but even these tomograms clearly indicate that changes have occurred within the repository. The density tomograms in Fig. 7c and 7.1f contain anomalous values in the area of the microtunnel, but they would not be reliable indicators of changes between dry and water-saturated conditions.

7. Conclusions and Outlook

Our investigations on HLW repository monitoring using seismic waveform inversions have shown that such an endeavour is generally feasible, but the problem is challenging. Likely changes within an HLW repository may only cause small variations of the seismic waveforms recorded outside of the repository. We recommend using sparker-type sources and firmly grouted multicomponent geophones or high-sensitivity accelerometers as the sensors. Traveltime and acoustic inversions are not expected to yield useful information. Instead, true elastic or even viscoelastic full-waveform inversions need to be performed.

Although this study has demonstrated the general feasibility of HLW repository monitoring based on seismic waveform inversions, more research is required before such an approach can be implemented. For example, the elastic waveform inversion algorithm described in [7] does not take into account anisotropy or anelastic attenuation. Incorporation of anisotropy is critical, because the directional dependence of velocities in clayey host rocks can be very pronounced (up to 30%). Finally, we emphasize that all waveform inversions shown in this study assumed 2D configurations. Realistic HLW repository designs will likely include 3D geometries. Conceptually, it is straightforward to extend the 2D inversion algorithms to 3D, but the computational costs for such an undertaking are substantial; it will be a few years before the necessary computational resources are available.

8. Acknowledgements

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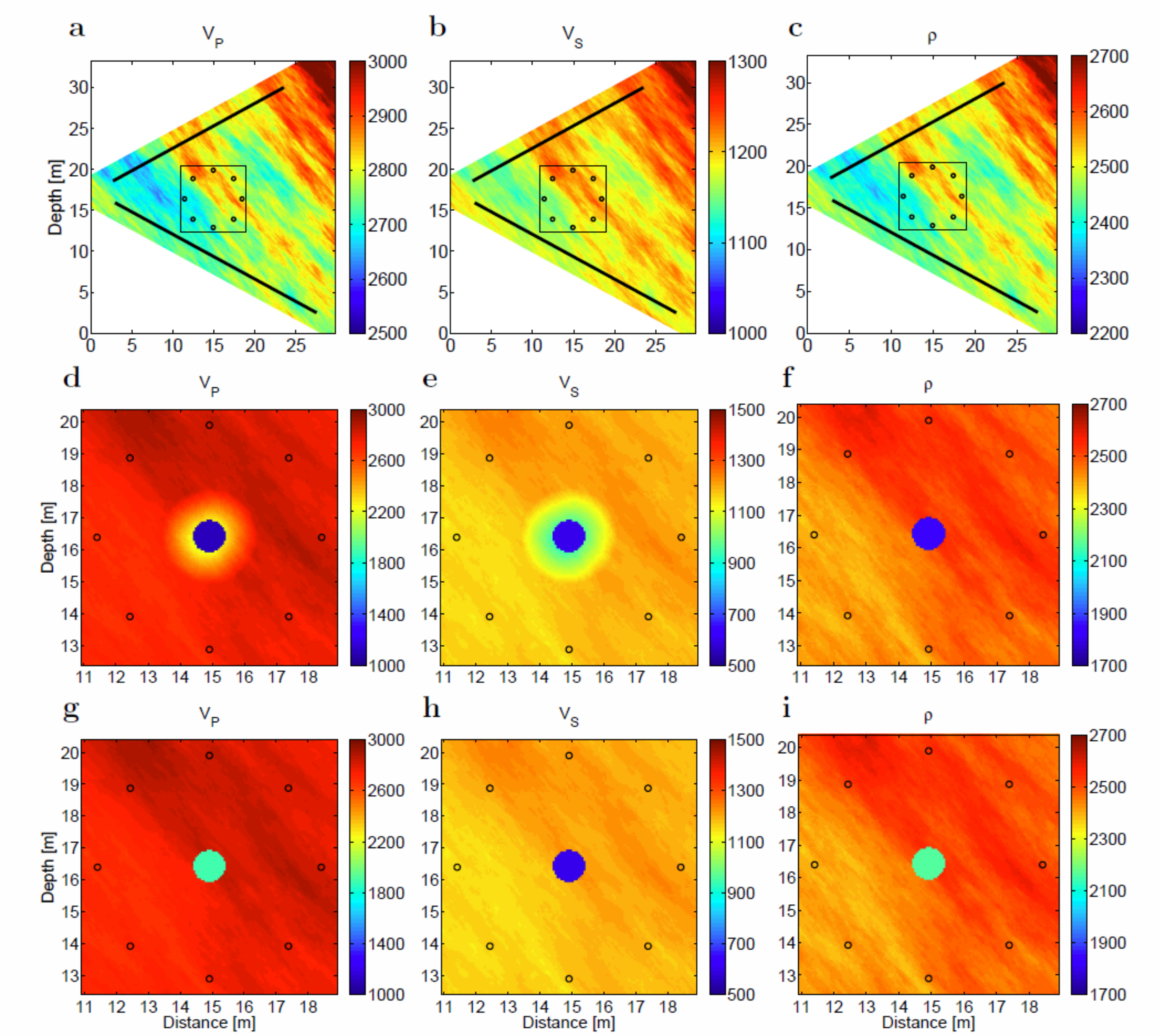

Figure 6.1: Models used to generate seismic waveform data for different repository scenarios. (a) - (c) show Vp, Vs and *values bef*
and black circles identify the monitoring region and the locations of geophones employed for the monitoring, respectively. (d) - (i) show close-ups of the black boxes (a) - (c) with the addition of a 1-m-diameter microtunnel and 1-m-wide EDZ. (d) - (f) show values for a dry repository, whereas (g) - (i) show values after water saturation.

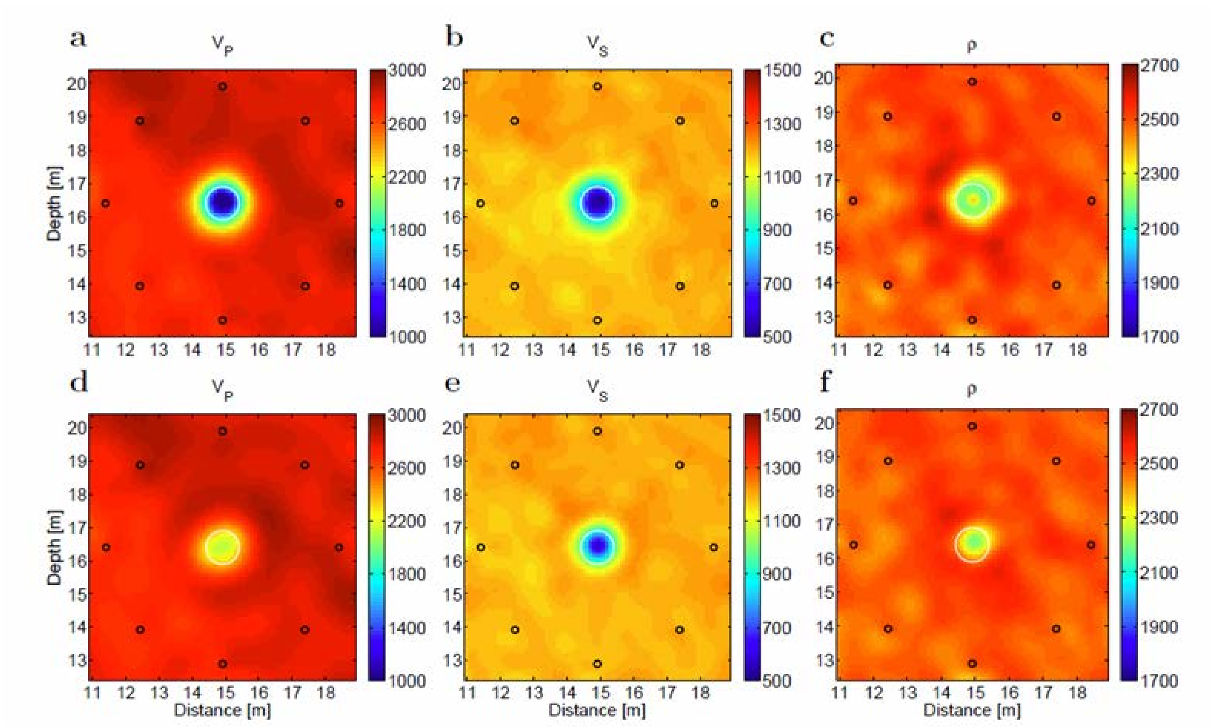

Figure 7.1: Close-ups of the waveform inversion results for pressure sources located in both boreholes and eight 2-component geophones at 3.5 m distance from the microtunnel centre (black circles). The inversion is performed for the 8 m x 8 m domain that is shown in the figure. (a) - (c) correspond to the dry repository scenario, whereas (d) - (f) correspond to a water-saturated repository.

References

[1] Bohlen, T., *Parallel 3-D viscoelastic finite difference seismic modelling.* Computers & Geosciences, 2002. **28**(8): p. 887-899.

[2] Marelli, S., E. Manukyan, H.R. Maurer, S.A. Greenhalgh, and A.G. Green, *Appraisal of waveform repeatability and reliability for crosshole and hole-to-tunnel seismic monitoring of radioactive waste repositories.* Geophysics, 2010. **75(5)**: p. Q21-Q34.

[3] Maurer, H.R., S.A. Greenhalgh, S. Marelli, E. Manukyan, and A.G. Green, *Receiver coupling effects in seismic waveform inversions.* Geophysics, 2012. **77**(1): p. 1-7.

[4] Pratt, R.G., *Seismic waveform inversion in the frequency domain, Part 1: Theory and verification in a physical scale model.* Geophysics, 1999. **64**(3): p. 888-901.

[5] Marelli, S., H. Maurer, and E. Manukyan, *Validity of the acoustic approximation in full-waveform seismic crosshole tomography.* Geophysics, 2012. **77**(3): p. R129-R139.

[6] Maurer, H., S. Greenhalgh, and S. Latzel, *Frequency and spatial sampling strategies for crosshole seismic waveform spectral inversion experiments.* Geophysics, 2009. **74**(6): p. Wcc79-Wcc89.

[7] Manukyan, E., S. Latzel, H. Maurer, S. Marelli, and S.A. Greenhalgh, *Exploitation of data-information content in elastic-waveform inversions.* Geophysics, 2012. **77**(2): p. R105-R115.

Wireless Transmission of Data from the HADES Underground Laboratory to the Surface

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Summary

As part of the European 7th Framework Programme project MoDeRn, Nuclear Research and Consultancy Group (NRG) performed experiments in order to demonstrate the feasibility of wireless data transmission from a deep geological disposal facility to the surface by low frequency magnetic fields. The main objective of NRG's contribution is to characterize and optimize the energy use of this technique within the specific context of post-closure monitoring of a repository. For that, measurements have been performed in the HADES underground laboratory (URL) located at Mol, Belgium, at 225 m depth. The experimental set-up utilizes a loop antenna as a transmitter that has been matched to the existing infrastructure of the HADES. Between 2010 and 2012 NRG carried out several experiments at the HADES URL in order to test the technical set-up and to characterize the propagation behaviour of the geological medium and the local background noise pattern. Potential transmission channels have been identified up to 1.8 kHz and data transmission has been demonstrated at several frequencies, with data rates up to 10 bit/s and bit error rates <1%. A mathematical model description of the most relevant characteristics of the transmitter, transmission path, and receiver has been developed and allows to analyse possible options to optimize the set-up. With respect to the energy-efficiency, model calculations and results so far have shown that data transmission over larger distances through the subsurface is a feasible option. To support the predictions on the energy need per bit of transmitted data, additional experiments are foreseen.

1. Introduction

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

An important factor for the characterization of the signal attenuation by a medium is the electrical conductivity σ of the medium. Large conductivity values that fulfil the criterion

$$\sigma >> 2 \cdot \pi \cdot f \cdot \varepsilon \qquad \textit{Eq. 1}$$

with

σ	conductivity [S/m]
f	frequency [Hz]
ε	permittivity [A·s/V·m]

induce the so-called "skin-effect" [1], with the *skin depth* δ equivalent to

$$\delta[m] = \frac{1}{\sqrt{\pi \cdot \mu \cdot \sigma \cdot f}} \qquad \textit{Eq. 2}$$

with

μ	permeability [V·s/A·m]

results in an attenuation of the magnetic field that can be estimated roughly by $e^{-r/\delta}$ (*r* = transmission distance in [m]), equivalent to -8.7 dB per skin depth.

The electrical conductivity σ of geological media can vary to a large extent, from µS/m to mS/m for rock salt and crystalline rock, and mS/m to S/m for argillaceous rock. The water-filled porosity of a geological media has a large influence on the conductivity ($\sigma_{\text{ground water}} \approx 0.5$ S/m). In case of the Dutch generic disposal concept in argillaceous rock, the repository is foreseen to be situated in Boom Clay, a host rock with relevant water content (35-40%, [2]). Above the layer of Boom Clay, highly conductive sandy aquifers are situated, limiting the application of high frequency radio waves, too.

Within the European 7th Framework Programme project MoDeRn, *Monitoring Developments for safe Repository operation and staged closure*, NRG is conducting tests on the wireless transmission of monitoring data over large distances through geological media using low frequency magneto-induction techniques. These techniques are applied e.g. in mine communication and rescue (“trapped miner detection”) [3, 4, 5] or military communication, both on medium distances [6] and globally [7]. For these applications, the used frequency ranges from a few tens of Hz to a few tens of kHz. The specific objective of NRG’s contribution is to characterize and optimize the energy use of this technique within the specific context of post-closure monitoring. This should help to judge the principal feasibility of long-term wireless data transmission from an underground repository through the enclosing host rock and the overlying geosphere to the surface.

The applications summarized in the previous paragraph use different technical set-ups that are optimized for the particular purpose. In case of the transmission of monitoring data from a radioactive waste repository to the surface, a number of specific requirements and boundary conditions for the application of wireless techniques can be defined:

- fixed antenna locations exist and the transmission path and distance are known
- the transmission properties of the host rock and overburden are invariable and can be determined
- a large range of antenna geometries and sizes can be implemented within a disposal concept when a horizontal loop-antenna set-up is selected
- localized sources of interferences, both underground and on the earth’s surface, can be eliminated or reduced

- no specific timeframe for data transmission is necessary
- high transmission speeds are not necessary
- an accurate transmission of data is essential
- the supply of energy in the disposal is limited

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

- energy use per bit of transmitted data
- amount of data that need to be transmitted

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

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

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

2. Methodology

Within the MoDeRn project, wireless data transmission experiments have been performed by NRG in the HADES Underground Research Laboratory (URL) in Mol, Belgium [8], situated at 225 m depth in a 100 m thick layer of Boom Clay. With respect to the electrical conductivity of the transmission path, conditions are quite comparable to those expected for the generic Dutch disposal facility in Boom Clay [9]. Although the depth of the HADES URL is about half of the generic depth for the Dutch disposal design (225 m vs. 500 m), other URLs situated in granite, salt rock or Opalinus clay have not been considered for NRG´s transmission experiments because of the lower conductivities of these host rocks. To be able to extrapolate the results of the experiments performed in Mol to a depth of 500 m, a proper characterization of the frequency-dependent field propagation behaviour was performed.

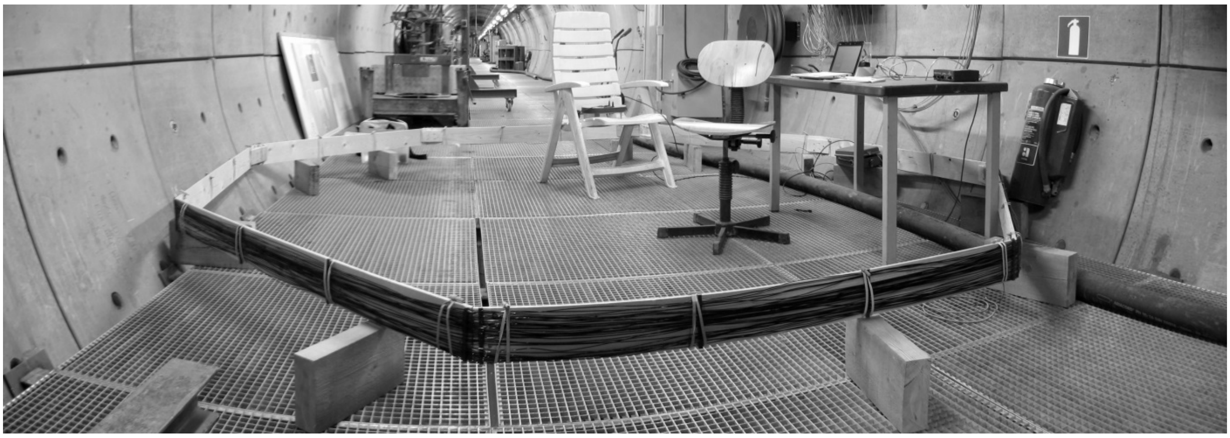

Figure 1: Transmitter antenna ECN-1 in the HADES URL

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

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

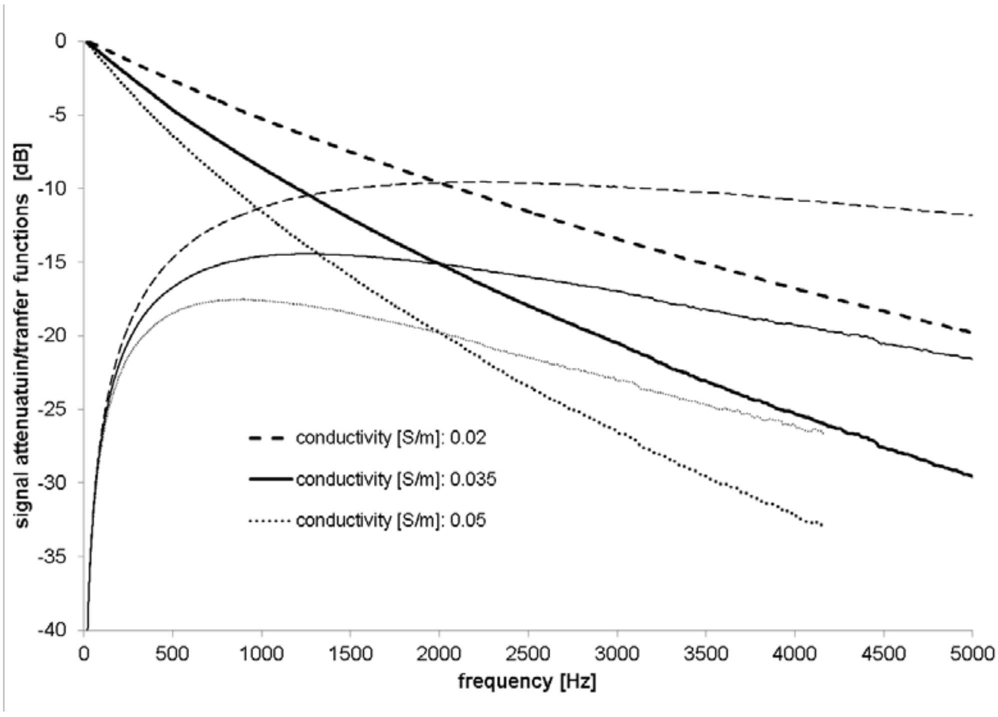

Figure 2: Estimated frequency--dependent signal attenuation (thick curves) and transfer functions (thin curves) for transmission experiments from the HADES URL to the surface.

Based on the data provided in [10], a first estimation was made on the frequency range to be used for the signal and data transmission experiments. Figure 2 shows the frequency-dependent attenuation by interactions with the geosphere and a (simplified) transfer function for different electrical conductivities derived from [10]. Evaluating these and other factors, a frequency range between 200 Hz and 5 kHz had been chosen for the experiments.

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

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

3. Results

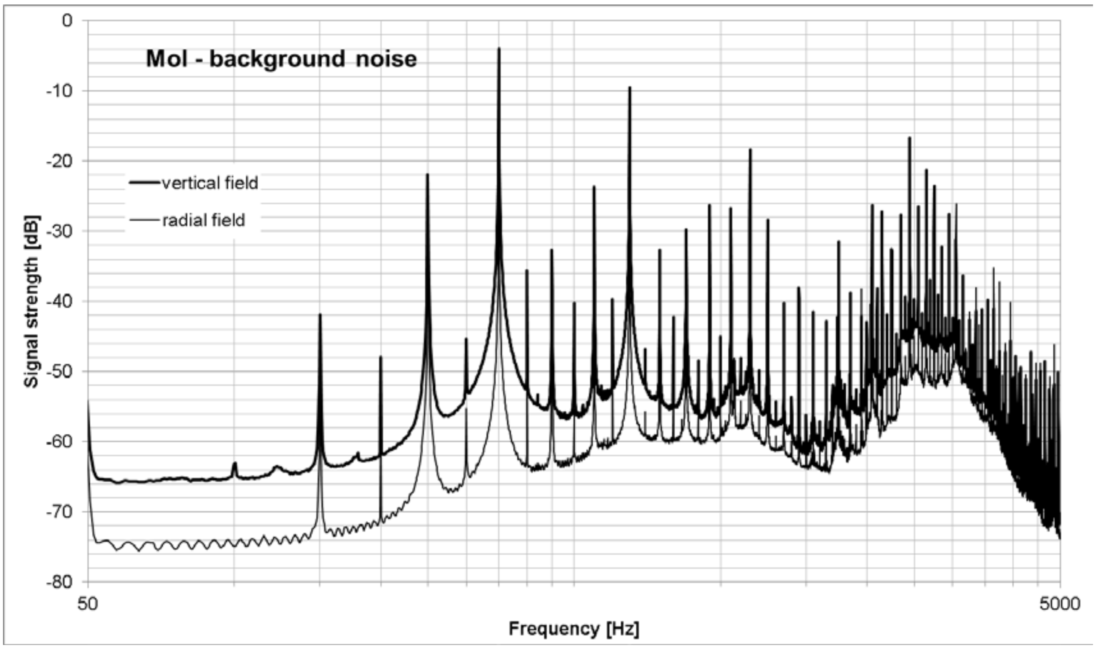

Figure 3: Vertical and radial component of location specific electromagnetic noise pattern at the surface in Mol

Figure 3 shows the radial and vertical electromagnetic noise recorded at the surface in Mol, on top of the HADES URL. As a result of a large number of harmonics of the 50 Hz power network, strong interferences are visible over the whole frequency range envisaged for data transmission. The radial field component was larger than expected from approximation equations used in literature [11]. However, these approximation equations are only valid under near-field condition, which are clearly not present above 500 Hz (i.e. skin depth δ > 225 m). At frequency ranges around 1.5 kHz, the signal-noise ratio (SNR) of the radial field was more favourable than that of the vertical field.

The strong peaks depicted in Fig. 3 also affect the maximum bandwidth that can be achieved for data transmission: Under the given conditions, data rates will be limited to less than 25 sym/s. Comparison with the noise pattern of a recreational area close to the NRG-site in Petten, The Netherlands, show that much lower background levels are achievable (data not shown). Technical improvements of the receiver realized during the project result in a higher sensitivity of the set-up and allow the detection of magnetic fields <100 fT. The increased receiver sensitivity could be demonstrated in the recreational area, but it was of less relevance in Mol under the conditions as depicted in Fig. 3, because here the background noise is clearly the limiting factor.

Figure 4 shows the reception of signals transmitted from the HADES URL to the surface. Signals up to 2.2 kHz can be received, with the highest SNR located between 1.0 and 1.7 kHz. It should be noted that without the interferences present at the Mol site, optimum data transmission frequencies may be higher. Fitting of the electrical conductivity σ of the transmission model resulted in a value of 35 mS/m, which is close to the values reported in [10].

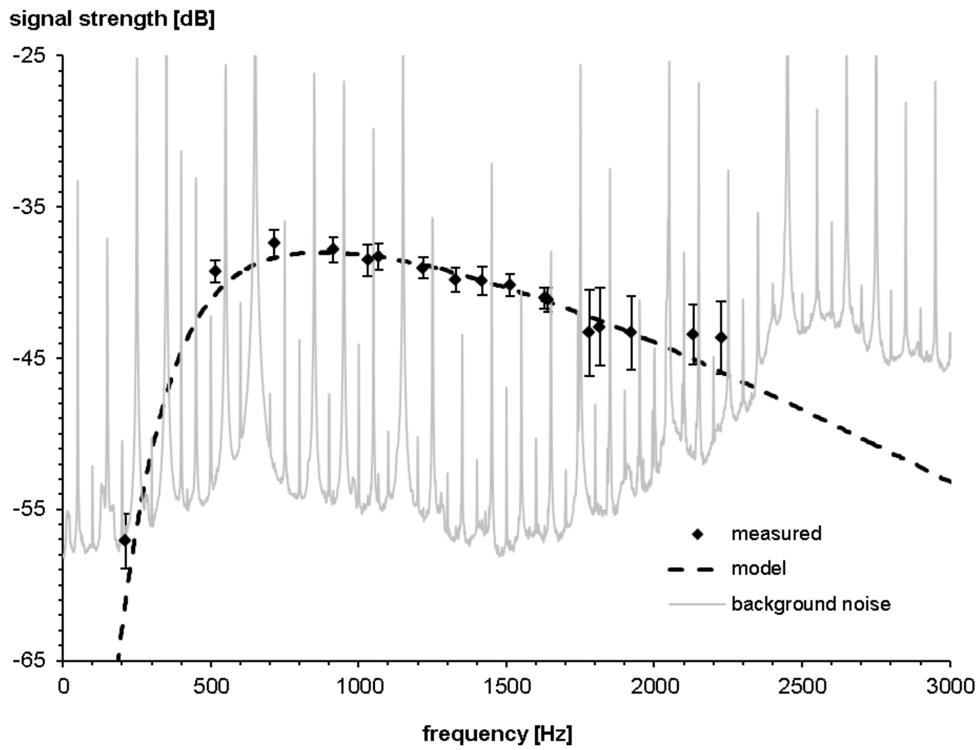

Figure 4: Background noise pattern, measured and calculated signal strength at the surface in Mol. Assumed conductivity of the geosphere σ = 35 mS/m

After having acquired sufficient data on the propagation behaviour of the geological medium and the local electromagnetic noise pattern, data transmission experiments had been carried out. First experiments have demonstrated the ability to transmit data from the HADES URL to the surface at two frequencies with data rates up to 10 bit/s and bit error rates (BER) below 1%. Table 3-1 summarizes a first set of indicative results. It should be noted that the length of the experiments was too short to obtain meaningful statistical conclusions, i.e. errors are not randomly distributed but could be partially attributed to single events (e.g. cars passing by).

Table 1: Bit Error Rates (BER) measured in the first data transmission experiments.

	Transmission frequency	
Data Rate	**1031.3 Hz**	**1066.4 Hz**
3 bit/s	0 dB: 0.4% - 6 dB : 0.9% -12 dB : >1%	0.0%
5 bit/s	0.4%	0.1%
10 bit/s	>1%	0.7%

4. Discussion

The experiments summarized in the previous sections clearly demonstrated the ability to transmit data through approximately 225 m of highly conductive geological medium, even under unfavourable experimental conditions as present in Mol (limited space for transmission antenna and large local interferences).

The next step was to analyse the energy need for a generic disposal concept and to identify potential options to increase the energy efficiency. A mathematical model has been developed that describes the expected signal strength on the surface on basis of the most relevant characteristics of transmitter, receiver and transmission path. The model is used to analyse the complex interactions of different parameters, and is used to design an optimized set-up for data transmission and to estimate minimum energy demand for signal transmission.

Several calculations have been performed in order to design the most energy-efficient set-up for different situations. A preliminary rough estimation of the energy need, based on the results obtained so far, is summarized in Table 2.

Table 2: Estimated energy need for data transmission for different situations.

Set-up	**Transmitter Power**	**Achievable Data Rate**	**Energy per Bit of Data**
HADES URL small antenna (r = 1.85 m)	12 W	20 bit/s	0.6 Ws/bit
HADES URL	0.8 W	50 bit/s	0.02 Ws/bit

assuming no interference from power network			
HADES URL large transmitter antenna (r = 75 m)	<10 mW	20 bit/s	<0.5 mWs/bit
Dutch generic reference concept at 500 m, large transmitter antenna (r = 100 m)	<20 mW	50 bit/s	<0.4 mWs/bit

In order to substantiate the estimations in Table 2, two additional measurements are planned:

- a data transmission experiment at the HADES URL will be performed with an improved set-up in order to support the estimated energy use as quoted in the first row of Table 2;
- an additional surface-surface measurement will be performed in order to demonstrate the sensitivity of the set-up, allowing to support the estimated energy need in the second row of Table 2.

The results of these tests will be available in the near future and will be discussed in the oral presentation.

5. Conclusions

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

The estimation of the energy need shows that transmission of monitoring data from a geological disposal facility to the surface is feasible with about 20 mW of energy per bit of transmitted data, but additional measurements are required in order to support the model calculations. Extrapolation of these results to more favourable conditions will be supported and verified by additional field experiments close to the NRG-site in Petten.

6. Acknowledgements

We greatly acknowledge the kind support of Jan Verstricht and other members of the EURIDICE staff during our experimental work at the HADES URL in Mol, Belgium. NRG has received funding for this work from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement no. 232598 and from the Ministry of Economic Affairs, Agriculture, and Innovation, The Netherlands.

References

[1] Clemmow, P.C. *An Introduction to Electromagnetic Theory*. Cambridge University Press, Cambridge, U.K, 1973

[2] Fernández, A.M.; Melón, A.; Sánchez, D.M.; Gaucher, E.; Tournassat, C.; Altmann, S.; Vinsot, A.; Maes, N.; De Craen, M.; Leupin, O.; Wersin, P.; Astudillo, J. *Study of Different Argillaceous Formations Performed in the Context of the FUNMIG Project. Pore Water Chemistry and Physical, Mineralogical and Geochemical Properties in Boom Clay, Callovo Oxfordian, Opalinus Clay and Boda Claystone rock samples*. Publicación Técnica: Madrid, 2009

[3] Murphy, J.N., and H.E. Parkinson (1978).*Underground mine communication*. Proceedings of the IEEE, 66 (1), p.26-50

[4] Powell, J.A. *An Electromagnetic System for Detecting and locating Trapped Miners*. Report of Investigations 8159, Bureau of Mines, United States Department of the Interior, 1976

[5] Mine Site Technologies. *http://www.minesite.com.au/products/ped-system*

[6] Ultra Electronics. *Magneto Inductive Rock Phone*. Product technical specification brochure, Ultra Electronics Maritime Systems, San Bernadino, USA, 2009

[7] Barr, R., D. Llanwyn Jones, and C.J. Rodger (2000). *ELF and VLF radio waves*. Journal of Atmospheric and Solar-Terrestrial Physics 62, p.1689-1718

[8] *http://www.euridice.be*

[9] Van de Steen B, Vervoort A. *Mine design in clay. CORA-project TRUCK-I*. CORA report 98-46, Katholieke Universiteit Leuven, Belgium, 1998

[10] Boisson, J.-Y. (ed.). *Catalogue of the characteristics of argillaceous rocks*. OECD/NEA/RWMC/IGSC Working Group on Measurement & Physical Understanding of Groundwater Flow Through Argillaceous Media "Clay Club", 2003

[11] Shope, S.M. *Above-the-Earth Field Contours for a Dipole Buried in a Homogeneous Half-Space*. Bureau of Mines Report of lnvestigations 8781, United States Department of the Interior, l983

New wireless data transmission system based on high frequency radio communication: design, development and testing results under repository conditions

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Summary

The main goal of the collaborative MoDeRn project, comprising 18 partners representing 12 countries worldwide and including 8 Waste Management Organizations, is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during the staged approach of the disposal process. One of the tasks carried out to accomplish this goal has consisted in the design, development and test under "real conditions" of a new wireless system, based on high frequency radio transmission (HF), capable of monitoring the physical parameters inside a repository cell independently of the host rock type.

Such development represents a step forward to obtain a system capable of transmitting the evolution of the physical parameters inside a repository under the harsh prevailing conditions imposed by both the element itself to be monitored (for instance the canister enclosing radioactive waste), the engineered barriers into which they will be embedded and the surrounding host rock.

In order to achieve the aforementioned objectives and to obtain a suitable monitoring system for the target application, the following key points have been addressed: data transmission technology (transmission media), communication protocols, available power sources, expected environmental conditions & suitable sensors.

The following results were obtained:

1. A suitable radio communication frequency was selected for the wireless transmission through clay host rock in particular, based on high frequency bands, considering penetration and energy optimisation.
2. Preliminary signal testing with promising results was carried out at El Cabril (Spain) and at Tournemire URL (clay host rock-France).
3. Prototypes of the HF wireless system were manufactured for demonstration purposes.
4. A demonstration of the system was installed at Grimsel URL (Switzerland) and is currently running. The wireless system was applied to four in-situ experiments at Tournemire URL (France) too.
5. The protection process of the developed system (patent) was initiated.

1. Introduction

Spent nuclear fuel and long-lived radioactive waste must be contained and isolated for very long periods, and current schemes for its long-term management involve disposal in deep geologic repositories. The successful implementation of a repository program for radioactive waste relies both on the technical aspects of a sound safety strategy and of a scientific and engineering excellence, as well as on societal aspects such as stakeholder acceptance and confidence. Monitoring is considered crucial in serving both ends. It underpins the technical safety strategy and quality of the engineering, and can be an important tool for public communication, contributing to the public understanding of the repository behavior and the increase of confidence in it.

The growing interest in monitoring the repository prior to closure is consistent with a general consensus that future work is required after receipt of a license to construct and operate. It is expected to contribute to a transparent disposal process acceptable to stakeholders and to provide further basis supporting a future decision to close the repository. This is consistent with socio-political feedback received on earlier disposal program developments, many of which have effectively halted further progress towards implementing a repository, irrespective of their demonstrated technical and scientific soundness. From these, a consensus appears to have emerged, that an informed, stepwise approach provides an acceptable basis permitting progress from a licensing stage through progressive construction, operation and ultimately closure of a repository

To further build upon these prior and parallel developments, the European Commission has decided to include the Topic *Strategies and technologies for repository monitoring* in its 7th Framework Program to request corresponding proposals. A Grant (Agreement n°232598) was awarded to the collaborative MoDeRn project, whose main goal is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during the staged approach of the disposal process.

18 partners representing 12 countries and including 8 Waste Management Organizations joined their efforts since 2009, and aim at developing a “roadmap to repository monitoring” by 2013, which addresses these issues. The partners represent organizations responsible for radioactive waste management in the EU, Switzerland, the US and Japan as well as organizations having relevant monitoring expertise. Other partners offer substantial experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organizations, industry) in highly technical issues.

For the development of the repository monitoring several key issues must be addressed. After identifying relevant monitoring objectives, as result of implementer’s requirements and stakeholder expectations, the capacity to provide some information to meet those objectives should be determined. A prior evaluation of the present technical capability for the repository monitoring identified few promising monitoring technologies that required of further development as the wireless techniques and their adequate power sources.

2. Rationale and methodology

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.

The approach of AITEMIN research was to develop a wireless data transmission system based on high frequency radio bands for the wireless transmission for energy optimisation, capable of connecting a geological repository with the surface in several steps. This system is also called short range (distances in the order of several metres) wireless data transmission.

The applied methodology followed three steps:

1. Laboratory work, to select the best solutions under a controlled environment: different frequencies were evaluated to find a reasonable balance between wave penetration and power consumption.
2. Field testing, to test under more realistic conditions the solutions already considered valid at the lab: two testing campaigns were carried out, one at El Cabril (Spain) and another at Tournemire URL (France).
3. Finally the wireless system was installed and applied for demonstration at Grimsel URL (Switzerland) and Tournemire URL.

3. Results

After defining the basis for the short range wireless system the following development methodology was adopted.

<u>1.- Laboratory work</u>

The laboratory testing was carried out in the workshop at AITEMIN's facilities in Leganés, Madrid. A shielded propagation tube was designed and built for that purpose. It is composed of three parts (metallic tubes) coupled together, as depicted in Figure 1.

The characteristics of the propagation tube are the following:

- It provides a "clean" radio environment suitable to test signal propagation.
- It assures a unique propagation path between transmitter and receiver.
- It allows the testing of the propagation through different materials.

Different materials and tube lengths (central part) were prepared for testing the radio frequencies. The materials used were:

- Dry bentonite
- Tournemire argillite
- Salty water
- Dry non-reinforced concrete

The tests were performed with different radio equipment from 2.4 GHz ZigBee radio transceivers to a few hundreds of MHz radio transceivers. Based on the obtained results, the most promising frequencies to be applied for wireless transmission, in terms of best transmission, were selected for the next step (field testing).

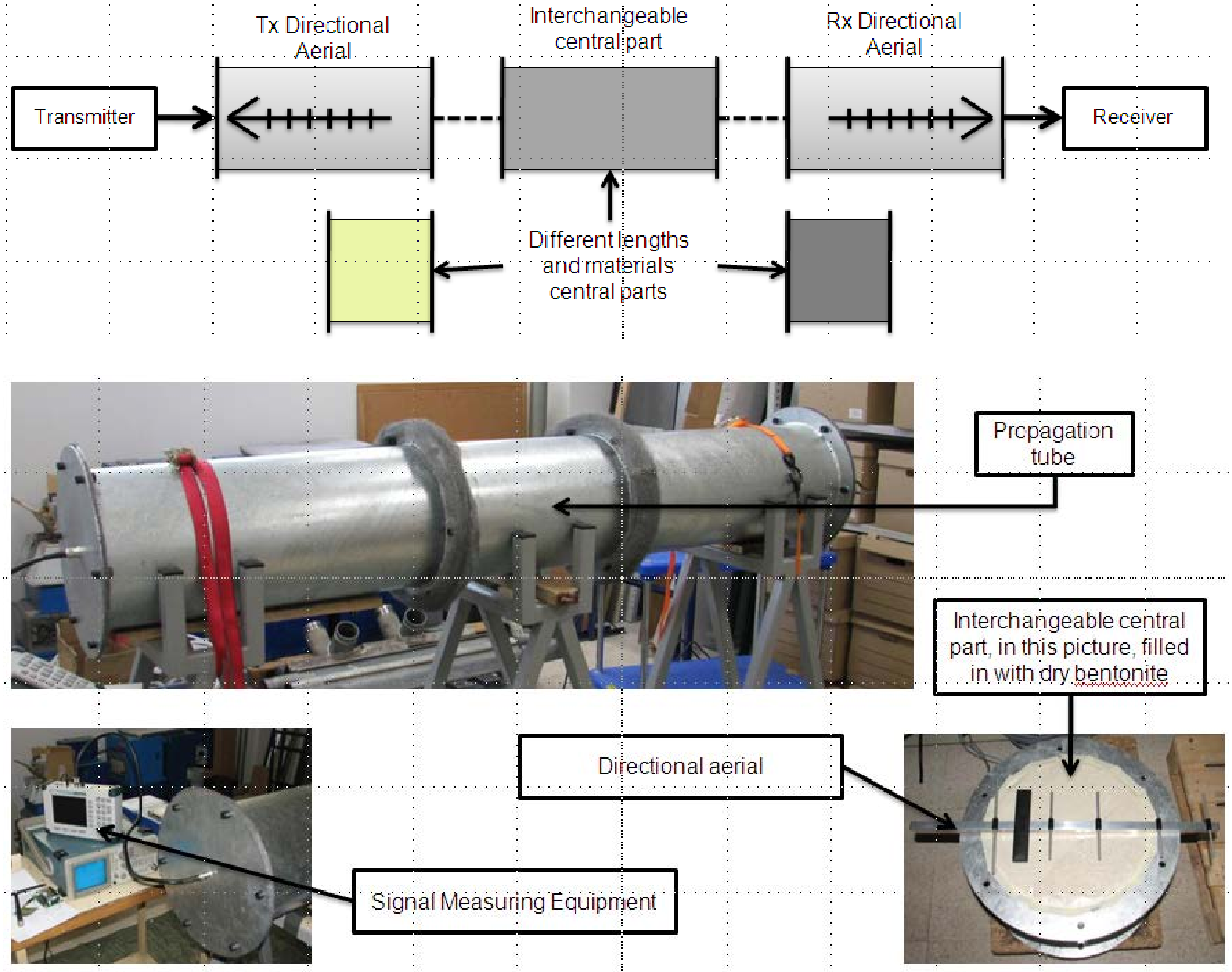

Figure 20: Layout of propagation tube (top) and view of the laboratory assembly (bottom)

2.- Field testing

The following testing phase was carried out in El Cabril facilities, the surface storage facility of low and very low activity radioactive waste owned by ENRESA and located in Córdoba, Andalusia, South of Spain. The objective of these tests was to verify the previous conclusions on the most suitable frequencies to use but under more realistic conditions, avoiding the constraints imposed by the propagation tube.

Figure 21: Surface gallery and soil layers (left) and transmitter unit and battery in tunnel (right)

The tests were carried out in an existing concrete tunnel buried under different soil layers, which is part of another experiment in progress at El Cabril. The radio transmission was done from the concrete tunnel side (through an existing slot to avoid the concrete) and trying to capture the signal at the surface (through the soil layers) by means of a receiver and a spectrum analyser.

As a result of the tests, the lower frequencies were considered as the most suitable, being a compromise solution for the band width (decreases with frequency) and penetration of signal (inversely proportional to frequency). These devices allow communications speed of few kbps, which is enough for the data transmission during long periods (hours or days) without a significant reduction of the life of batteries.

Thanks to IRSN collaboration it was possible to perform an additional field test to determine the viability of the selected frequency. The field test was carried out in Tournemire facilities in September 2010. The testing was carried out with the same frequencies used at El Cabril with bi-directional trans-receivers and a power of 500 mW each. The aerials used in both cases are omni-directional, small size and low price (gain of approximately 0 dBi).

For the testing, one of the devices was installed in the so called "side borehole" (100 mm diameter and 45º from tunnel wall) that cuts the principal borehole of Ø60 cm; the measurements were taken from the tunnel side by means of a receiver attached to a spectrum analyser. *Figure 22* shows the tests configuration. The different points represent:

- A: Signal measured in borehole mouth.
- B: Maximum signal measured in tunnel wall (as expected, it is coincident with the minimum distance between tunnel and transmitter).
- C: Distance from borehole mouth with signal level higher than -100 dB
- D: Distance between transmitter and borehole mouth.

In order to prevent undesired propagation paths though the side borehole, several shields were located at approximately 20 cm from the transmitter at both sides. The effectiveness of the shields was tested by measuring with the spectrum analyser at the side borehole mouth. Therefore, after the verification that the only possible path for propagation was though the rock, several measurements were taken locating the transmitting device at different depths along the side borehole (distance D).

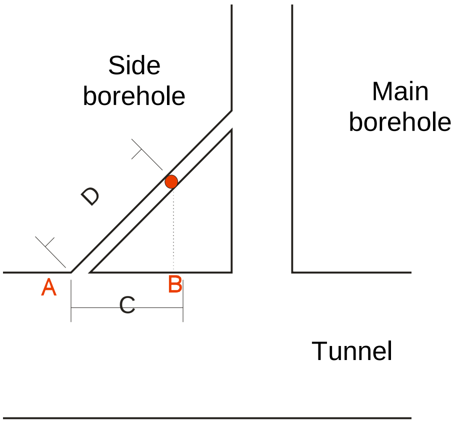

Figure 22: Test layout (left) and insertion of receiver/transmitter unit in cables borehole (right)

<u>3.- Demonstrators</u>

The main objective of this work is to demonstrate and analyse the capability of the short range wireless system under realistic conditions that is, embedded in the engineered barrier system.

GTS Demonstrator

The first activity consisted on the installation of the wireless system in the low-pH plug test, which was built during the ESDRED IP project and is running at the Grimsel Test Site URL. It is aimed at demonstrating the potential of underground use of wireless sensor and transmission networks, part of which would be immersed in solid material (buffer, concrete, rock, etc).

The layout of the GTS consists of a 1000 m long branching laboratory tunnel and a central building which houses the whole infrastructure such as offices, the ventilation plant, workshops and so on (Figure 2 overleaf shows the locations of the most important experiments which have been performed in the GTS). The laboratory tunnel has a diameter of 3.50 metres and was bored using a full-face tunnelling machine (TBM).

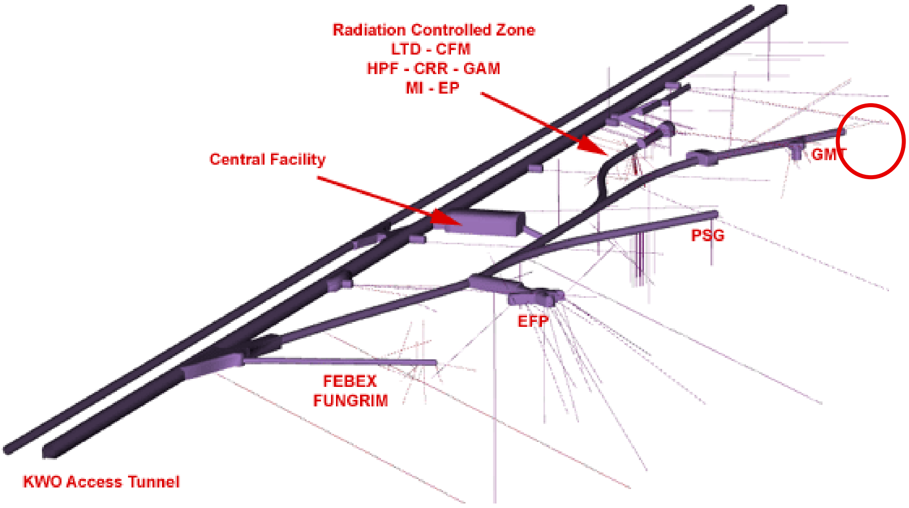

Figure 23: Layout of Grimsel Test Site, the low-pH plug test built during ESDRED IP project is located at the end of the VE tunnel (marked with a red circle).

To monitor the performance during the system test, a number of sensors were installed at different locations in the rock, in the bentonite and in the shotcrete mass: total pressure cells, humidity sensors of different types, piezometers and displacement sensors *Figure 24*). The sensors are mainly conventional (wired) ones but a number of them were connected to a wireless transmission system. These wireless transmitted sensors were installed as a part of the TEM Project, which is run by NAGRA at the GTS URL. The sensors were connected, through the necessary data acquisition units, to the main DADCS for the monitoring and management of the test, which worked in unattended mode and could be contacted with modem for remote supervision.

The demonstration exercise consisted on the installation of five High Frequency Wireless (HFW) based sensing units (see *Figure 25* below). Each HFW node can incorporate up to four sensors: pore pressure, total pressure, humidity and temperature, providing the power supply and gathering the data from all of them. Two of them were installed in the bentonite buffer through boreholes drilled in the shotcrete plug (see *Figure 24* left side, below). The remaining three sensing units were installed in the shotcrete plug and in the rock mass, two of them to measure pore pressure in the plug and the last one measuring pore pressure in the rock around the bentonite buffer (under the plug).

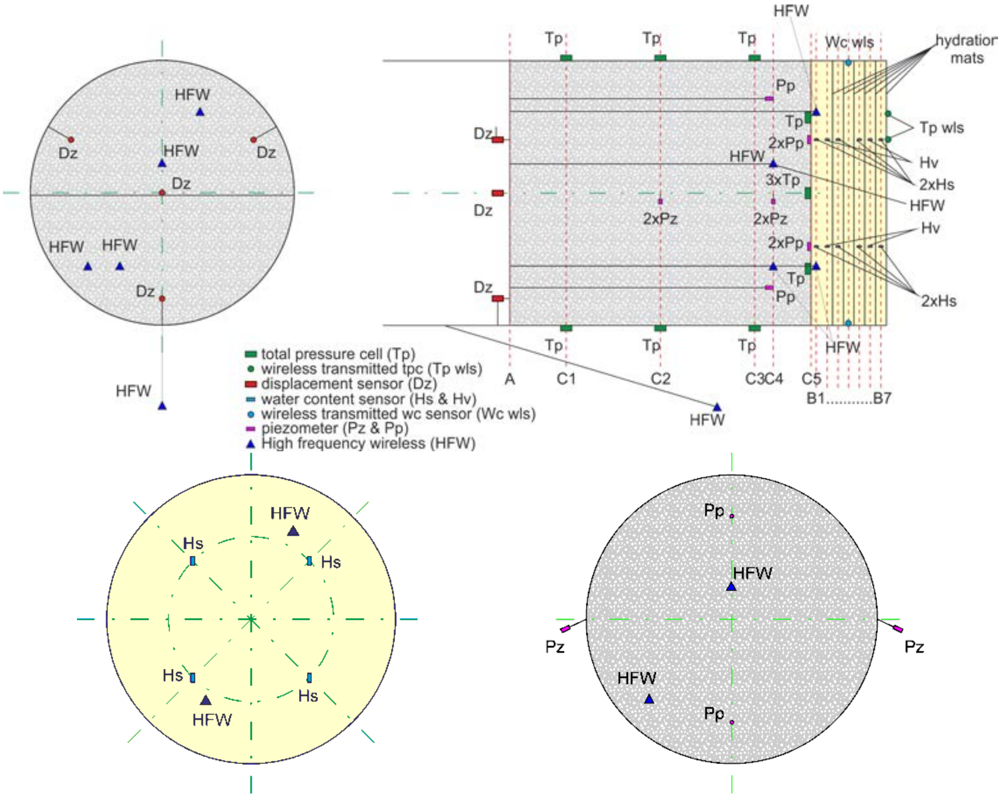

Figure 24: Layout of installed instrumentation (including HFW). Section of instrumented sections in bentonite (left) and concrete (right) including the wireless instrumentation.

The demonstration exercise consisted on the installation of five High Frequency Wireless (HFW) based sensing units (see *Figure 25* below). Each HFW node can incorporate up to four sensors: pore pressure, total pressure, humidity and temperature, providing the power supply and gathering the data from all of them. Two of them were installed in the bentonite buffer through boreholes drilled in the shotcrete plug (see *Figure 24* left side, below). The remaining three sensing units were installed in the shotcrete plug and in the rock mass, two of them to measure pore pressure in the plug and the last one measuring pore pressure in the rock around the bentonite buffer (under the plug).

The signals from the HFW nodes are collected at the open gallery and integrated into the existing AITEMIN data monitoring and control system. The data trends are reported periodically and compared with the already installed monitoring systems.

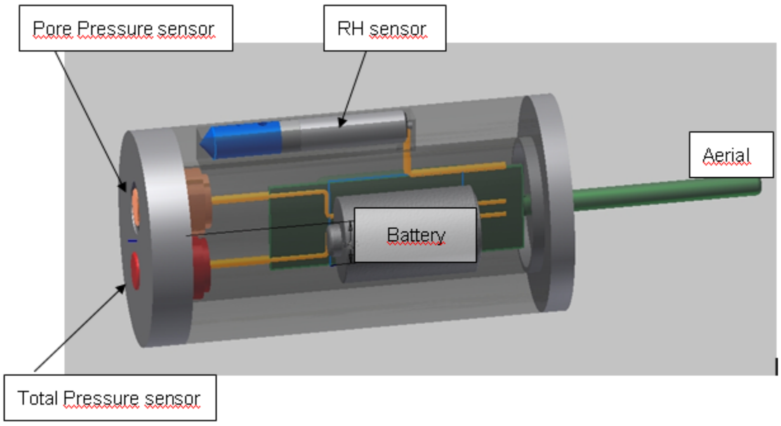

Figure 25: Sketch of the HFW node.

Tournemire Demonstrator

The IRSN's SEALEX project aims to perform a series of in situ experiments with seal cores similar to those in the disposal concepts presented in ANDRA's Dossier 2005. The seal cores will be made from Wyoming MX80 bentonite (clay-based material) in different ways: precompacted blocks of bentonite/sand with different ratios and powder/pellet mix.

In situ experiments are emplaced in the Tournemire Research Laboratory (Toarcian argillite), via horizontal boreholes (diameter 60 cm, length 5 to 5.4 m) excavated from recent drifts (2008). Each experiment (*Figure 26*) represents a generic seal mock-up (i.e. either at a relevant scale with respect to actual cell seals, or with relevant characteristics), except for the presence of instrumentation and of an artificial resaturation system. Two types of monitoring experiments have been installed, reference tests (which include intracore instrumentation) and performance tests (no-intra-core instrumentation) used to seal the overall permeability.

Currently four in situ experiments have been installed, as shown in *Table 1*:

Table 1: SEALEX experiments already installed

Denomination	Type	Core	MX80/sand	Installation
RT-1	Reference	Precompacted disks	70/30	December 2010
PT-N1	Performance	Precompacted disks	70/30	June 2011
PT-N2	Performance	Precompacted disks with joints	70/30	January 2012
PT-A1	Performance (altered scenario)[1]	Precompacted disks	70/30	June 2012

Note 1: confining plug failure.

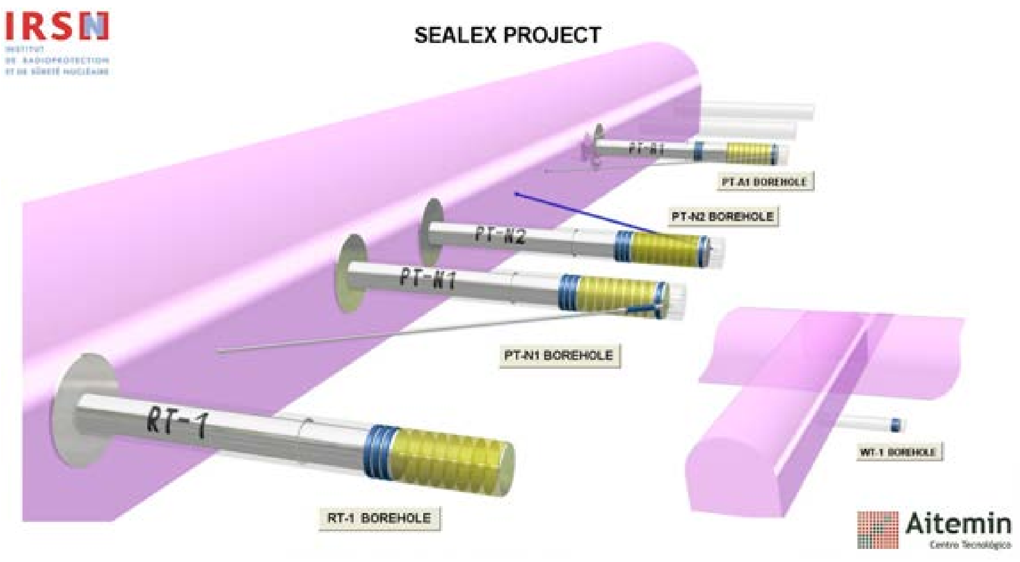

Figure 26: SEALEX experiment layout

The instrumentation in the bentonite core is intended to measure some hydromechanical parameters: total pressure, water content and pore pressure. For the performance test the short range wireless system was applied to avoid the pass of cables along the core and consits on a transmitter radio module connected to the core sensors (wireless node). Each wireless node powers and transmits the information of a maximum of five sensors. The transmitter sends the information to the receiver unit, which is installed in a side borehole (called bottom borehole).

The wireless systems are running properly since their installation, and as the void space of the test is flooded from the very beginning, the saturation degree provided by RH sensors is now over 80%.

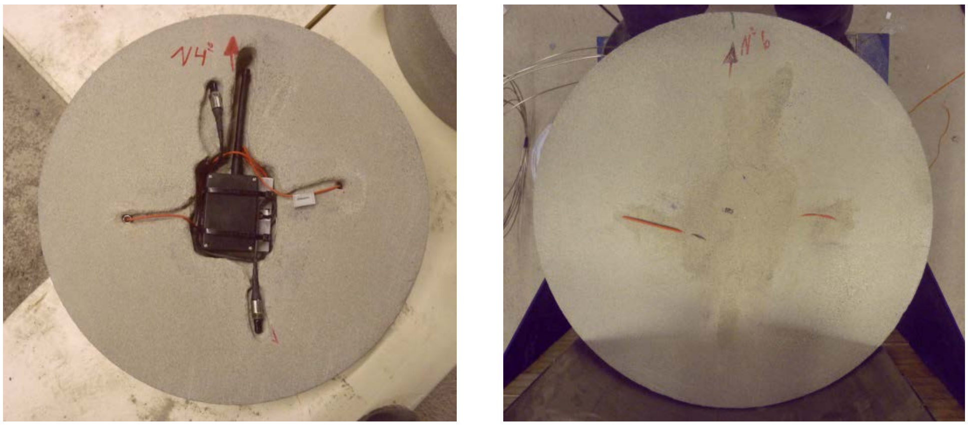

Figure 27: Wireless node installed within a core block, before and after filling-in the gaps.

4. Discussion

As result of the activities performed to achieve the target objectives a short range wireless monitoring system was designed, built and demonstrated having the following characteristics

<u>System structure</u>

It is composed of a number of instrumented (up to 6 sensors each) wireless nodes buried in the repository engineered barrier system, plugs or the host rock. Each node supplies power to the sensors and collects their information through short cables. Up to 16 nodes communicate the data to a wireless receiver, located a few meters away (distance depending on the media and conditions), which re-transmit the information by cable to a centralised data acquisition system.

Wireless transmission technology

The transmission technology is based on high frequency bands (European ISM) due to the higher data rate capability in comparison with lower frequency bands and the much lower energy needed in the long term to power the units. The radio units are certified according to ETSI EN 300 220-3 & EN 301 489-3 standards, having a maximum transmission power of 500 mW (+27 dBm).

Communication protocol

A proprietary protocol was established for the communication between the different electronic devices due to the lower power needs and lower hardware costs.

Power source

The current design integrates long lived batteries in the devices, based on Lithium Thionyl Chloride (Li-$SOCl_2$) chemistry, which supply a very high energy density, a wide operating temperature range and a very low self-discharge (lower than 1% per year). This results in an expected lifetime of up to 25 years, depending on the number of sensors in the units and the communication rate.

Environment conditions

The electronic devices were designed to withstand the harsh environmental conditions inside the repository, including high pressure, high humidity and temperature levels, etc.

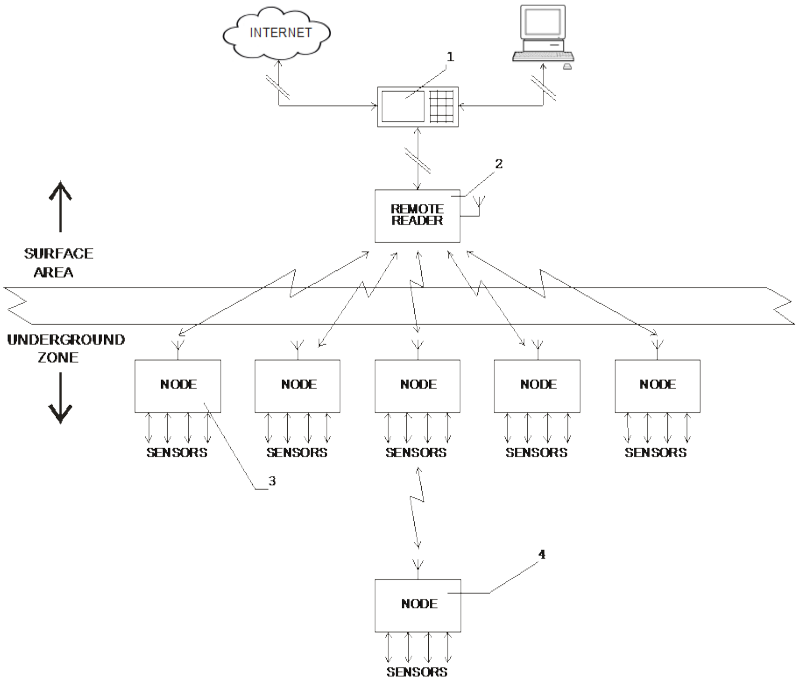

Figure 28: Wireless system structure

<u>Sensors</u>

Each wireless node can power and read measures of at least six sensors, performing a previous analysis of the signal and detecting possible measurement failures, and repeating the process when necessary. Current design admits typical sensors with voltage or current output and Sensirion type HR sensors (digital) but future developments will incorporate additional sensor technologies. The expected minimum penetration of radio signal (at full saturation) ranges from 3.5m in Clayey rock to 5m in Bentonite.

<u>Legal Protection</u>

The system was applied for a European patent.

5. Conclusions

A new short range wireless system able to transmit the evolution of the most relevant physical parameters inside a repository, i.e. pressure, temperature, humidity, etc, was designed and developed.

It is intended to apply the technology under the harsh conditions imposed by the elements to be monitored (for instance the canister that is enclosing the radioactive waste), the engineered barriers used in the repository and the surrounding host rock. Therefore, the system components will work immersed in harsh conditions of 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.

The short range wireless system is intended to transmit the information to a safe, i.e. non-radiological, outside area using a non-intrusive method and always preserving the safety of the disposal facilities. The system is intelligent enough to perform self-diagnosis so to detect possible sensors failures or wrong measures.

The long term performance of the system will be evaluated thanks to the running demonstrators but up to now it has been working without major difficulties for more that 1.5 years.

6. Acknowledgements

The research leading to these results has been possible thanks to the funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement n° 232598 (MoDeRn project) and from ENRESA under contract No. 0079000025.

References

[1] ZigBee Alliance. [http://www.zigbee.org/].

[2] Centers for Disease Control and Prevention, www.cdc.gov. Through-the-Earth and Other Types of Communication Systems for Underground Coal Miners for Disaster and Normal Operations. (William H. Schiffbauer, Gary L. Mowrey and Jürgen F. Brune).

[3] Battery University, www.batteryuniversity.com. How to prolong lithium-based batteries.

[4] Metering International, www.metering.com. Designing a 20 year AMR device (Tom Galuska). Metering International Issue 1 2004. Page 52.

[5] NASA Johnson Space Center (JSC). Space Radiation Effects on Electronic Components in Low-Earth Orbit. PRACTICE NO. PD-ED-1258, April 1996.

[6] RFCS. RAINOW Project (RFC-CR-0503).

Wireless data transfer in salt rock

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Summary

The measurement of processes up to the point of long-time monitoring of abandoned mines or mine parts is a need in salt mining and final waste disposal. Recent available measurement technology is often based on data transfer via cable connections and a power supply by an underground available power network. This is in contradiction to the commonly aspired fluidic pressure tightness of sealing or to the integrity of flow barriers as well as to the technical effort to keep the monitored mine excavations open.

In the scope of a research and development project subsidised by the German Federal Ministry of Economy and Technology (BMWi) a concept for wireless data transfer using radio propagation through mainly dry salt rock was developed by IBeWa-Ingenieurpartnerschaft (IBeWa). Successful tests were performed at different reference sites. Recent tests in a drift sealing at the Morsleben repository for radioactive waste (ERAM) are kindly supported by the German Federal Office for Radiation Protection (BfS). The measuring concept allows the wireless transfer of data from different physical parameters in dry salt rock up to several hundred metres distance. The patent-protected radio sensors were extended time tested and reached in the recent configuration about 10 million measurements and about 760000 data transfers. Depending on the measuring problem (e.g. frequency of measurement) actually a measurement time up to several decades seems to be possible.

1. Motivation

Electromagnetic waves are in use for many decades in order to explore geological structures of saliniferous formations (e.g. ground radar) and became state of the scientific and technical knowledge. However, data transfer through rocks based on propagation of electromagnetic waves seems to open many applications in mining. Data transfer based on propagation of electromagnetic waves is defined by the electromagnetic properties of the rock, its pore space and the contained fluids.

Monitoring in salt mining is a fundamental basis for excavation planning, optimising of production and long-term, post-abandoned monitoring. That is reason for the importance of installation of measurement technology under the condition of surface and underground mining. However, monitoring of fluidic tight sealed spaces is in contradiction to cable based data transfer because of potential leakage along the cable connection. In this situation, wireless data transfer exhibits an excellent alternative for ambitious monitoring concepts.

Against this background, a concept for the wireless data transfer from fluidic tight sealed mine working to an underground based as well as a surface based data acquisition (DAQ) was developed and successfully tested in the scope of the R&D-project *"Zerstörungsfreie in situ-Permeabilitätsmessung / non-destructive in situ permeability determination"* [1].

2. Basic information

The demands on wireless data transfer is defined by the measuring task and hence are according to experience very broad. This is because of variety of possible input-signals of sensors, their wattage, the measurement and transfer frequency, the variability of measurement and transfer frequency as well as the need of external control and possibly embedding of scoping-control processes. For a better understanding, the complete measurement and transfer circle can be divided into:

– the transfer of control parameters (programming of sensors),
– the actual acquisition of the indicated value (physical or chemical parameters, e.g. pressure, stress, temperature, humidity, concentration),
– the transmission of digital coded data and
– the receiving and recording of sent data (including modulation processing and logging).

There is no need to explain the different measure technologies for the broad variety of sensors to measure different parameters. Generally, these are documented in detail.

Wireless data transfer is focused on the monitoring of processes in inaccessible cavities and was developed for long periods. This is the reason for an appropriate and careful assortment of sensor technique to achieve the measuring tasks. Especially, the knowledge of time-dependent change of the measuring signal (long-time stability) and of the influence on the thermodynamic boundary conditions, e.g. compensation of temperature, alteration of batteries), have to be considered. These circumstances have to be already integrated into the preparation of the measurement and transfer concept.

The result of the measurement is an analogue signal which is transferred into a digital data structure having a 16 bit resolution by an analogue digital converter. This data is transferred in short pulses within the frequency band 433 MHz (ISM-band). The ISM-band covers the frequencies from 433.05 MHz to 434.79 MHz. The application of ISM-frequency bands is globally regulated by the articles 5138 and 5150 of the VO-Funk. The ISM-band at 433 MHz is approved as SRD for region 1 (inter alia Europe, Africa, Russia, parts of Asia) for industrial, scientific, medical and private use. The approval and use is representatively focussed on superficial application. Based on limited range, disturbances or interferences with other transfer processes is less relevant or completely irrelevant for applications in mines as defined by the VO-Funk. However, frequencies in the range of 410 MHz to 470 MHz (mine voice and alarm radio) or of 433 MHz to 470 MHz (mine remote active radio) can be used in mines referring to the general allocation for usage in mines (mine radio communication) [5]. To avoid radio technological interactions the applied radio parameters have to be site-related coordinated with the mine authorities (person responsible for mine radio).
For transmission process of wireless data transfer the sensor uses normally a bar flagpole antenna with aligned dimensions. The radio propagation is defined by the geoelectric properties of the rocks. Within a rock consisting of the gain skeleton (minerals / crystals) and the filled

pore spaces (fluid, e.g. gas and/or liquid) the propagation is the result of the dielectric conductivity of the particular components as well as of the polarisation and reflection effects between these components. The range of data transfer is dependant on the frequency, the transmission power, radiant emittance characteristic of the antenna (antenna gain), the dielectric constant (absolute permittivity or dielectric conductivity of rocks), the resulting, site and rock specific attenuation factor as well as the information band width (bit/s). The mentioned dependencies, their relevance and site-relevant determination will be discussed again in conjunction with the test measurements in chapter 4. Because of the definition of the transmission frequency within the ISM-band and the limitation of the electric transmission power with the purpose of minimising the power consumption an improvement of the transfer process is primarily possible by the enhancement of the antenna gain of the transmitting and receiving aerial.

Relating to the geoelectric properties of rocks it can generally be assumed that the propagation of radio waves reduces with increasing electric conductivity or with other words with increasing liquid content in the pore space. Therefore, good conditions for radio propagation is found in compact, dry rock salt having water contents in the magnitude of ≤ 0.02 Ma% [2] and attenuation constants in the order of 0,7-2.4 dB/m (e.g. rock salt from the Südharz-Kalirevier) [4]. There is further data of attenuation constants available for a variety of salt rocks. The experience from recent applications has revealed that the measurement of site-related transfer conditions in advance allows a detailed planning and dimensioning of the measurement and transfer facilities.

The data receiving from the on different channels sending sensors occurs in dependence on the site and receiving conditions either by a bar flagpole or beam antenna. A microprocessor controlled receiving unit allows the bi-directional communication with the wireless sensor. The transmitting and receiving process is organised in a way to avoid any data loss. In case of no contact between the transmitting and the receiving unit an intermediate storage will be performed in persistent data storage. This enables the system to carry out self-sustaining measurements (monitoring) even without permanent contact between sensor and receiving unit. The read-out may take place at a later moment.

After a recorded receive of data a serial RS485 bus system transfers the data to a logger. In this way several radio sensors can simultaneously be controlled and read-out by one receiver unit. Data can be read-out from logger via USB or WLAN interface.

3. Hardware

Figure 29 shows the recently tested wireless sensors. The different types demonstrate on one hand the opportunity and on the other hand the necessity of the essential constructive adjustment of the sensor body to the measuring task and the conditions governing location. The size of wireless sensors is mainly affected by the required power supply (battery power) which depends on the power consumption of measuring sensor units and the frequency of transmission.
Due to the previous application of the wireless sensors in borehole having a diameter of 70 mm the sensor antenna was designed as a bar flagpole antenna. However, the design of a beam antenna is also principal possible depending on the available space and the possibility of positioning of the receiving unit.

The electronic interior of the wireless sensor basically consists of the following components: measuring sensor unit, micro controller, high grade transformer, amplifier and storage units, radio module, and power supply unit.

The sensor and antenna bodies are designed accordingly to the measuring task non-corrosive, pressure-resistant and watertight. Up to this stage high grade stainless steel and pressure-resistant synthetics were used for bodies of sensors and antenna units.

In the scope of the research and development project the developed wireless sensors as well as the wireless data transfer through dry salt rock are proprietary by patent law.

4. Tests and application

The sensors depicted in Figure 29 were used for functionality and range tests in various lithologies under different installation conditions. Beside tests in various salt rock formations tests were also performed in soil and rock formations having higher water contents.

A selection of results is shown in Table 2. The attenuation influence of moisture in pore spaces is clearly demonstrated by this data. The water content of the Freibergian gneiss and in the natural soil attenuate as expected the range of radio propagation down to a few meters or decimetres. On the other side ranges up to 200 m are proved for rock salt having low water contents in the order of $\leq$ 0.02 Ma.-% [2] and in carnallite rock. Recently, the coupling with a newly method of wireless data transfer through wet rock is tested in order to overcome these limitations of radio based data transfer through rocks.

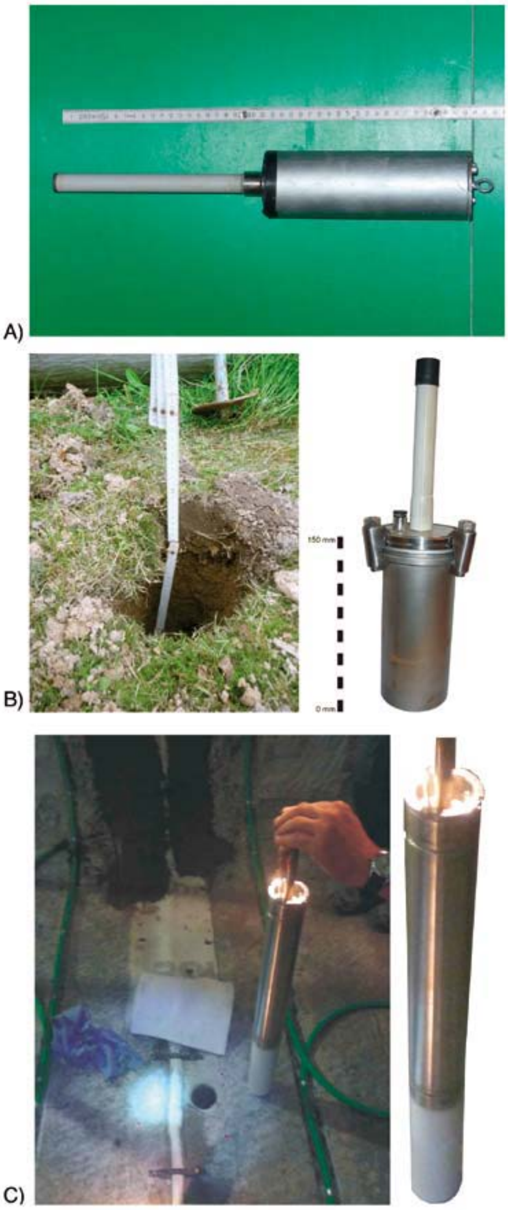

Figure 29: Different design of tested radio sensors

Table 2 Results of range tests within different lithologies

Lithology	Locality	Results
Rock salt, Werra-Member (Na1)	Mine Merkers	distances up to 200 m
Potash salt, Staßfurt-Member (K2)	Mine Teutschenthal	distances up to 100 m
Argillaceous, detritus rich soil	City of Freiberg	distances up to 15 m
Freibergian gneiss (PR3F)	Mine Reiche Zeche, Freiberg	distances up to 3 m

Based on the test of functionality three wireless sensors are applied in a sealing dam consisting of hydraulic hardening material which is explained more detailed in [3] for monitoring of process parameters in the scope of a construction test. Figure 30 shows schematically the alignment of the wireless sensors in the contours of the test location. To avoid negative influences of temperature increase during the hardening of dam material on the durability of the used lithium batteries and to optimise the antenna position wireless sensors were installed in boreholes radial to the construction site.

One of the sensors is exemplary shown in Figure 29C right before installation. All sensors are directly hydraulic connected to the contact area between building material and ground.

The sensors are continuously measuring and transferring process parameters of the construction test and of special tightness tests using gas and liquids since their installation in November 2010. The position of sensors in reference to the construction is depicted in Figure 30. Sensor 20 and 21 are installed in the floor level whereas the sensor 22 is situated in the S-face of the drift.

The frequency of measurement was repeatedly changed between 1 Hz and 1.2E-5 Hz during this period. The measurements were switched off and restarted. Figure 31 gives a summary of logged data.

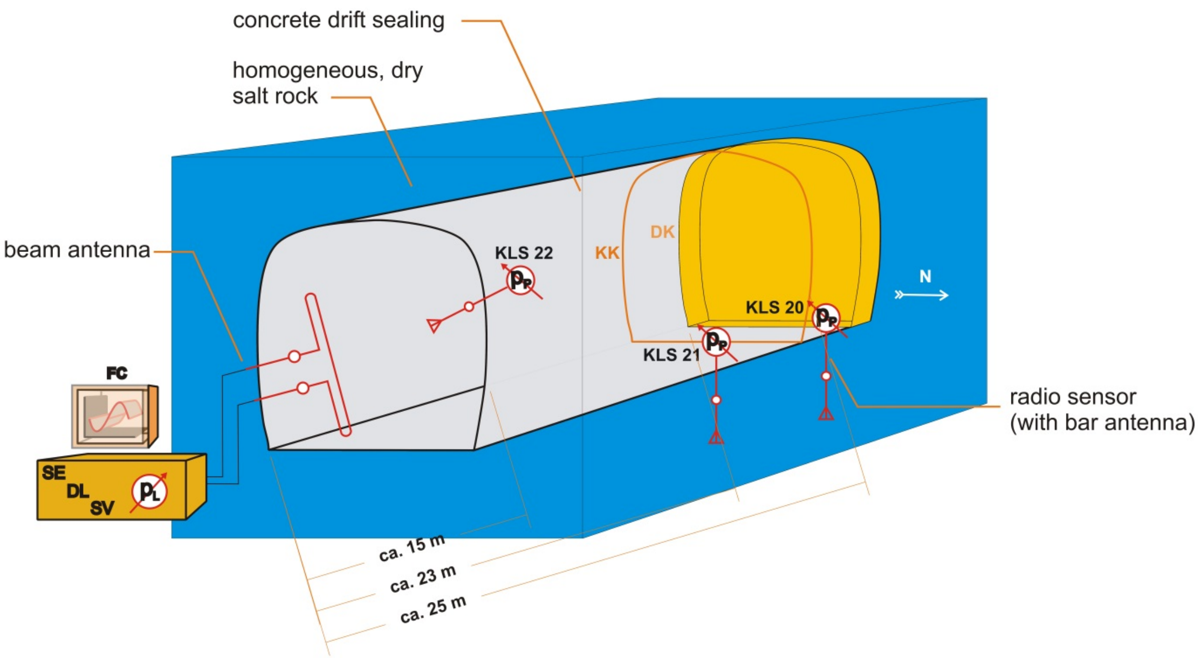

Figure 30: Position of radio sensors within the concrete drift sealing

An actual power consumption of about 10 Wh was detected of the period of ca. 700 d (almost 2 a). This results in recent, relative power consumptions of ca. 8 % (KLS21 und KLS22) and ca. 12 % (KLS20) at specific battery capacities of the KLS[25]. Based on this data it is possible to assume a theoretically continuation of measurements for further ca. 18 a (KLS21 and KLS22) or ca. 11 a (KLS20) at the same frequency of measurement. Alteration processes of batteries caused by frequent and large temperature fluctuation can be excluded as far as possible based on the conditions governing location. However, the long-term behaviour of the used battery packs can not be finally evaluated based on the recent experiences.

[25] KLS - wireless sensor

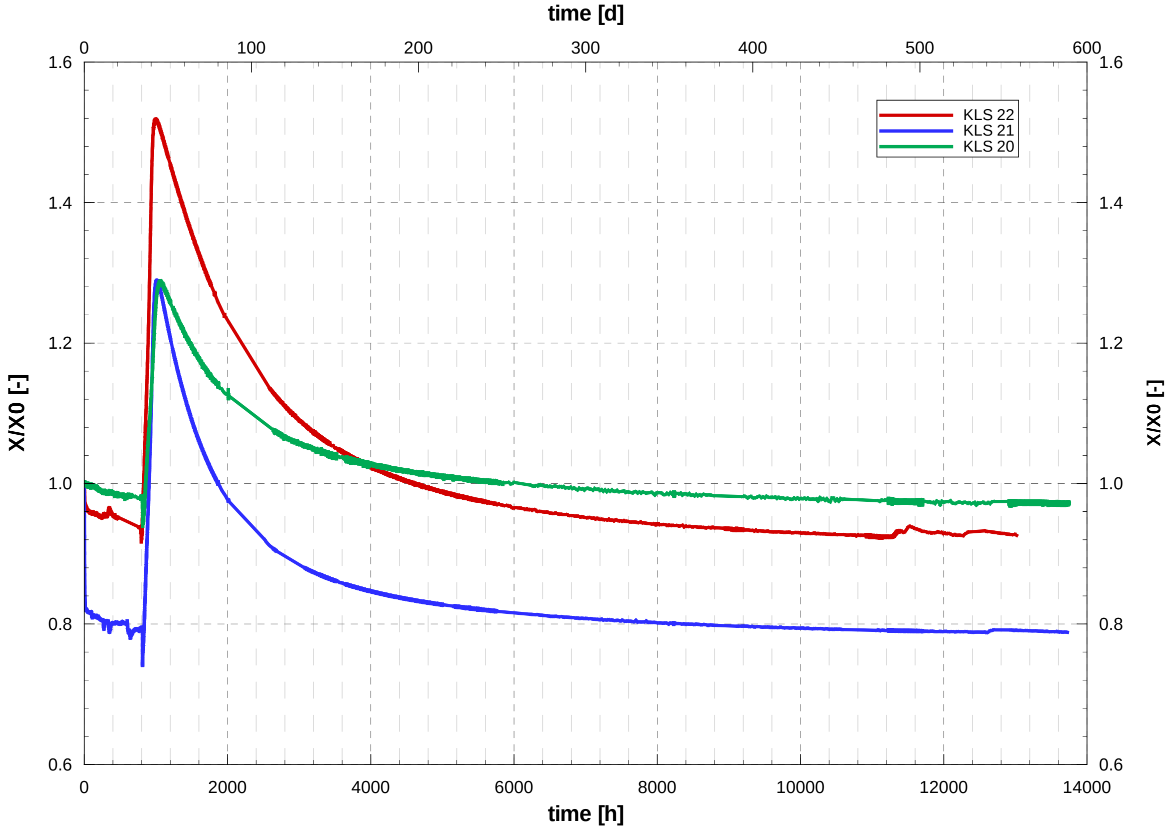

Figure 31: Normalised load curve of a parameter measured by the radio sensors

In order to evaluate the attenuation by the construction material and the surrounding rocks limiting the radio propagation measurements of field strength/ emission power were performed for the single sensors and the transmission equivalents were determined. As example Figure 32 shows the results of the measurements of field strength/ emission power for KLS20.

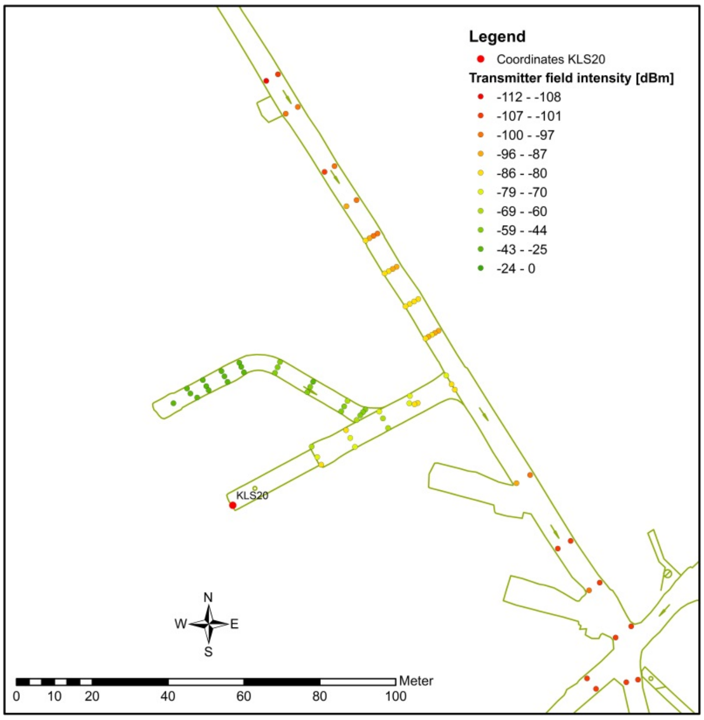

Figure 32: Measurement of transmitter field intensity for sensor KLS20 at the test site

The measurements were performed at different stages of construction. Comparison of the time-dependant results reveals an influence of the moisture distribution as well as orientation of the transmitting antenna in reference to the wet construction material on the transmission equivalent. This data subsequently enables to evaluate the radio propagation at the site, to determine the rock specific attenuation constants and to make conclusions for the positioning of the receiving antenna. Assuming a homogeneous geological situation the attenuation is mainly influenced by construction material.

The preparatory performance of appropriate power measurements gives the opportunity of optimising and dimensioning of sensor position as well as of configuration of necessary transmitting antenna and power.

5. Efficiency options and vision

The recently reached functionality and the power spectrum of the wireless data transfer system can be summarized as following:

- bi-directional communication between the sensor and the receiver unit including control of measurement and transfer frequency,
- operative connection to a variety of sensor types having different output signals, e.g. voltage, amperage, resistance, to realise individual measuring tasks, e.g. monitoring of mine air (moisture, temperature, CO_2 content), monitoring of convergence and other rock mechanical parameters, monitoring of fluid pressure, humidity of materials, saturation and capillary pressure,
- range of data transfer is lithology and geology dependent (ranges of about 200 m are actually reachable),
- extension of ranges are possible (e.g. by application of radio transponders),
- period of application depends on the conditions governing location, amount of measured parameters, power consumption of necessary sensors as well as on the measure and transfer frequency,
- embedding of data into an online database by GSM modem and continuously visualization is principal possible,
- coupling with other concept of wireless data transfer makes the system to a powerful monitoring tool.

The actual experiences based on tests and application of wireless sensors have shown an individual modification of the applied sensor technique and radio communication units to the conditions governing location and the measuring task is essential of an optimal use. This requires a concept planning, dimensioning, potentially test measurements at the site of usage as well as a technical co-ordination. A wireless data transfer over a long time excuses this effort of preparation.

Eventually, a vision of wireless data transfer in salt rock is a monitoring of open and particularly closed mines and repositories without any cable connection. In the case of closed mines and repositories, this means a long-lasting wireless data transfer from ground sites to the surface through dry and wet rocks.

6. Summary

Monitoring of inaccessible or badly accessible mine parts in salt mining represents a great challenge because of installation and measurement technical difficulties. Data transfer via cable connection is often in contradiction to the aspired fluidic tightness of technical and geological barriers. For this reason a concept of wireless data transfer within salt formations was developed and successfully tested for three wireless sensors over a duration of recently ca. 700 d (almost 2 a).

The data communication concept is based on the usage of the ISM frequency band for bi-directional communication between individual configurable, wireless sensors and a combined receiver and data acquisition (DAQ) unit. Depending on the measuring problem and the conditions governing location, the data communication concept can be individually modified as well as dimensioned based on site-related measurements.

Tests at different sites and in different lithologies revealed ranges up to 200 m. The experience from test measurements shows the need of individual modification in order to accommodate the measuring problem and the conditions governing location. This is mainly because of the process variety and consequently the sensor technology that has to been chosen as well as the geoelectric properties of different lithologies.

Recently, a combined system of the presented radio transmission of monitoring data and a data transfer through wet ground is subject of intensively research. The vision of a wireless monitoring of closed sites is the fundamental of this effort.

7. Acknowledgments

The research leading to these results has received funding from the German Federal Ministry of Economy and Technology under grant agreement n° 02E10447. We are grateful for the important financial support as well as for the excellent administrative and technical supervision by the associates of the project executing organisation for water technology and waste disposal at the Karlsruhe Institute of Technology.

The performance of in situ reference test at different localities were supported by the Bundesamt für Strahlenschutz (German Federal Office for Radiation Protection), DBE GmbH, KALI GmbH, GTS GmbH & Co KG and the TU Bergakademie Freiberg. We like to thank all participants for their commitment and the uncomplicated help during the realisation of measurements.

References

[1] IBeWa (2012): Non-destructive in situ permeability determination. IBeWa-Ingenieurpartnerschaft subsidised by the German Federal Ministry of Economy and Technology (BMWi) FKZ: 02E10447, current project

[2] Keller, S. (2007): Long-term safety analysis for a high active waste (HAW) repository in salt rock. - Geological reference model for a high active waste (HAW) repository site in rock salt. Technical report (contribution to project ISIBEL), Bundesanstalt für Geologie und Rohstoffe, Hannover, 79 S.

[3] Mauke, R.; Stahlmann, J.; Mohlfeld, M. (2012): In situ-Verification of a Drift Seal System in Rock Salt - Operating Experience and Preliminary Results. SaltMech7, 16th – 19th April 2012, Paris, France, Bundesamt für Strahlenschutz (BfS)

[4] Mehlhorn, H. (1983): Specific damping of electromagnetic waves in salt rock. KDT-guideline, July 1983

[5] RegTP (2004): General allocation for usage in mines (mine radio communication). gazette 7, Agency for regulation of telecommunication and post, Bonn, 31.03.2004

Abbreviations

BfS	-	German Federal Ministry of Economy and Technology
BMWi	-	German Federal Office for Radiation Protection
DAQ	-	data acquisition
DK	-	pressure chamber
ERAM	-	Morsleben repository for radioactive waste
IBeWa	-	IBeWa Consulting Freiberg
GSM	-	Global System for Mobile Communications
ISM	-	industrial, scientific and medical band
K2	-	potash seam “Staßfurt”
KK	-	control chamber
KLS	-	wireless sensor
Na1	-	rock salt, Werra-Member
PR3F	-	Freibergian gneiss
SRD	-	short range devices
USB	-	universal serial bus
VO	-	enforcement order
WLAN	-	wireless local area network

Reduced scale tests to assess corrosion of a steel overpack in the Belgian Supercontainer

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Summary
An experimental testing program is underway to verify the feasibility of constructing the Belgian Supercontainer. The Supercontainer is designed with a concrete buffer completely surrounding a carbon steel overpack. The concrete buffer is made using ordinary Portland cement and calcareous aggregates to provide high alkaline conditions with pH above 13 to form passivation and to favour slow and homogeneous corrosion of the steel overpack. Samples of the metal overpack taken from a recent mock up experiment after one year of testing showed the presence of a passive layer on the steel surface and the complete absence of corrosion suggesting that the concrete materials perform as designed.

A new test is being planned to quantify the observations made earlier in the mock up test. The new test will incorporate a new corrosion sensor developed by the research group SURF of the Vrije Universiteit Brussel (VUB). A prototype of the new sensor has been tested in a laboratory-scale test using a reduced scale model of the Supercontainer to evaluate its potential for use in the Supercontainer feasibility testing program. Preliminary results using the new sensor indicate a rapid onset of corrosion at the beginning of the test followed by an equally rapid decrease in corrosion after only a few days. The results suggest that the new sensor is capable of detecting corrosion ‘as it happens’ and that it can measure the evolution of corrosion in the carbon steel overpack. The results offer encouraging basis for use of the sensors in future corrosion testing as well as in monitoring applications.

1. Introduction

The Supercontainer (SC) is the Belgian reference concept proposed by ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, for the packaging of vitrified high-level radioactive waste (HLW) and spent fuel [1, 2]. The general conceptual design of the Supercontainer appears in Figure 1. It is based on a multiple barrier system that includes an outer steel envelope, a concrete buffer and a water-tight carbon steel overpack containing one or more waste canisters. The concrete buffer completely surrounds the overpack. The thickness of the concrete varies between 54 and 70 cm depending on the waste contained in the Supercontainer.

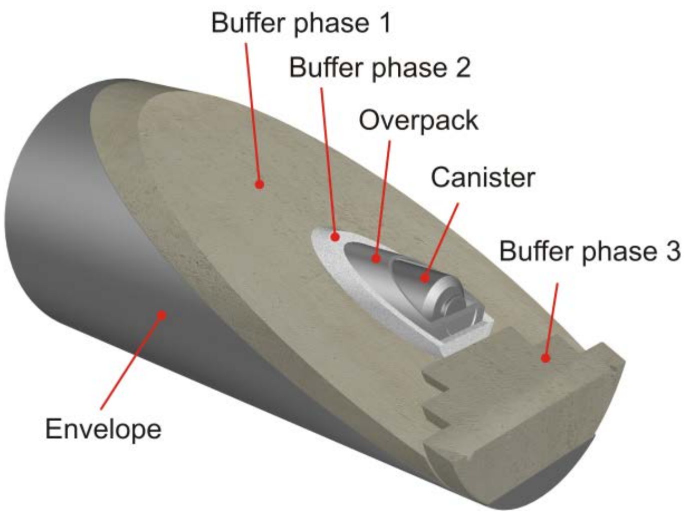

Figure 1: Belgian Supercontainer concept

The carbon steel overpack has a thickness of 30 mm and a diameter ranging from 429 to 973 mm. The current reference material to construct the overpack is the P355 QL2 grade carbon steel. The long-term safety function of the overpack is to contain the radionuclides during the thermal phase, which will last several thousands of years. One of the long-term functions of the concrete buffer is to provide a high alkaline chemical environment that favours the formation of a tightly adhering passive oxide film on the external surface of the carbon steel overpack, which protects the underlying metal and is believed to result in very low, uniform and almost negligible corrosion rates.

2. Half-Scale Test

In order to demonstrate the feasibility to construct the SC, one half-scale experiment has been performed [3] and another is being planned. The half-scale test gets its name from its scaled dimensions. It has a true diameter scale, but it is limited in height to approximately half of a real SC. Figure 2 shows a general view of the half-scale test setup.

The concrete buffer consists of non-reinforced, self-compacting concrete (SCC) made using ordinary Portland cement (OPC) and limestone aggregate with a water/cement ratio of 0.5. The overpack consists of a carbon steel container with a diameter of 508 mm and a thickness of 15.06 mm. Inside the overpack are four heating elements to simulate the heat generated by the radioactive waste in a real overpack. After installing the heating elements, the simulated overpack is filled with dry, clean sand. The sand has a good thermal conductivity and helps create a homogeneous heat distribution inside the overpack.

The first half-scale test (HST I) started in July 2009 and was dismantled in December 2009. A major goal of this experiment was to study the early-age thermo-mechanical behaviour of the concrete buffer. Another was to check the feasibility of constructing the SC. The results of the HST I provided sufficient confidence to conclude that the SC can be constructed using current industrial techniques. However, the test also provided an opportunity to learn from a number of shortcomings that had not been anticipated before the test.

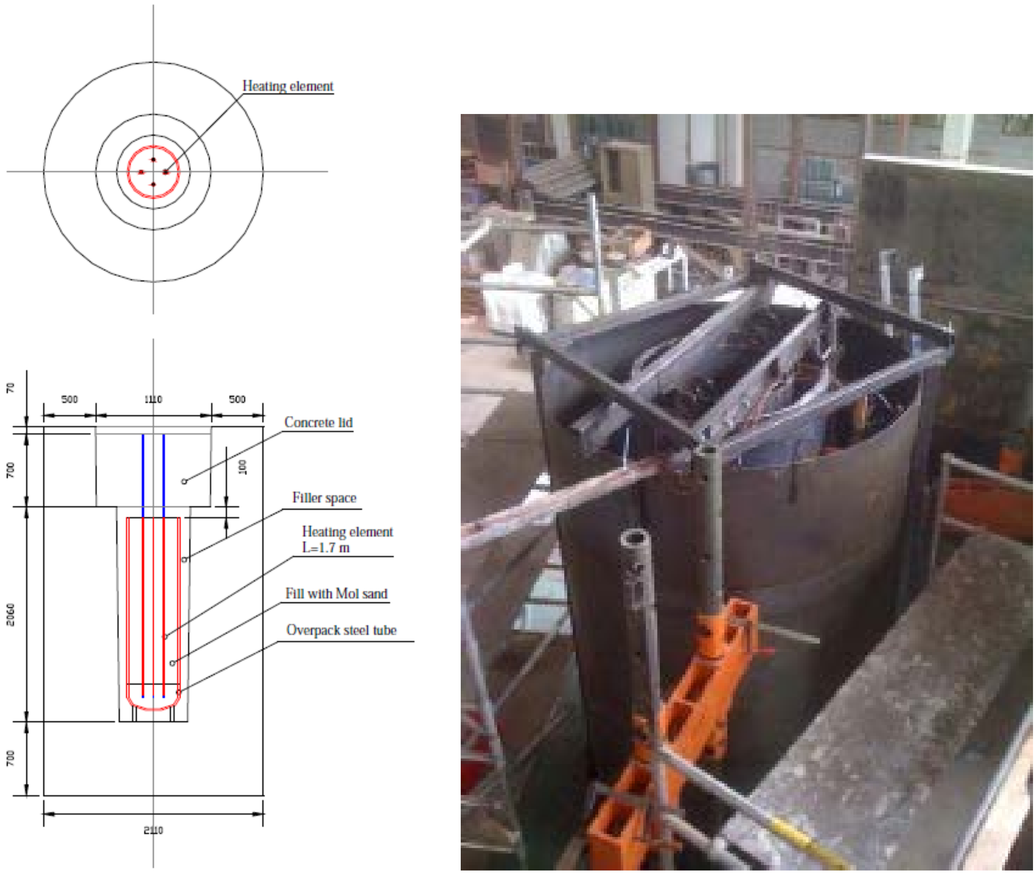

Figure 2: General cross-section [left] and assembled mould before start of test[right]

A second half-scale test (HST II) is being planned to start early 2013. This test has the following main objectives:

- confirm some of the observations made during the first half-scale test;
- further characterise the thermo-mechanical behaviour of the concrete buffer with particular emphasis on the potential development of cracks; and
- study the corrosion behaviour of the carbon steel overpack;

Table 1 lists the parameters monitored during the first half-scale test as well as those planned for the HST II.

The corrosion behaviour of the carbon steel overpack will be studied by monitoring the corrosion potential and the instantaneous corrosion rate. The corrosion sensor PermaZEN, developed in the Zensor project at the Electrochemical Research Group and Surface Engineering (SURF) of the VUB, is being considered for measuring the instantaneous corrosion rates of the carbon steel overpack. The applicability of this newly developed corrosion sensor for measuring instantaneous corrosion rates in a concrete mix has recently been verified in a laboratory-scale test setup.

Table 1. Monitoring parameters and instrumentation in the 1st and 2nd Half-Scale Tests.

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

3. Laboratory-scale corrosion sensor test

The objective of the test was to evaluate the feasibility of measuring instantaneous corrosion rates of carbon steel embedded in a concrete buffer. A schematic of the PermaZEN laboratory test setup appears in Figure 3. The laboratory test set up consisted of a plastic container of approximately 70 cm in height and 50 cm in diameter. A carbon steel cylinder with an outer diameter of 10 cm, a height of 30 cm and a thickness of 4 mm was inserted in the centre of the plastic container, as shown in Figure 4.

The plastic container was first filled with the concrete mixture up to half of its height. Ni auxiliary electrodes were then inserted in the concrete and symmetrically distributed around the steel cylinder, at a distance of approximately 5 cm from the steel surface. The Ni electrodes (4 by 8 cm) were mounted in an epoxy resin and then ground with SiC paper to a 1000 grit finish. After emplacement of the Ni electrodes, sufficient concrete was added to completely cover the electrodes and metal cylinder.

The measurement of corrosion rates obtained with the PermaZEN corrosion sensor is based on a proprietary technique protected under patent application PCT/EP2012/063410. Its principle consists of applying low amplitude, multi-frequency AC signals between the steel cylinder and the Ni auxiliary electrodes. The recorded responses are then analysed and interpreted using a non-empirical algorithm to calculate the equivalent corrosion rate. In the present setup, the measurements are repeated for four Ni electrodes embedded in the concrete, as shown in Figures 3 and 4.

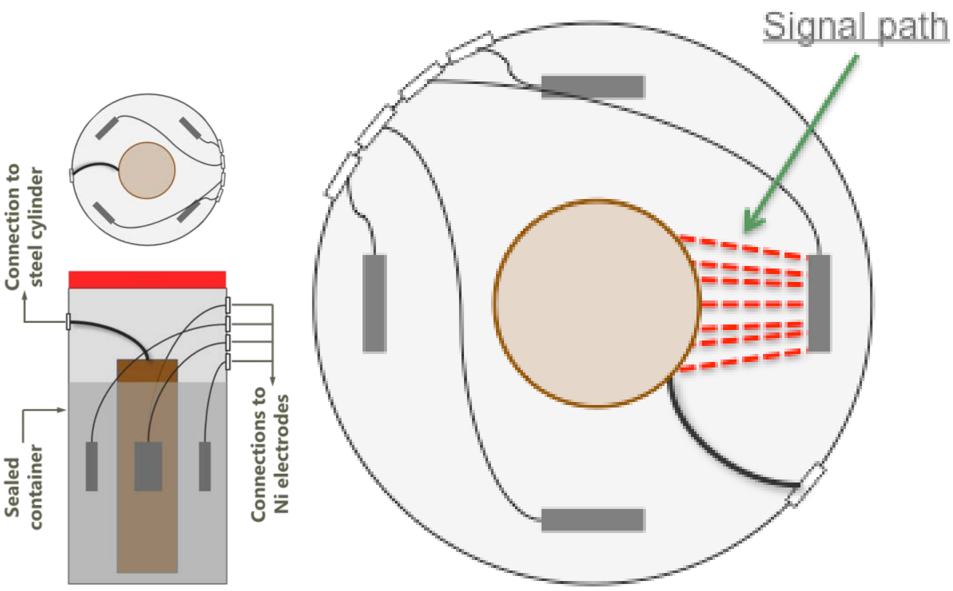

Figure 3: Schematic of the PermaZEN laboratory-scale test setup

Figure 4: Set up of laboratory-scale test [left] showing the steel cylinder and [right] during casting of the concrete mixture

4. Results

Figure 5 shows the accumulated corrosion rate recorded for Electrode 2. The corrosion rates shown are based on an arbitrary unit that reflects the level of corrosion measured. Measurements are foreseen in a future test to correlate this arbitrary corrosion rate to a real corrosion rate expressed in, for example, µm/year. The signal value is however linearly related to the actual corrosion rate. The graph shows a gradually decreasing corrosion rate with time as displayed by the curve which becomes less and less steep with time. This is because larger parts of the surface of the steel cylinder are getting passivated.

Figure 6 shows the instantaneous corrosion rates recorded for Electrode 4 after 18 days of exposure. The measured corrosion rates are generally low, which is indicative of the passive state of the steel surface. However, short 'outbursts' of active corrosion were observed. This intermitting corrosion behaviour is typically observed in field conditions.

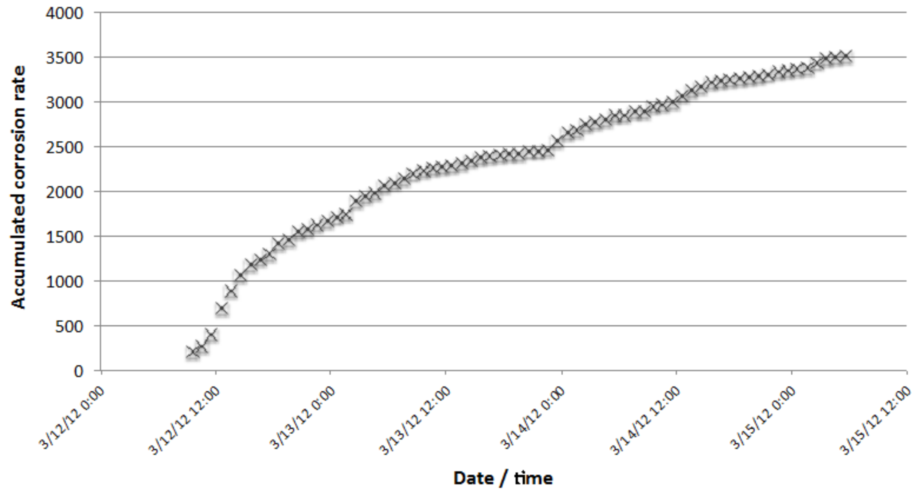

Figure 5: Accumulated corrosion rates recorded for Electrode 2 after 6 days of exposure

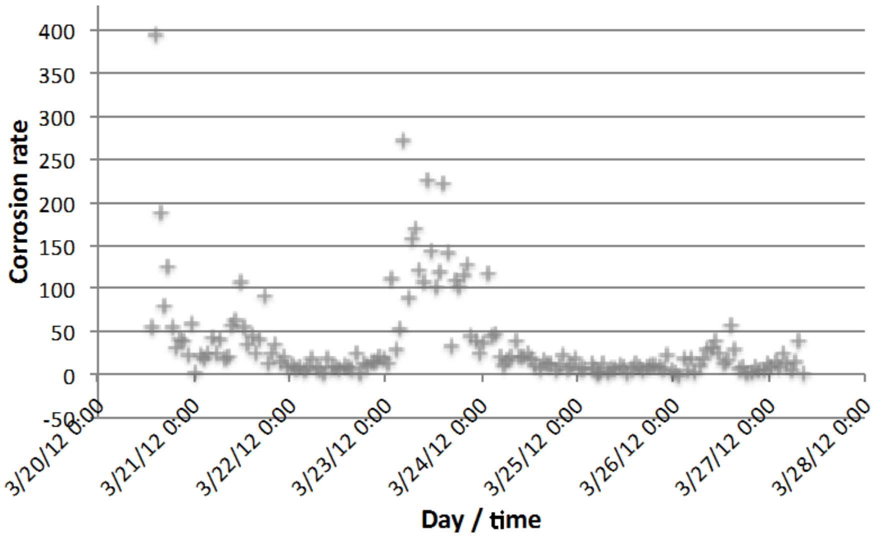

Figure 6: Instantaneous corrosion rates recorded for Electrode 4 after 18 days of exposure

After six months of testing, the measured corrosion rates were below the detection limit of the system. This detection limit can, however, be increased by increasing the measuring period. To test the functionality of the system, a current of 1 mA was applied between the steel and one of the Ni electrodes with the steel acting as the anode. This operation aimed at reactivating the steel surface under galvanostatic control. The corrosion rates recorded after this operation are shown in Figure 7. These indicate a significant decrease of the corrosion rate after only 4 days, clearly indicating the reactivation of passivity of the metal surface.

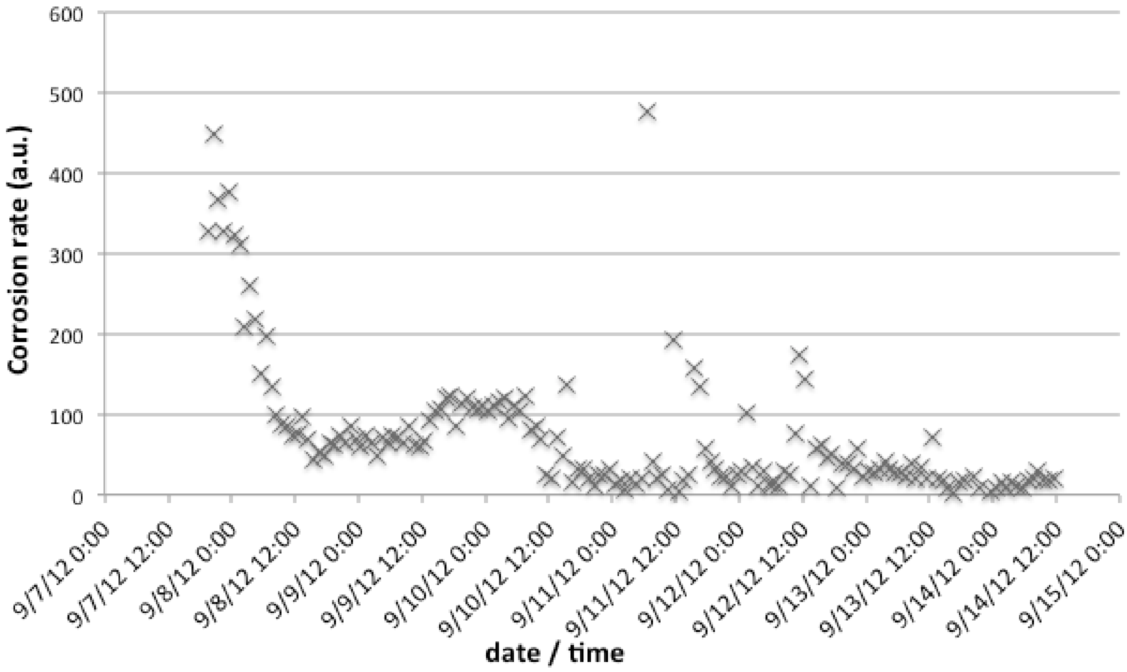

Figure 7: Instantaneous corrosion rates recorded after reactivation of the steel surface

5. Conclusions

The results of a laboratory test performed to evaluate the feasibility of measuring instantaneous corrosion rates of carbon steel exposed to a concrete buffer so far suggest that the PermaZEN corrosion sensor developed at the VUB can measure the evolution of corrosion of the carbon steel overpack in the Supercontainer. The results show a rapid onset of corrosion at the beginning of the test followed by an equally rapid decrease in corrosion after only a few days of testing. The measured corrosion rates after six months of testing were below the detection limit of the system suggesting that the metal surface was passivated.

The functionality of the system was verified at the end of the test by applying a current of 1 mA between the steel cylinder and one of the Ni auxiliary electrodes, with the steel acting as the anode. The results showed a significant decrease of the corrosion rate after only 4 days, clearly indicating the reactivation of passivity of the metal surface.

References

[1] ONDRAF/NIRAS (2009), The Long-Term Safety Strategy for the Geological Disposal of Radioactive Waste, ONDRAF/NIRAS report NIROND-TR 2009-14 E.

[2] ONDRAF/NIRAS (2010), Feasibility strategy and Feasibility Assessment Methodolgy for the geological disposal of radioactive waste, ONDRAF/NIRAS report NIROND-TR 2010-19 E.

[3] Areias, L., Craeye, B., De Schutter, G., Van Humbeeck, H., Wacquier, W., Villers, L. and Van Cotthem, A. (2010). Half-scale test: an important step to demonstrate the feasibility of the Belgian supercontainer concept for disposal of HLW. Proceedings of the 13th International Conference on Environmental Remediation and Radioactive Waste Management, ICEM2010, Tsukuba, Japan.

Spatial Time Domain Reflectometry (Spatial TDR) for Moisture Monitoring in Geological Repositories – Technology, Feasibility, and Limitations

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Summary

The Institute of Material Research and Testing at the Bauhaus-University Weimar has designed and tested monitoring concepts based on Spatial TDR for qualitative and quantitative moisture monitoring in geological repositories. These studies cover combined theoretical, experimental, and numerical investigations on the electromagnetic wave propagation along transmission line structures embedded in homogeneous as well as in-homogeneous sealing materials such as swelling clays or magnesia concrete. Based on the designed concepts automated Spatial TDR monitoring systems were developed and evaluated in different configurations in large scale laboratory investigations for preparation of possible in-situ applications in clay or salt formations. The developed Spatial TDR systems were implemented for moisture monitoring in constructions of underground barriers in a salt mine in Teutschenthal (Germany). The systems consists of (i) a TDR base station for automated two sided Spatial TDR measurements, data storage and transfer, (ii) flexible passive Spatial TDR sensors, and (iii) modules for data visualization and data analysis. The Spatial TDR technology provides a useful tool for high resolution temporal and spatial monitoring of the water content evolution in geological repositories. The passive TDR sensors are robust, long term stable and have a high sensitivity to moisture. However, the major challenge for the quantification of the absolute content of concentrated aqueous pore solutions is the consideration of the influence of the frequency dependent high frequency electromagnetic (HF-EM) material properties of the (i) pore solution, (ii) host rock, and (iii) sealing materials in the used moisture retrieval algorithm. This topic needs to be addressed in further research activities.

1. Introduction

Since the late seventies time domain reflectometry (TDR) has been a well-known and accepted measurement method for determining the water content of porous materials [19]. The classical TDR technology is based on the measurement of the travel time of a high frequency electromagnetic (HF-EM) step pulse propagating along a bifurcated short (10 to 30 cm) TDR probe, which was inserted into the material. The apparent permittivity ε_{app} of the material, which is strongly related to the volume fraction of water, is determined from measured pulse travel time [10]. ε_{app} depends on the appropriate sensor type as well as the effective complex permittivity of the investigated material $\varepsilon^*_{r,eff} = \varepsilon'_{r,eff} - j\varepsilon''_{r,eff}$ ([15], [20]), which is a function of the HF-EM properties of the solid phases (texture, mineralogy), their interaction with water vapour and aqueous solutions as well as structure (density, particle shape and pore size distribution) [22]. Conventional TDR is restricted to the point-wise determination of material moisture, or mean water content, along a TDR probe. However, applications in geotechnical engineering, hydrology and agriculture require the determination of the temporal evolution of the water content distribution on larger scales for characterizing hydraulic processes in soil and rock formations or engineering structures ([5], [9], [10], [11], [16]). Besides pulse travel time the TDR signal contains valuable information which can be used to retrieve the spatially distribution of HF-EM material properties along the TDR probe with an improved measurement, calibration and analysis technique ([4], [5], [17]). This technology applied with long transmission line sensors (50 cm to 5 m) is called Spatial Time Domain Reflectometry (Spatial TDR, [16]). The MFPA Weimar has designed and tested monitoring concepts based on Spatial TDR for qualitative and quantitative moisture monitoring in geological repositories within the framework of the R&D programme "Disposal of Hazardous Waste in Deep Geological Formations" of the German Federal Ministry of Education and Research (BMBF). Based on the designed concepts automated Spatial TDR monitoring systems were developed and evaluated in different configurations in large scale laboratory investigations for preparation of possible in-situ applications in clay or salt formations [10]. The developed Spatial TDR systems were implemented for moisture monitoring in constructions of underground barriers in a salt mine in Teutschenthal (Germany) [11].

2. Spatial TDR Technology

He et al. ([1], [2]) provided a theoretical framework to unambiguous reconstruct an 1 D distribution of electromagnetic parameters from two sided reflection and/or transmission measurements in time domain based on the analytical or numerical solution of the non-homogeneous boundary value problem. Due to this theoretical findings attempts were intensified to develop appropriate inversion algorithms to reconstruct the distribution of the volumetric water content from Spatial TDR measurements in porous media such as soils ([4], [5], [14], [17]). In Figure 1-1 the Spatial TDR technology implemented for water content estimation in a dike model [16] based on the fast time domain inversion kernel of Schlaeger (2005) [17] is represented.

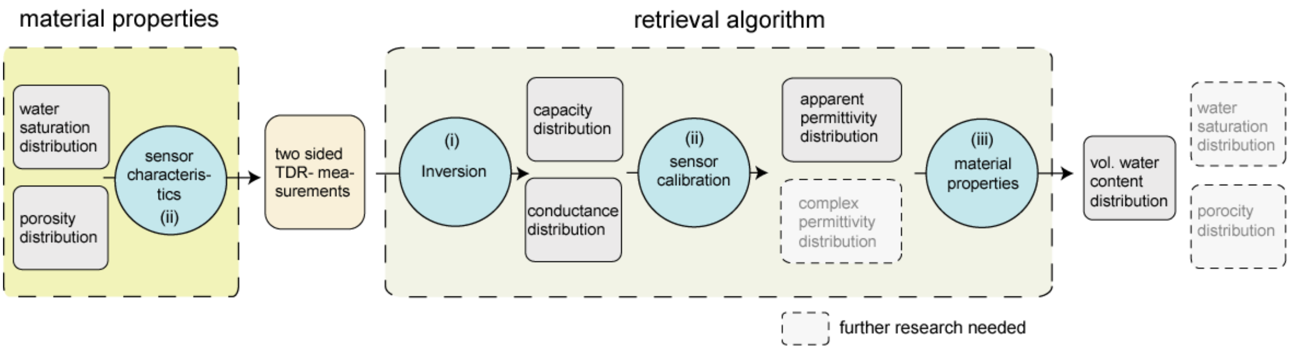


Figure2-1: Schematic illustration of the Spatial TDR methodology.

The volumetric water content is retrieved from two sided TDR measurements in three steps. (i) The distribution of the sensor characteristics (capacitance and conductance profile) along the Spatial TDR Sensor is inverted based on the TDR measurements, (ii) the distribution of the sensor parameters is converted in an apparent relative permittivity distribution of the material based on the known sensor characteristics and (iii) the volumetric water content distribution is estimated from the permittivity profile based on the relationship between electromagnetic material properties and volumetric water content. Below, the appropriate steps in the retrieval algorithm and the technology used are described.

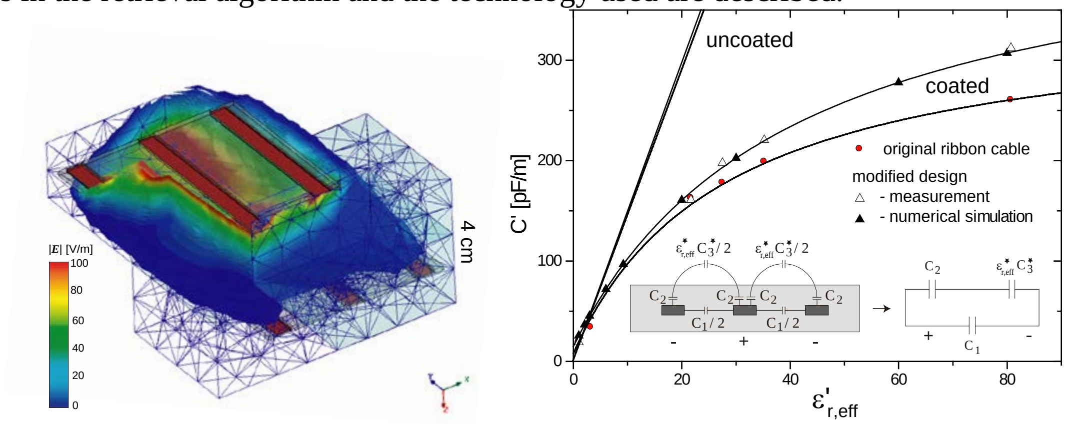


Figure 2-2: (left) Spatial sensitivity represented by the electric field distribution of a 10 cm ribbon cable section at a frequency of 1 GHz obtained from 3D electromagnetic field calculations. (rigth) Capacitance C' of the sensor as a function of the real part of the effective permittivity $\varepsilon'_{r,eff}$ of the surrounding material.

2.1. The Spatial TDR Sensor

Conventionally TDR probes are designed with non-insulated metallic rods as transmission lines in the form of either a two- or a three-rod configuration [15]. This kind of probe is frequently used for point-wise measurements of the water content in applications ([4], [18]). Advantages of the use of non-insulated metallic rods are (i) a high sensitivity to the surrounding material (Figure 2-2) and (ii) the possibility of the direct calculation of the permittivity of the material surrounding the waveguide from the wave velocity [3], which can be determined using simple travel time analysis routines. However, due to a strong attenuation in materials with high clay content or a high ion concentration in the aqueous pore solution the TDR signal is strongly distorted [10]. Hence, the maximal sensor length is drastically reduced < 10 cm. For longer transmission lines, insulated flexible planar ribbon cables (PRCs) can be used. These sensors show much less pulse attenuation than uncoated metallic rods in the same medium on the expense of the sensitivity (Figure 2-2, left). Several cables with different geometries have been developed and manufactured in the past, from simple concentric insulation to sophisticated multi-wire structures with unilateral sensitivity. The PRC shown in Figure 2-2 was originally used to measure volumetric water contents in snow, in sealing elements of landfills [5] or in dike models [16]. The RPC has a sensitive area of 1 cm up to 2 cm on both sensor sides (Figure 2-2, left, [16], [20]). A PRC is a transmission line characterized by an equivalent circuit with capacitance C, conductance G, inductance L and resistance R, per unit length, respectively (see section 2.3). These parameters are functions of the probe geometry and the electromagnetic properties of the material surrounding the probe. Both L and R are parameters which can be assumed to be constant along the probe [5]. In contrast, C and G are strongly dependent on the surrounding material.

Lundstedt and Norgren (2003) [14] proposed a relationship between complex relative permittivity $\varepsilon^*_{r,eff}$ and C or G in terms of a complex capacitance $C^* = C' - jC''$ using a simple capacitance model (Figure 2-2, right):

$$C^*(\varepsilon^*_{r,eff}) = C' - jC'' = C - j\frac{G}{\omega} = C_1 + \frac{\varepsilon^*_{r,eff}\, C_2 C_3}{C_2 + \varepsilon^*_{r,eff}\, C_3} \qquad (1)$$

Herein $\omega = 2\pi f$ is angular frequency with frequency f. The parameters C_1, C_2 and C_3 were determined experimentally or numerically from 3 D electromagnetic field calculations ([5], [16]).

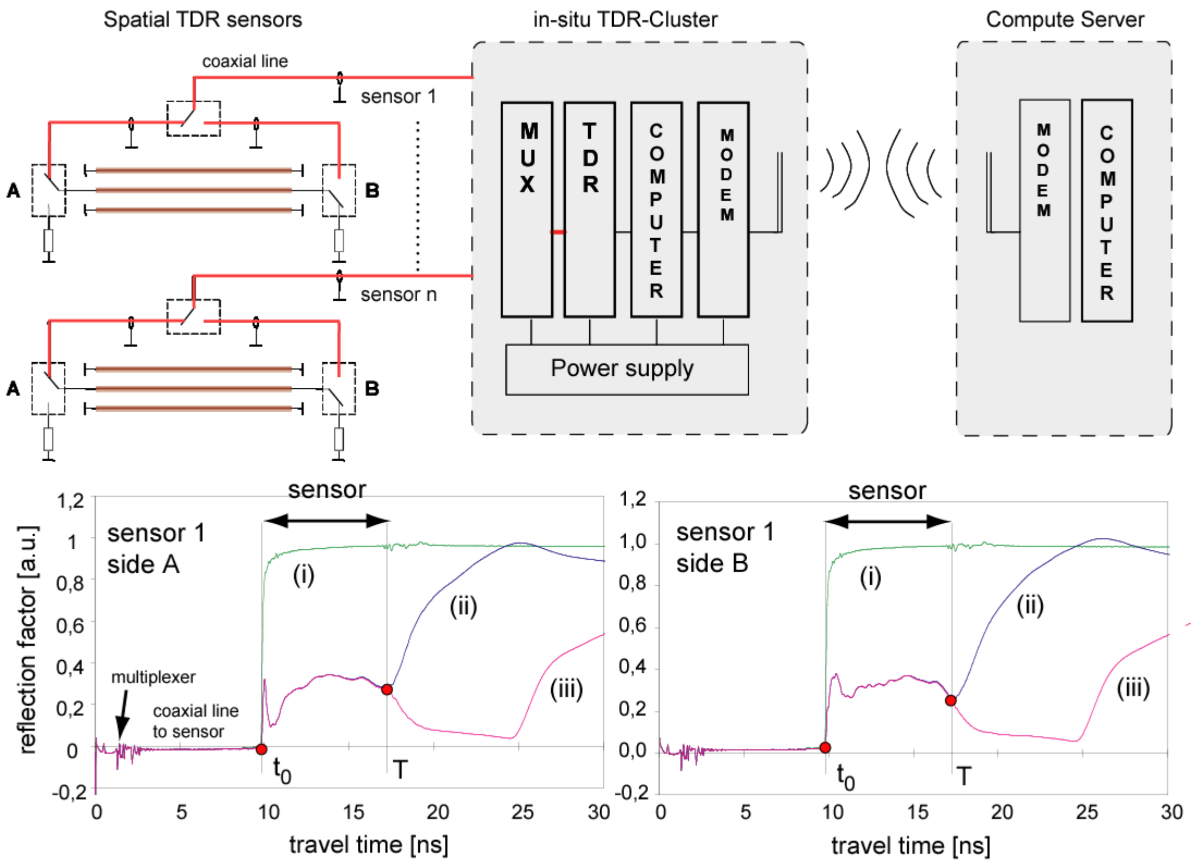


Figure 2-3: (top) Simplified schematic illustration of the automated Spatial TDR monitoring system. (bottom) Example of a complete TDR measurement set for one sensor at one time step obtained from side A and B (see text for details).

2.2. The Spatial TDR measurement concept

In Figure 2-3 the measurement concept of the modular Spatial TDR technology is represented. The system consists of a controlling unit for automatic TDR measurements with a wired connection for data transfer and remote control. However, the used industry computer is also equipped with an exchangeable memory card to store TDR measurements for several months. Furthermore, the system consists of a TDR measurement device connected to the passive Spatial TDR sensors with coaxial lines via a multiplexing system. Each measurement set consists of six single measurements, three from each sensor side (A,B): (i) two calibration measurements at the connection between coaxial lines to the sensors and sensor head with defined impedance of 110 kΩ, (ii) two measurements of the sensor with a impedance of 110 kΩ at the sensor end A or B, respectively, as well as (iii) a control measurement with 50 Ω impedance.

2.3. The Spatial TDR inversion kernel

In order to reconstruct the capacitance $C(x)$ and conductance $G(x)$ distribution along the sensor simultaneously, two independent TDR measurements (i.e. from both sides of the transmission line, see Figure 2-3) are needed with the resulting TDR reflectograms $V_1^m(x,t)$ and $V_2^m(x,t)$. The telegraph equations (see [16], [17]):

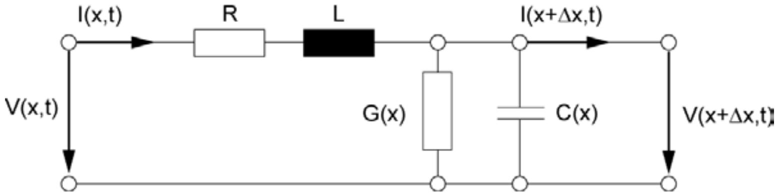


Figure 2-4: (a) Equivalent circuit of a short section of a transverse electromagnetic (TEM) transmission line. $V(x,t)$ *and* $I(x,t)$ *are the voltage and the current at the beginning and end of the section (c.f. [5]).*

$$\begin{aligned}\frac{\partial}{\partial x}V(x,t) &= -L\frac{\partial}{\partial t}I(x,t)\\ \frac{\partial}{\partial x}I(x,t) &= -G(x)V(x,t)-C(x)\frac{\partial}{\partial t}V(x,t)\end{aligned} \tag{2}$$

characterize the variation of voltage $V(x,t)$ and current $I(x,t)$ due to an incident voltage step along the transmission line, which can be described with the equivalent circuit model of Figure 2-3. For the inverse determination of $C(x)$ and $G(x)$ the direct problem with full wave solution $V_1^s(x,t)$ and $V_2^s(x,t)$ is solved for both measurements with a given robust starting guess based on an uniform distributions for $C(x)$ and $G(x)$ obtained from the integral travel time along the sensor. The simulated TDR reflectograms are compared between the first main reflection at $t=t_0$ and the second main reflection at $t=T$ (see Figure 2-3) with the measurements using the error function:

$$J(C,G)=\sum_{i=1}^{2}\int_{t_0}^{T}\left[V_i^{(s)}(x_i,t)-V_i^{(m)}(x_i,t)\right]^2 dt\,. \tag{3}$$

The conjugate gradient of this error function can be calculated directly by means of the corresponding adjoining partial differential equation of the given telegraph equations (2). The conjugate gradient is necessary to determine the improved distributions of $C(x)$ and $G(x)$, which are used for the next iteration step. This procedure is repeated until a minimum error function is reached. The direct calculation of the conjugate gradients is one reason for the fast iterative search. However, during the optimization process it is necessary to calculate the solution of the direct problem for many different distributions of $C(x)$ and $G(x)$. For this reason it is also important to use an algorithm for the solution of partial differential equations that is computationally efficient to guarantee a fast convergence [17]. However, the PEcoating (insulation) of the sensor conductors represented by the two capacitances C_1 and C_2 leads to an elimination of the direct current conductivity component which in turn induced an artificial frequency dependent polarization in the presence of concentrated aqueous solutions. This can result in dispersion in the measured sensor capacitance which is not considered in the used inversion scheme and needs to be addressed in further research activities.

2.4. Electromagnetic material properties of porous mineral materials

Porous mineral materials consist mainly of four phases: solid particles (various mineral phases), pore air, pore fluid as well as a solid particle - pore fluid interface (Figure 2-5). In principle the fractions of these phases vary both in space (due to composition and density) and time (due to changes of water content, porosity, pore water chemistry and temperature).

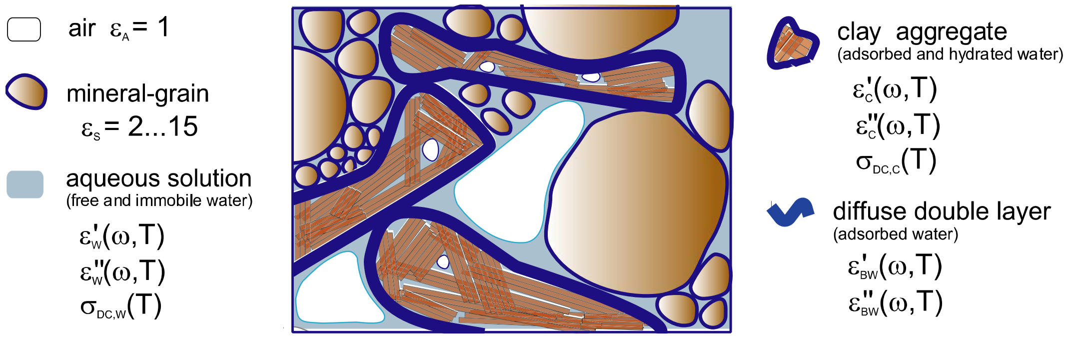


Figure2-5: Simplified schematic illustration of the stucture of an unsaturated porous clay rock sample. Indicated are the contributions of the single components to the dielectric material properties in terms of a complex effective relative permittivity $\varepsilon^*_{r,eff} = \varepsilon'_{r,eff} - j\varepsilon''_{r,eff}$ *with real* $\varepsilon'_{r,eff}$ *and imaginary part* $\varepsilon''_{r,eff}$ *[21].*

The electromagnetic properties of the solid particles can be assumed to be frequency independent in the considered temperature-pressure-frequency range. Real relative permittivity ε_G of inorganic dielectric mineral materials varies from 3 to 15 (see citations in [21], [22]). The pore fluid as well as the interface fluid can be considered as an aqueous solution with a temperature-pressure-frequency dependent relative complex permittivity $\varepsilon^*_W(\omega, T, p)$ according to the modified Debye model [7]:

$$\varepsilon^*_w(\omega, T, p) - \varepsilon_\infty(T, p) = \frac{\varepsilon_S(T, p) - \varepsilon_\infty(T, p)}{1 + j\omega\tau(T, p)} - j\frac{\sigma_{DC}(T, p)}{\omega\varepsilon_0} \qquad (4)$$

with the high frequency limit of permittivity $\varepsilon_\infty(T, p)$, the static permittivity $\varepsilon_S(T, p)$, relaxation time $\tau(T, p)$, direct current conductivity contribution $\sigma_{DC}(T, p)$ and permittivity of free space ε_0. Under atmospheric conditions the dielectric relaxation time of water $\tau(T)$ depends on temperature T according to the Eyring equation with Gibbs energy or free enthalpy of activation $\Delta G^\#_W(T) = \Delta H^\#_W(T) - T\Delta S^\#_W(T)$, activation enthalpy $\Delta H^\#_W(T)$ and activation entropy $\Delta S^\#_W(T)$. Furthermore, Gibbs energy of the interface fluid $\Delta G^\#_d(T)$ is a function of the distance from the particle surface (for quantitative approaches see [21]). In case of concentrated aqueous salt solutions the concentration and ion species dependence of the Debye-parameter in equation (1) further have to be considered (see [8]). Hence, the effective electromagnetic transfer function of the porous mineral material in terms of effective complex permittivity $\varepsilon^*_{r,eff}(\theta, n, \rho_i, \omega, T, p)$ is a function of volumetric water content θ, porosity n, ion speciation and concentration ρ_i, frequency $\omega = 2\pi f$, temperature T and pressure p. In Wagner et al. (2011) [22] several broadband approaches were discussed to model $\varepsilon^*_{r,eff}$. The authors concluded that the class of power law models based on the Lichtenecker and Rother type mixture equation provide a useful approach in practical applications ([18], [22]):

$$\varepsilon^{*a(\theta,n)}_{r,eff}(\theta,n,\rho_i,\omega,T,p)=\Omega_{a(\theta,n)}(\rho_i,\omega,T,p)+(1-n)\varepsilon_G^{a(\theta,n)}+(\theta-n)\,. \qquad (5)$$

The parameter $0 \le a \le 1$ contains structural information of free and interface water and the term $\Omega(\rho_i,\omega,T,p)$ represents the contribution of relaxation processes [21]. However, for the development of robust mixture approaches under consideration of high concentrated salt solutions as well as structural changes with hydration there is the need of systematic investigations by broadband dielectric spectroscopy of unsaturated and saturated porous media under controlled thermal-hydraulic-mechanical-chemical (T-H-M-C) conditions.

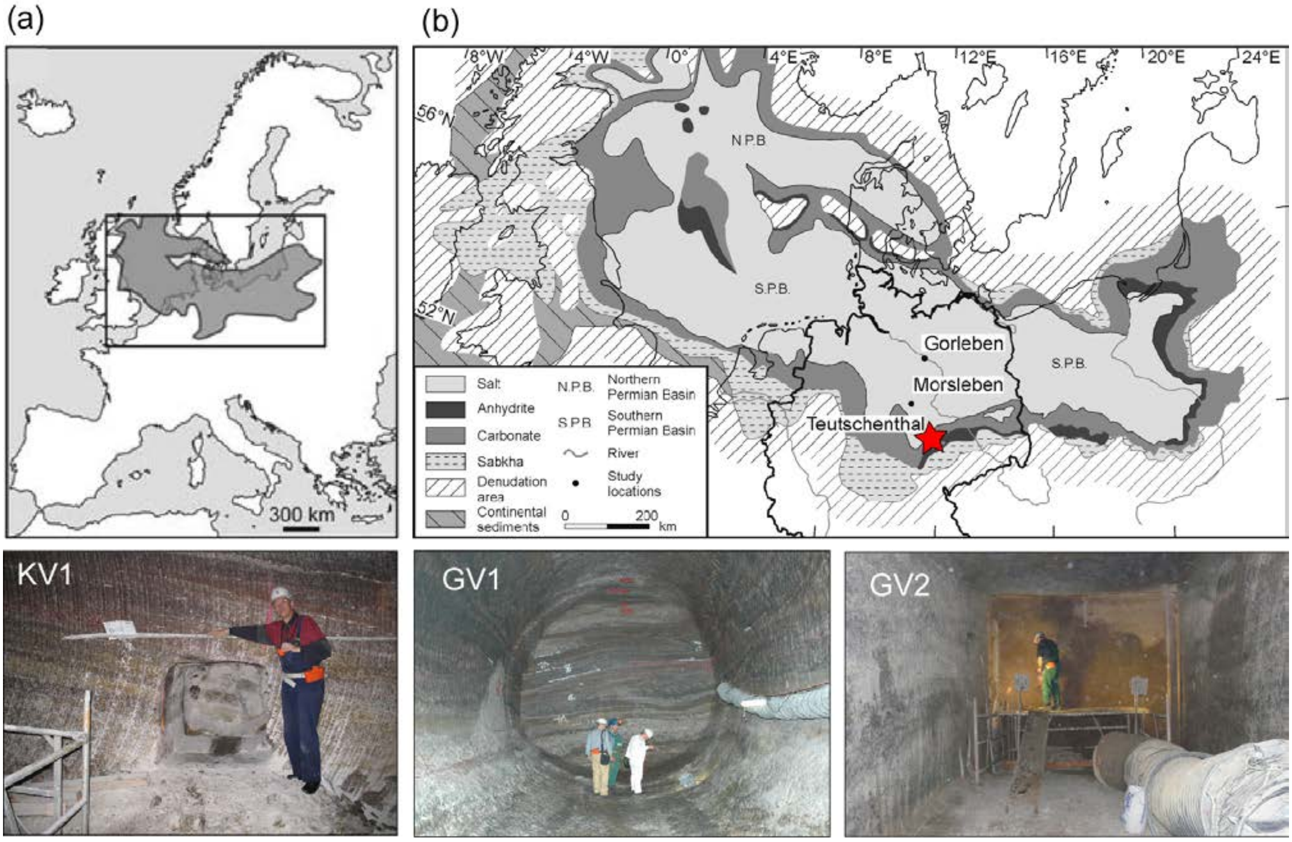
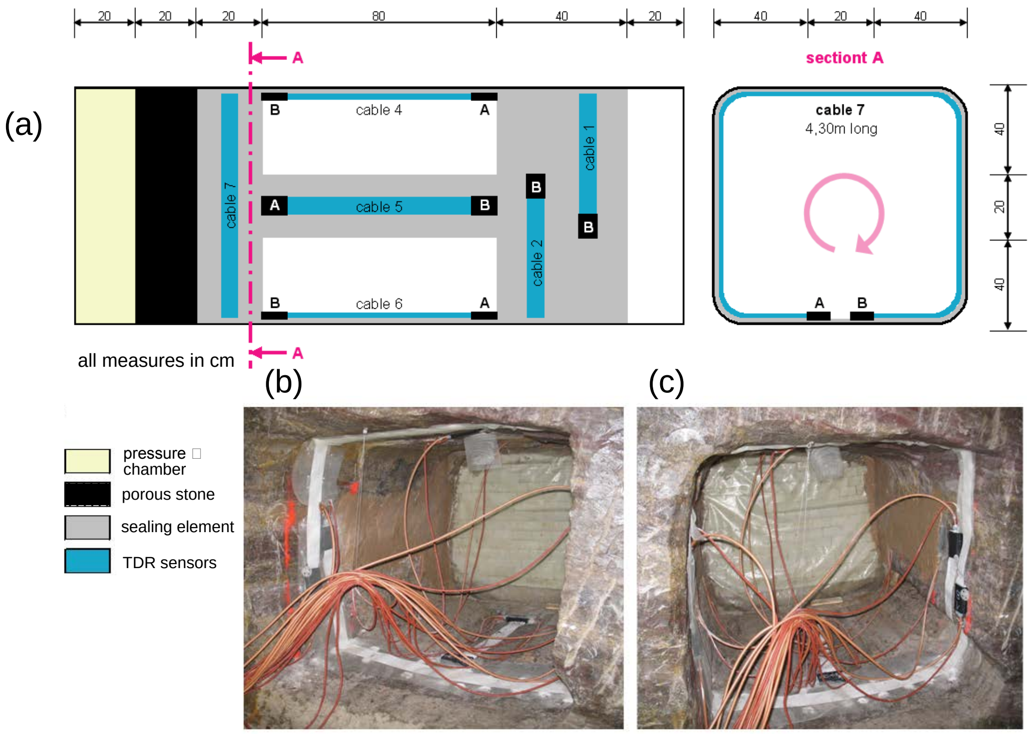


Figure 3-1: (a) Map of the Late Permian Zechstein Basin with (b) location of the salt mine Teutschenthal in the Stassfurt Formation Saxony-Anhalt, Germany (modified after [12], [12]). (bottom) Smal scale (KV1) and large scale (GV 1 and 2) in-situ test sides in a depth of 800 m.

3. In situ application

The developed Spatial TDR systems were implemented for moisture monitoring in constructions of underground barriers in a salt mine in Teutschenthal (Germany) in a depth of 800 m in close cooperation with the R&D project "CARnallitic Long-term sAfety sealing constructions – CARLA" (BMBF grant agreement 02C1204, Figure 3-1). The systems consists of (i) a TDR base station (see Figure 2-3) for automated two sided Spatial TDR measurements, data storage and transfer, (ii) flexible passive Spatial TDR sensors, and (iii) modules for data visualization and data analysis. One system equipped with seven sensors was adapted for the use in a small scale pilot test site (KV1). Based on the results of the pilot test two further optimized systems were implemented with four 4 m cable sensors in two large scale experiments (GV1 and 2).

The sealing element in KV1 consisting of a magnesia concrete monolith and has a cross section of 1x1 m^2 and a length of 2 m. The conceptual design of the element includes a pressure chamber to expose a saturated aqueous $CaCl_2$ or $MgCl_2$ aqueous solution. To monitor spatial and temporal moisture evolution TDR sensors were installed at the boundary between concrete barrier and host rock (Figure 3-2). In Figure 3-2 (d) the spatial and temporal evolution of the moisture in terms of apparent permittivity is represented during the sensor installation and placing the concrete sealing element. A high apparent permittivity here corresponds with a high volume fraction of water and vise versa. This means, that with decreasing permittivity the water saturation and/or porosity of the material decrease with hardening of the concrete. However, the major challenge for the quantification of the absolute content of concentrated aqueous pore solutions is the consideration of the influence of the frequency dependent HF-EM material properties of the (i) pore solution, (ii) host rock, and (iii) sealing materials in the used moisture retrieval algorithm. This topic needs to be addressed in further research activities. Here we restricted to discuss the results on the apparent permittivity level.



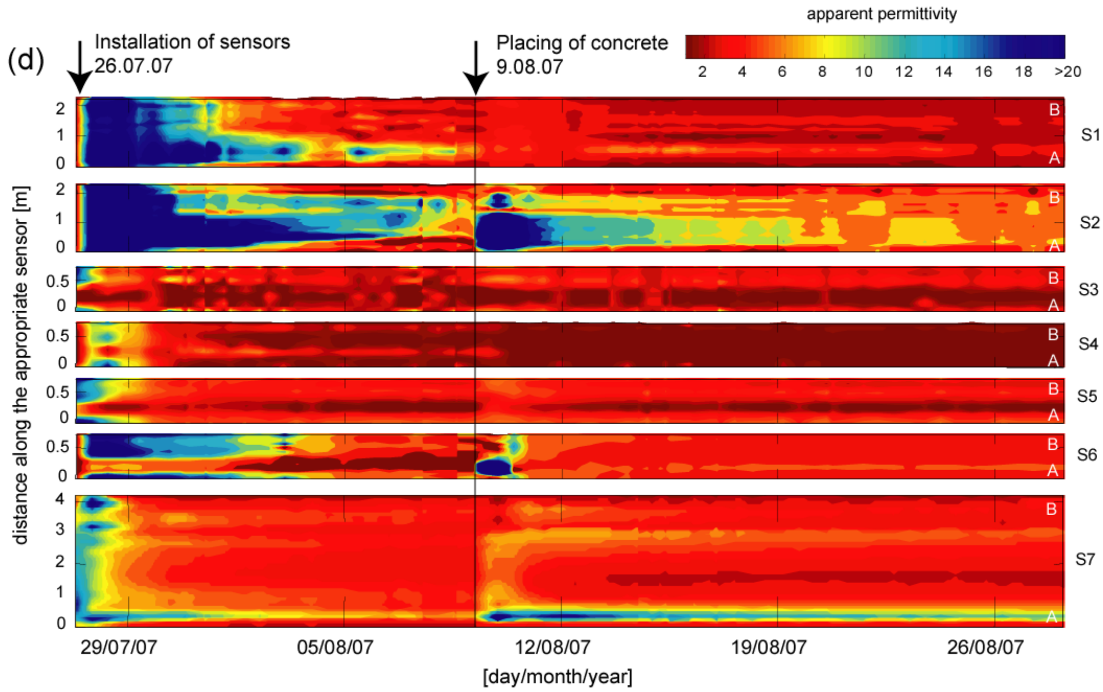


Figure 3-2: (a) Scematic illustration of the smal scale pilot test. (b,c) Installed Spatial TDR sensors prior to placing the concrete. (d) Retrived apparent permittivity distribution during installation of the TDR sensors and placing the magnesia concrete.

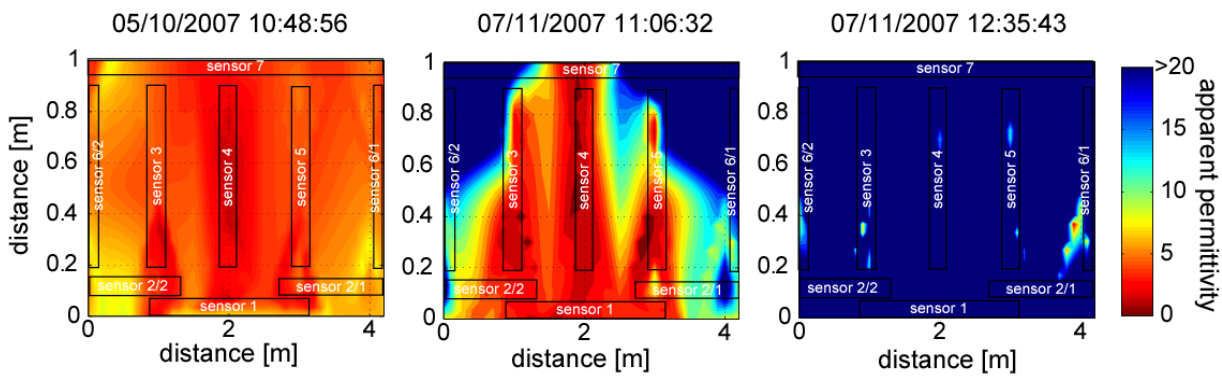


Figure 3-3: Interpolated 2D representation of the retrived apparent permittivity at the interface between host rock and sealing element at three time steps (from left to rigth): before, during and after ingress of the aqueous salt solution.

In Figure 3-3 the monitored interface between host rock and sealing element is given in an interpolated 2D plot of the apparent permittivity. The fast ingress of saturated salt solutions at the boundary between concrete barrier and host rock were successfully monitored. The results of the small pilot test show the applicability of the Spatial TDR technology to monitor temporal and spatial moisture evolution with high resolution. Hence, an equivalent Spatial TDR-system with four 4 m sensors was installed in two large scale experiments (GV 1/2). The cable sensors were sewed onto geotextiles and mounted with plastic towels on the host rock (Figure 3-4) prior to concrete placement. In Figure 3-4 (b) the spatial and temporal evolution of the permittivity along the sensors are represented in case of GV 1. The faster hydration and thus drying of the concrete at the top (cable sensor 2) and the higher volume fraction of the concentrated aqueous solution at the bottom of the sealing element was monitored. Furthermore, the retrieved low permittivity of sensor 2 (sensor position at 3 m) indicates the possibility of a gap between concrete and rock. To avoid any gap at the interface between rock and concrete 2 K-bitumen was injected. The injection and the resultant increase of the permittivity at the interface were monitored with Spatial TDR (Figure 3-4).

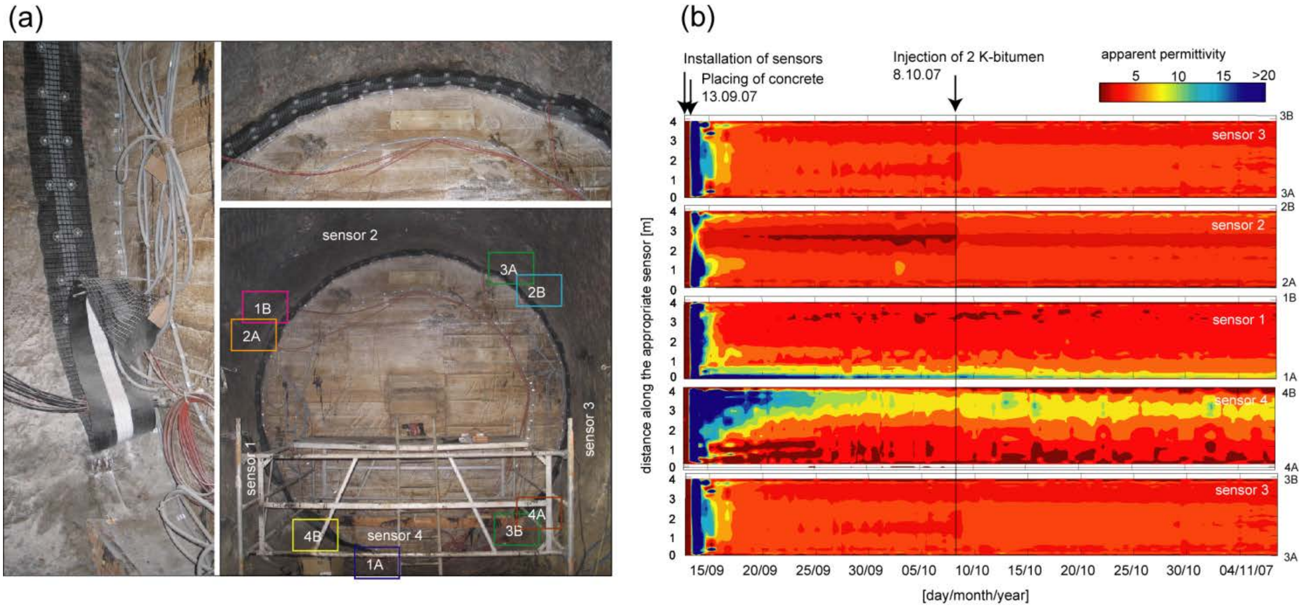


Figure 3-4: (a) Large scale (GV 1) in situ test with installed Spatial TDR sensors prior to placing the concrete. (b) Evolution of the permittivity distribution along the sensor.

4. Conclusion

The Spatial TDR technology provides a useful tool for high resolution temporal and spatial monitoring of the water content evolution in geological repositories. The passive TDR sensors are robust, long term stable and have a high sensitivity to moisture. However, the major challenge for the quantification of the absolute content of concentrated aqueous pore solutions is the consideration of the influence of the frequency dependent HF-EM material properties of the (i) pore solution, (ii) host rock, and (iii) sealing materials in the used moisture retrieval algorithm. In the current development state apparent permittivity distribution is retrieved based on a time domain inversion kernel assuming frequency independent material properties. This topic needs to be addressed in further research activities.

5. Acknowledgements

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References

[1] He, S., S.I. Kabanikhin, V.G. Romanov & S. Ström (1993) “Analysis of the Green’s function approach to one-dimensional inverse problems, Part I: One parameter reconstruction”, J. Math. Phys., 34, 5724-5746.

[2] He, S., V.G. Romanov & S. Ström (1993) “Analysis of the Green’s function approach to one-dimensional inverse problems, Part II: Simultaneous reconstruction of two parameters”, J. Math. Phys., 35, 2315-2335.

[3] Heimovaara, T. J., and W. Bouten (1990) “A computer-controlled 36-channel time domain reflectometry system for monitoring soil water contents”, Water Res. Res., 26, 2311 –2316.

[4] Heimovaara, Timo, J., Huisman, Johan, A., Vrugt, Jasper, A. and Bouten, W. (2004) “Obtaining the Spatial Distribution of Water Content along a TDR Probe Using the SCEM-UA Bayesian Inverse Modeling Scheme”, Vadose Zone J (3), pp. 1128-1145.

[5] Hübner, C. (1999) “Entwicklung hochfrequenter Messverfahren zur Boden- und Schneefeuchtebestimmung”, PhD thesis, Forschungszentrum Karlsruhe.

[6] Hübner, C. and Kupfer, K. “Modelling of electromagnetic wave propagation along transmission lines in inhomogeneous media", Measurement Science and Technology (18:4), 2007, pp. 1147-1154.

[7] Kaatze, U. (2007a) “Reference liquids for the calibration of dielectric sensors and measurement instruments”, Measurement Science & Technology, 18(4): 967–976.

[8] Kaatze, U. (2007b) “Non-conducting and conducting reference liquids for the calibration of dielectric measurement systems” In Proc. of the 7th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances – ISEMA, Hamamatsu, Japan, April 15–18, Ed. S. Okamura, Hamamatsu, Japan, pp. 3-11.

[9] Kupfer, K., Trinks, E. (2005) “Simulations and Experimental Investigations for Detection of Moisture Profiles Using Time Domain Reflectometry”, In Kupfer, K. (Ed.), Electromagnetic Aquametry, Springer, pp. 349-365.

[10] Kupfer, K.; Trinks, E.; Wagner, N.; Hübner, C. (2007) “TDR measurements and simulations in high lossy bentonite materials”, Meas. Sci. Technol. 18, pp. 1118-1136.

[11] Kupfer, K., Trinks, E., Wagner, N., Kuhne, M., Müller, B. (2009) “TDR-Measurements in Underground MgO-Concrete Barriers for Hazardous Waste in Salt Mines”, In Proc. of the 8th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances – ISEMA, Helsinki, June 1-5, Ed. P. Vainikainen, pp. 337-343.

[12] Küsetr, Y, Leiss, B., Schramm, M. (2010) “Structural characteristics of the halite fabric type ‘Kristallbrocken’ from the Zechstein Basin with regard to its development”, Int J Earth Sci (Geol Rundsch) (2010) 99:505–526.

[13] Küster, Y. (2011) “Bromide characteristics and deformation mechanisms of naturally deformed rock salt of the german Zechstein basin”, PhD-thesis, University Göttingen.

[14] Lundstedt J., M. Norgren, M. (2003) “Comparison between frequency domain and time domain methods for parameter reconstruction on non-uniform dispersive transmission lines”, Progress In Electromagnetics Research, Vol. 43, 1-37.

[15] Robinson, D. A., Jones, S. B., Wraith, J. M., Or, D., Friedman, S. P. (2003) “A Review of Advances in Dielectric and Electrical Conductivity Measurement in Soils Using TDR”, Vadose Zone J 2:444-475.

[16] Scheuermann, A., Hübner, C., Schlaeger, S., Wagner, N., Becker, R., Bieberstein, A. (2009) “Spatial-time domain reflectometry and its application for the measurement of water content distributions along flat ribbon cables in a full scale levee model”, Water Resour. Res., 45, W00D24 (1-15).

[17] Schlaeger, S. (2005) “A fast TDR-inversion technique for the reconstruction of spatial soil moisture content”, Hydrology and Earth System Sciences (9), 481-492.

[18] Schwartz, R. C., Evett, S. R., Pelletier, M. G. and Bell, J. M. (2009) “Complex permittivity model for time domain reflectometry soil water content sensing: I. theory”, Soil Sci Soc Am J, vol. 73, pp. 886–897.

[19] Topp, G. C., Davis, J. L. and Annan, A. (1980) “Electromagnetic determination of soil water content: Measurement in coaxial transmission lines”, Water Resour. Res.,16(3) 574-582.

[20] Wagner, N., E. Trinks, and K. Kupfer (2007a) “Determination of the spatial TDR-sensor characteristics in strong dispersive subsoil using 3D-FEM frequency domain simulations in combination with microwave dielectric spectroscopy”, Meas. Sci. Technol., 18, 1137– 1146

[21] Wagner, N. and Scheuermann, A. (2009) “On the relationship between matric potential and dielectric properties of organic free soils”, Can. Geotech. Jour., vol. 46, no. 10, pp. 1202–1215.

[22] Wagner, N., Emmerich, K., Bonitz, F. and Kupfer, K. (2011) “Experimental investigations on the frequency and temperature dependent dielectric material properties of soil”, IEEE Transactions on Geoscience and Remote Sensing (49:7), pp. 2518-2530.