Contract Number: 622177

Deliverable n°6.3

Modern2020 Final Conference Proceedings

Second International Conference on Monitoring in geological disposal of radioactive waste: Strategies, technologies, decision-making and public involvement

Work Package 6

Project Acronym	Modern2020
Project Title	Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal
Start date of project	01/06/2015
Duration	48 Months
Lead Beneficiary	Andra
Contributor(s)	Modern2020 Consortium
Contractual Delivery Date	31/05/2019
Actual Delivery Date	22/07/2019
Reporting period 3:	01/06/2018 – 31/05/2019
Version	1

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the partners of the Modern2020 project	
CO	Confidential, only for partners of the Modern2020 project and EC	

Foreword

Thank you for inviting the European Commission to contribute to the opening of the Second International Conference on Monitoring in Geological Disposal of Radioactive Waste, organised by the Euratom project Modern2020.

Instead of making a standard presentation with slides, I thought I would say a few words to reflect on the "raison d'être" of Monitoring and why the Euratom programme is supporting work on developing strategies and technologies in monitoring underground repositories.

Back in the 90' – Public and societal acceptance of final disposal of radioactive waste was already an issue. And I guess the idea of making a repository retrievable was conceived to help increase public acceptance. The Commission already started funding a project on this topic in 1992 and another one in 1997 (concerted action on the Retrievability of Long-Lived Radioactive Waste in deep underground repositories).

This topic has been addressed also by the OECD NEA in great details and Andra organised an International Workshop on the topic some 10 years ago. But if a National Programme decides to make its repository retrievable then the question is why would one decide to retrieve emplaced waste packages and based on which criteria.

This is a topic on the table at least at EC level since the early 2000's, with the first Euratom project called "Thematic Network on the role of monitoring in phased approach to geological disposal". On public acceptance, the report clearly acknowledged that "technical development must be accompanied by the development of social and political acceptance".

This was well understood at EC level and whenever a meaningful role is identified or proposed for the public and in particular directly concerned communities then the EC is asking for inclusion of public representatives in Research project.

Now, Modern2020 is the second major project on monitoring, funded by the Euratom programme.

The key questions asked by the Commission when calling for proposals on monitoring were and remain: Why (What strategy); What (Should be monitored from a scientific/technical point of view and from public expectation); How (What technology do we have) and When (At what stage of the repository programme should monitoring be implemented and for how long - only until closure or also post closure).

I understand that all the questions are complex issues.

Modern2020 being the second project in a row project, can we expect clear results and recommendations. Answers to these questions will be crucial to justify any continued support from Eurratom and also from the end-users i.e. in particular the Waste Agencies, and eventually from public and decision makers.

Christophe Davies

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EC project officer for the Modern2020 project and other projects in the field of radioactive waste management – geological disposal.

Acknowledgements

The Second International Conference on Monitoring in geological disposal of radioactive waste was held on 9-11 April in Paris, France and was organised by Andra, in the framework of the EC Modern2020 Project.

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1. Introduction

1.1 Background to the Modern2020 project

Long-lived radioactive waste must be safely contained and isolated for very long periods. Current programmes for its long-term management are focused on disposal in deep geological repositories. A successful implementation strategy for radioactive waste disposal should address both technical and societal needs, and monitoring aspects of the repository during its operational phase is considered beneficial in providing input to responding to these needs.

Monitoring contributes to the repository safety strategy and confidence in the performance of the disposal concept. It can contribute to verification of the performance of components of the disposal system and to the demonstration of compliance with regulatory requirements. Monitoring can provide an enhanced comprehension of the evolution of repository components and thus may facilitate disposal concept optimization. Monitoring can provide data and information that can contribute to public and stakeholder understanding of processes that could occur in an evolving repository; it can therefore assist in responding to concerns the public may have and can be used to build confidence in geological disposal.

The overall objective of Modern2020 is to provide the means for developing and implementing an effective and efficient repository operational monitoring programme that is driven by safety case needs and will take into account the requirements of specific national contexts and public stakeholder expectations, including those of local public stakeholders at (potential) disposal sites. Modern2020 participants cover national waste management programmes that have different waste inventories, host rocks, repository concepts and regulations

1.2 Objective of the International Conference

The objective of the second International Conference on Monitoring in geological disposal of radioactive waste, organised by the Modeern2020 project was twofold:

- to invite experts in the field of monitoring to contribute to and participate in discussions on how monitoring can inform the repository development process, how monitoring can assist dialogue with regulatory agencies, and how monitoring can contribute to confidence building in relation to the geological disposal of radioactive waste; and
- Present and discuss the results of Modern2020 project.

1.3 Scope of the International Conference

The scope of the conference was focused on monitoring activities to support evaluations of the performance of natural and engineered barriers in a geological repository as an approach to building confidence in the long-term post-closure safety case. The overall understanding of monitoring and its potential role in the disposal process will be presented and discussed in the light of expected monitoring needs, associated technical requirements, and the current state of the art regarding monitoring technologies and their future potential uses and limitations

The conference was organised around the following themes:

- **Monitoring technologies** with a focus on monitoring in underground environments, covering for example innovations in i) Monitoring sensor technology (low-power consumption or self-powered, energy harvesting & storage, wireless transmission, passive technologies, radiation tolerant etc.); ii) Long-term durability (performance beyond 10 years); iii) Fiber-optics; iv) Non-intrusive technologies seismic tomography, electrical resisitivity tomography;…); v) End-user procedures for performance qualification (radiation, long live…etc.).

- **Post closure safety and monitoring strategies** covering high level issues regarding the motivation for monitoring in relation to geological disposal facilities and other relevant monitoring programmes where concepts, procedures and strategies might be transferable. Topics of interest include specific objectives, parameter selection procedures, and strategies for implementation. A particular focus should be if/ how monitoring during the operational phase could build further confidence in long-term safety (i.e. following final closure of the facility). Theoretical as well as practical studies are of interest.

- **Long-term integrated monitoring** on the results of long-term (several decades) integrated monitoring programmes. Field experimental set-ups simulating different aspects of geological disposal are an essential tool in the development of geological disposal concepts. Such set-ups involve a lot of monitoring to provide the required data to the investigators. In addition to the use of monitoring data for the primary objectives of the set-up (e.g. model validation), these data also teach us about the sensor reliability in real conditions. In this topic, the focus is mainly on the other functions of monitoring that originally might not have been considered, such as: i) Long-term data management challenges; ii) Monitoring results and decision-making (e.g. adaptation of the experimental programme); iii) Enhancement of communication with external people (e.g. citizen stakeholders) by sharing monitoring data

- **Decision-making and response plans** on the use of monitoring data and information to support decision making during the repository operational phase. Topics of interest include planning for evaluating and responding to monitoring results, decision-making processes, and implementation of response plans. A particular focus s hould be if/how monitoring of the repository engineered barriers and nearby host rock could support decisions and actions taken during the operational phase. Theoretical as well as practical studies are of interest.

- **Citizen stakeholder participation** and strategies for engaging citizen stakeholders in the development of large infrastructure projects that involve monitoring. Contributions relating to experiences of how citizen stakeholder participation in other highly specialized research projects can influence the development of monitoring technology are also of interest.

Thirty-three oral presentations and thirty-one poster presentations were spread across nine 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 Structure of the Conference

The Modern2020 Final Conference was organized around ten sessions split into three days:

- Session 1: Opening Session
- Session 2: Key Conclusion from the Modern2020 Project
- Session 3: Monitoring Strategies
- Session 4: Poster session
- Session 5: Citizen Stakeholder Participation
- Session 6: Summaries of Monitoring Technologies
- Session 7a: Stakeholders Roundtable
- Session 7b: New Developments in Repository Monitoring Technologies
- Session 8: Long-term Integrated Monitoring System
- Session 9: Decision Making Process
- Session 10: Closing Session

1.5 Structure of the Proceedings

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

- An independent analysis and synthesis of the conclusions arising from Modern2020 project, based on the observations of independent experts in the geological disposal of radioactive waste and who acted as the "general rapporteur" for the conference.

- A detailed conference programme (Appendix A).

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

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

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

Section 2 of these proceedings was prepared by the independant rapporteurs. The discussion in this section reflects the rapporteurs' independent analysis, and does not necessarily reflect the opinions of the Modern2020 Project. Papers provided in Appendix C and Appendix D were prepared by the listed authors.

2. An Overview of the outcomes from the Modern2020 project

Piet Zuidema, Frank Hansen, Peter Simmons

2.1 Background and scope of report

The action 'Development and Demonstration of Monitoring Strategies and Technologies for Geological Repositories - Modern2020' is a European Commission (EC) project jointly funded by the Euratom research and training programme 2014-2018 and the project partners (waste management organizations (WMOs), TSOs, industry, other organisations). The project goals are defined within the Modern2020 agreement between the EC and the 29 project partners. The project is divided into six Work Packages (WPs). The work packages and their deliverables are listed in table 1.

As in several other EC co-funded projects, also the Modern2020 project decided to use rapporteurs for an evaluation of the work done within the project. This evaluation should include both the work package deliverables (as far as available at least as (final) drafts at time of the evaluation) and the participation at the project conference on April 9 to 11 2019 with the information from the submitted papers, the presentations by the project partners and the contributions from experts outside the Modern2020 project as well as from the discussions during the conference.

For the evaluation of Modern2020 a team of three rapporteurs was used. Frank Hansen had the task to evaluate WP2, WP3 and WP 4; Peter Simmons to evaluate WP5 and its interaction with the other WPs and Piet Zuidema to coordinate and integrate all the information into an overall evaluation, taking all WPs into account. The evaluation by the rapporteurs was done based on their individual expertise in past, present and future nuclear waste repository monitoring and its broader context. With their evaluation, however, it is not the intention that the rapporteurs ensure the outcomes or render a determination of the extent to which the project participants meet the intended goals according to the Modern2020 project agreement. This remains the responsibility of the project participants and the work package leaders.

In their summary, the rapporteurs come to the conclusion that the results of the Modern2020 products are commendable, in accord with the intent of the project and that all products together combine to render highly positive contributions to the international understanding of geological disposal monitoring and its implementation. This report summarizes the results of the work done by the rapporteurs. In preparation before the final conference, the rapporteurs consulted the available draft deliverables of the work packages and the draft conference papers, engaged in multiple videoconferences and had a face-to-face meeting with work package leaders on 8 April 2019. The rapporteurs participated in the final conference of the Modern2020 project and provided a combined oral assessment at the closing session of the conference. This report provides summary observations, professional opinions, and recommendations.

The report addresses the following three broad questions:

1. Has Modern2020 adequately addressed the issues described in the agreement of Modern2020?

2. What is the expected impact and the added value of the work done by Modern2020?
3. What is the status of monitoring now that Modern2020 has been completed?

After a short summary of the status of monitoring at the start of Modern2020 and the context of the work of Modern2020 (section 2), the report addresses these questions by going through the work packages 2, 3, 4 and 5 (section 3, 4, 5 and 6) and by providing some broader conclusions in section 7.

Table 1: Modern2020 project deliverables for WPs 2, 3, 4 and 5

WP2:	
D2.1	Decision-making Requirements, Monitoring Strategies and Methodologies for Screening the Preliminary Parameter List
D2.2	Monitoring Parameter Screening: Test Cases
D2.3	Decision Making, Performance Measures and Response Planning
WP3:	
D3.1	Synthesis report on relevant monitoring technologies for repository
D3.2	Wireless data transmission systems for repository monitoring
D3.3	Long term power supply sources for repository monitoring
D3.4	New sensors for repository monitoring
D3.5	Geophysical methods for repository monitoring
D3.6	Qualification methodology for repository monitoring equipment
WP4:	
D4.1	Full-scale In Situ Systems Test (Finland)
D4.2	HA Industrial Pilot Experiment (France)
D4.3	LTRBM (IRSN, France)
D4.4	FE and TEM results (Switzerland)
D4.5	Good practices for implementing a monitoring strategy
WP5	
D5.1	Monitoring the underground: specific challenges for engaging concerned stakeholders as compared to environmental monitoring
D5.2	Repository monitoring in the context of repository governance
D5.3	Engaging local citizen stakeholders in R&D at the European level: the case of monitoring for geological disposal

2.2 Starting point and context of Modern2020

2.2.1 Status of monitoring at the start and objectives of Modern2020

Modern2020 could build upon extensive information available on monitoring of geological repositories (geological disposal facilities, short: GDF). This information base was built up over the last 30 years by activities of international organisations and corresponding products (e.g. IAEA (1991, 2001, 2014), NEA (2014), EC (2000, 2004, 2013))and projects organised by these organisations as well as by national programmes including their bilateral and multilateral activities (e.g. activities in generic URLs). These and the more recent activities before the start of Modern2020 (e.g. the project MoDeRn by the EC as part of the 7th FP (EC (2013)) made it possible to focus the activities of Modern2020 on a few more detailed topics that were considered to be important and suitable for a collaborative project.

The Modern2020 project aims at providing the means for developing and implementing an effective and efficient repository operational monitoring programme related to the post-closure safety case, taking the requirements of specific national programmes into account. The work should allow the advanced European national radioactive waste disposal programmes to design monitoring systems suitable for deployment when repositories start operating in the next decade and support less developed programmes and other stakeholders by illustrating how the national context can be taken into account in designing dedicated monitoring programmes tailored to their national needs.

Most repository programs have come to acknowledge the indispensable role of stakeholder engagement. Looking back to earlier years in geologic disposal efforts, there existed an uneven partnership between social and technical issues. The vital and complex role of stakeholders has now assumed an enduring partnership in the process of acceptance and licensing of repositories in most national disposal programs world-wide. Modern2020 commits a substantial effort toward understanding stakeholders' role as well as their expectations. Successful stakeholder participation undoubtedly requires innovative means, which have been sought in Modern2020, and proves to be as important and demanding as any of the technical facets of repository science.

2.2.2 Context of the work performed within Modern2020 project

The technical scope of Modern2020 focuses on monitoring the engineered barrier system (EBS) and the surrounding host rock during operation of a GDF to provide additional information to continually assess the scientific basis that supports the licensing decision to start waste emplacement and to provide information that supports the post-closure safety case and the licensing basis for eventual closure of the GDF. Monitoring of performance concurrent with operations allows many years of data acquisition that informs decision making for the next steps in waste emplacement. Monitoring in concert with ongoing science and technology (not necessarily in the underground setting) could provide information leading to design changes or choices of modified disposal procedures. In some country contexts, advancing design bases and associated research is termed 'optimisation' and is used interchangeably here. Continuous surveillance is also highly relevant for a broad spectrum of stakeholders, particularly the local population at the site of a GDF. To accomplish both the scientific-technical aspects and address societal engagement, the Modern2020 project couples the primarily technical goals with a strong element of stakeholder involvement and social outreach, as reviewed in report section 3.4.

Most of the research and outreach activities reported within Modern2020 do not take place in operating repositories and therefore use large-scale demonstrations and other experiments as proxies for operational-period monitoring. Stakeholder involvement takes the form of face-to-face interaction of stakeholders with project participants, as well as taking part in an iterative, Delphi-style survey.

Virtually all the activities undertaken within Modern2020 can be directly linked to the repository operational phase. To place the Modern2020 activities into context, it should be recognized that an operating repository is obligated to execute a variety of monitoring regimes, such as:

- Monitoring to stay within the planned limits of repository operation ('operation window') to be in line with the technical requirements of emplacing the EBS and the waste and to ensure health, safety, and the protection of the environment
- Monitoring and surveillance to ensure security and safeguards
- Monitoring and testing to ensure preparedness to act in case of unexpected events or unexpected system behaviour, including emergency preparedness
- Testing and evaluation of design, construction, and operations including technical installations as input to the periodic review considering optimisation
- Monitoring and testing of relevant phenomena for post-closure safety and the corresponding licensing basis

Before undertaking Modern2020, multiple programs involving field testing, site characterization, conceptual designs, prospects of licensing, and assorted related activities gave rise to consensus opinions among nations on monitoring and related issues. Modern2020 built upon these matters of international concurrence as it defined the subject material embraced in its initiative. Consensus existed on a spectrum of ideas where operational-period monitoring becomes important for program advancement and fruition. For example, national contexts are comparable in the scope as well as in the inherent limitations placed upon monitoring. These issues were considered as a basis for the Modern2020 project and are briefly summarized below.

There is international agreement that monitoring and testing of relevant phenomena for post-closure safety involves a broad spectrum of issues that undoubtedly start very early in the program. These investigations may include regional monitoring (e.g. seismicity, high-precision geodesy) starting during site screening and site selection to establish long-term geological stability. Other site characterization monitoring might include host rock response to excavation, which in turn changes hydraulic heads and influences porewater chemistry. These measurements establish background evidence for host rock behaviour and properties. In addition, experiments and tests, as well as demonstrators, in generic URLs or on site at representative locations allow assessment of relevant parameters within the EBS and its immediate environment. This includes full-scale EBS demonstrations with subsequent dismantling and inspection and comparing inferred information obtained by monitoring to direct inspection of actual conditions. This deliberate process provides important validation of monitoring methods, as well as assessment of modelling capabilities.

It is broadly accepted that a key goal of monitoring is to inform decision making, perhaps involving optimisation steps and to evaluate and confirm the basis for the post-closure safety case. Practically speaking, 'decision making' occurs in a step-wise fashion as milestones are approached, debated, and decided. Examples may include preparation of progressive project licensing targets, such as site characterization, license application for construction, operation and eventually closure. Monitoring during operations (the subject of Modern2020) includes time-wise data acquisition, and its purpose is correspondingly attached to provide additional input to evaluating the scientific basis upon which operation of the repository is justified and predicated.

There is general consensus that a repository program must be able to adapt to changes, which are anticipated from technical advances of monitoring technology, with evolving design alternatives as part of optimisation, or other programmatic circumstances. As part of the corresponding decision-making, periodic updates of the safety-case - taking the results from monitoring and information from other sources into account - are an integral part of repository development. Results of monitoring or other information that call into question the adequacy of assumptions, data, or analyses of the post-closure safety case and the license application baseline information, will initiate additional examination and evaluation that may lead to some changes in the operational procedures or in the design; this may in an extreme case also involve retrieval of some or all waste packages.

It is recognized that planning and implementing a monitoring program involves a broad range of boundary conditions. One fundamental requirement asks that monitoring must not compromise the barrier system for post-closure safety. This forethought limits sensor placement and cable usage. One strategy to circumvent this challenge is the use of proxies for the EBS, if justified especially designed to be dismantled at the end of the observational period in an appropriate manner. Inadequate interferences with issues of relevance to operational safety are not acceptable.

The international repository community recognizes that measured quantities be relevant, representative, and transferable to the safety case. These considerations can be a particular challenge for heterogeneous host rock response. Additionally, monitoring test plans are required to quantify expectations and thereby identify trends or datapoints of observations that fall outside the range used in the licensing basis. Awareness of 'the unexpected' (issues not explicitly envisaged in the monitoring program) is essential. Implementation of an objective response process is supported by a transparent and vigilant management culture that also ensures the ability to adequately act on the results of monitoring, particularly when the unexpected happens.

Furthermore, there is broad consensus on the limitations that monitoring can provide to arguments of post-closure safety. It is acknowledged that monitoring cannot provide a direct proof of safety; the time-scales of the evolution of the repository barrier system in comparison to the duration of monitoring establish practical limits on what can be observed and achieved with monitoring.

There is also agreement that all these issues imply that a long-term repository monitoring program will most likely be combined with a science and technology program with elective research and development to ensure contemporary understanding of the advancing state-of-the-art. This will feed into periodic updates of the post-closure safety case that will also be used to evaluate whether there is room for improving design or operational procedures for specific elements of the GDF in those cases where the planned duration of the operation of the GDF is long (e.g. 50 years and more).

Finally, there is an overriding concurrence that involvement of and interaction with all relevant stakeholders is essential for the success of implementation. This is also true for the issue of monitoring.

To capture all the issues mentioned above, it is agreed that a systematic and traceable approach is needed to define a monitoring program that considers the specific nature of the disposal system at hand and the nation-specific boundary conditions and requirements. The documentation of the monitoring program is obligated to provide a traceable record of its development and be understandable to the relevant stakeholders and future generations.

Taking these broadly accepted issues into account, it was decided to focus Modern2020 on the themes mentioned in section 1 and as summarized below:

- Refine methods and guidance to develop monitoring programmes (with clearly defined design basis, monitoring strategies and decision-making procedures) that take the nation-specific boundary conditions into account (repository concept, national requirements, etc.) with the main emphasis on direct observation of the EBS and surrounding host rock during the operational phase
- Perform research and development of relevant monitoring technologies with a special focus on technologies where negative interferences with the system of engineered barriers (EBS) can be kept small
- Analyse the experience made with experiments and demonstrators with respect to monitoring implementation
- Refine means to effectively engage local citizen stakeholders early in the RD&D phase on monitoring

2.3 Rapporteurs' findings on the work packages

The reported findings on the respective work packages are based on information in the draft deliverables, presentations by work package leaders, by other presentations related to the topics of the respective work packages, and discussions during the conference. To some extent the findings are also influenced by the professional background and experience of the rapporteurs.

2.3.1 Monitoring Programme, Design Basis, Monitoring Strategies and Decision Making (WP2)

The development of a specific and implementable operational-period monitoring program to provide additional information to evaluate and confirm (or not) post-closure safety and the corresponding licensing basis and to provide input to decision-making comprises the following steps.

1. Identify phenomena and corresponding parameters important for post-closure safety.
2. Determine quantities that are related to the performance of these phenomena and parameters and that can be observed with available technology.

3. Design test plans for these quantities.
4. Determine trends and distributions of the expected evolution for the observed quantities.
5. Prepare the evaluation of observed quantities and the process to act for situations with significant deviations of observed quantitites from expected evolution.

Important phenomena and parameters for evaluating post-closure safety and compliance with regulatory requirements are identified via review of uncertainty and sensitivity results for repository performance and obtained as a part of the post-closure safety case and the underlying performance assessment (PA). PA provides uncertainty and sensitivity analysis results for a variety of factors (e.g. features, events and processes (FEPs) or safety functions), for a variety of locations (e.g., waste package, engineered barriers, host rock), and for a variety of calculated quantities (e.g., state parameters such as temperatures and pressures or concentrations, deformations, release rates, dose rates) at different points in time. These comprise the 'what' 'where' and 'when' questions, as written in Work Package 2. Examination of the sensitivity analysis results will show which of the uncertain PA inputs are most important in determining uncertainty in quantities that are fundamental to evaluating post-closure safety and compliance with applicable regulatory requirements. These inputs would be primary candidates for monitoring.

Then one must determine whether these candidates for monitoring can be observed with available technology. Down-selection of options involves potentially far-ranging assessment of the spectrum of available technologies and evaluation of their respective Technical Readiness Level (TRL). The TRL is then balanced against feasibility of implementation within the repository, such as accessibility or potential impact on and interference with safety barriers. Inherent to these assessments are strategic choices concerning how the measurement system will be deployed; either directly monitor the EBS and surrounding host rock or implement experiments as proxies for the EBS including scheduled (visual) investigations through dismantling.

All the activities up to here are described with the Modern2020 screening methodology, which comprises an update and refinement of the corresponding part of the MoDeRn workflow published in 2013. This workflow (or a variant of it) will most likely be used not only for the initial development of emerging monitoring programs but also for periodic re-evaluation.

Next, the distribution of expected evolution of the quantities to be observed must be derived (e.g. by modelling, taking variability and uncertainty into account). This may be challenging and require specific model development because this early phase with the HLW being fully contained in canisters is not always captured in the details of the PA models.

Then, the observation program starts with continuous comparison of observations with trends and distributions of expected evolution. This involves careful data evaluation, taking heterogeneity of the system into account and requires a clearly defined process to identify deviations, to categorize such deviations (e.g. misfunctioning of sensors; local effect of heterogeneity; system evolution not as expected, but of not related to any safety functions; relevant to one or more safety functions), with each of the categories requiring different types of action. The process for acting on significant deviations needs also careful planning.

The data management process also includes the abstraction of information for decision-making and/or for the next update of the safety case. Repository monitoring will lead to massive data volumes requiring a well-planned data management hierarchy for quality control, storage, dissemination, and knowledge preservation.

All the topics mentioned need to be included in the design of an observational and experimental program, which must be carefully recorded in a referenced and searchable database. Metadata associated with the documentation should explain the underlying design basis of the repository and the chosen monitoring strategy. These record systems will comprise large quantities of data, which must be transparent and understandable to external stakeholders and future generations. One means to ensure durability of a long-term record system is to exercise it regularly, as would be expected in a stepwise licensing and evaluation repository program. Advancing software and hardware will require migration to new hardware and applications. Maintenance of the repository database should occur as a formal exercise on a periodic basis and represents a challenge to long-term programs like nuclear waste repositories.

As part of WP2, seven test cases were conducted by project participants to identify which parameters should be monitored where and for what reason. The project participants largely followed implementing principles of the Modern2020 workflow, but at the same time, illustrated a significant breadth in approaches. This finding acknowledges that each program will tailor their individual monitoring program based on national policy, waste inventory, site geology, and disposal concept and modify the detailed approach to identify what to monitor and how to do it. The test cases illustrate a philosophical appreciation of parameter down-selection processes embracing the processes described in WP2 and integral to the Modern2020 workflow.

In conclusion, the content of Work Package 2 of Modern2020 is found to be comprehensive, mature and complete. WP2 acknowledges and provides examples of how monitoring strategies can be implemented and evaluated through deliverable reports in this work package. Variations from the point of view of the rapporteurs could include ancillary use of monitoring of proxies (mock-ups) of the disposal system that are not *integral* to the disposal activity. These add-ons to disposal activities would allow inspection of the proxies or monitoring of larger-scale rock response under conditions that would not compromise operations or long-term safety barriers.

From the point of view of the rapporteurs, some more in-depth mentioning e.g. of monitoring proxies or monitoring of larger-scale rock response as well as other monitoring targets would be valuable as these are also viable options to be used during operational monitoring in support of the safety case.

2.3.2 Research and development of relevant monitoring technologies (WP3)

WP3 involved application and evaluation of high-level novel technology to monitoring practices. In most cases, these investigations explored the forefront of technology and were being investigated within the scope of Modern2020 because this research is not being pursued elsewhere due to the unique challenges inherent in long-term nuclear-waste disposal monitoring. Specifically, WP3 investigated sensor technology and capabilities, longevity/survivability, data transmission, and power sources mainly focussed on their application for EBS monitoring with the boundary condition of non-accessibility and the requirements of wireless data transmission and long-term in situ power supply. As a complementary methodology geophysical tomography has also been further developed as this non-intrusive method is useful in combination with other monitoring technologies. WP3 represents an impressive effort. The concepts are well integrated and thought out, including robust sensors, wireless transmission options and long-term power sources. Several facets of WP3 are however not yet ready for deployment because the Technical Readiness Level is too low. There are, however, good prospects that future developments might be successful and may lead to their application. In this respect, the methodology to qualify new technology is very important. Interaction with industry has led to first concepts for qualification procedures but this still needs further work. The ideas on future work should be carefully evaluated as the next-generation of monitoring research is considered.

WP3 established the research agenda in this specialty area. We cannot fully perceive the ultimate monitoring deployment of emerging technology; the remaining development will surely require long-term and persistent research. Geologic repositories also have a long path ahead. Therefore, elements of WP3 are consistent with needs and applications of geologic repository monitoring. Remaining and currently identified challenges include both long-range and short-range wireless data transmission, integration and verification of the power sources, improvement of wireless energy transmission, the overall design of the monitoring systems with multiple wireless sensor nodes and the qualification of new technology. The vision developed in WP3 seems to identify a particularly promising area for investment. The EC and project partners sponsoring Modern2020 deserve due credit; if they did not have the vision to embark on this mission, who would?

In conclusion, Work Package 3 of Modern2020 is found to be comprehensive, innovative and is considered important for future work.

2.3.3 Demonstration of monitoring implementation at repository like conditions (WP4)

The Modern2020 WP4 examined four demonstrators:

- Virtual full-scale in situ systems test (Finland)
- High activity monitoring cell (France)
- Long-term rock and buffer monitoring combined with a test bench for wireless technology (France)
- Full-scale emplacement (Mt Terri URL) and test and evaluation of monitoring system (Grimsel URL) (CH)

These four demonstrators were extensively reported during the final Modern2020 conference. Lastly, a summary of good practices for implementing a monitoring strategy was discussed.

The four demonstrators are rather different in their nature and their status of completion. The full-scale experiment of Posiva is a virtual experiment aimed at monitoring the performance of the EBS with very limited or no direct measurements on elements of the EBS itself; most likely monitoring of the EBS will be related to proxies.

The experiment of Andra on a disposal cell in the URL in Bure is very close to the planned future monitoring but more densely equipped with instrumentation than would most likely be deployed for real monitoring. In contrast to the other experiments, much emphasis is also put on monitoring of the conditions and installations for retrieval of the waste packages to demonstrate readiness for reversal if needed (e.g. evolution of geometry of disposal tube).

One special feature of the experiment in Tournemire by IRSN is the test bench for evaluation of wireless technology. Preliminary results using the test bench are promising, different materials within the EBS installation were identifiable and changes in resistivity due to water injection in the EBS are expected to be noticeable. The methodology developed for the electrode installation in boreholes proved to be successful; however, electrode contact resistance remains a challenge. The test bench has been used for WP3 and remains available for future use.

The experiment of Nagra and its partners in the Mont Terri URL is related to the nearfield evolution and is very densely equipped with a variety of sensors. The experiment has several elements that closely resemble EBS monitoring. It has recently been implemented and the long-lasting observation phase is still in its early stages.

The experiment of Nagra and its partners in the Grimsel URL is related to the evaluation of the performance of different sensors made in conjunction with the dismantling of the EC FEBEX experiment managed by Enresa. This provided opportunity for detailed inspection of instruments and findings from monitoring and comparison to those predicted from modelling, such as hydration of bentonite.

In these experiments, many examples of sensor performance were obtained. Two test cases championed by Nagra in Mont Terri and Andra in Bure produced well-developed reports, which were available for review at the time of the final conference. These field tests were heavily instrumented and recorded thousands of readings of hundreds of sensors. This very act creates a challenge for handling, analysing and reporting 'big' data. How will the massive data files be transparently acquired, catalogued, analysed, and reported to stakeholders and regulators? How will records be preserved in an accessible data base for future use or reference? These activities included extensive efforts having direct relevance to future choices to be made for repository monitoring.

Finally, the role of large-scale experiments in URLs with respect to stakeholder engagement is essential and should be acknowledged. Actual demonstration of results that one can see, photograph, and feel goes well beyond abstractions from computer models. This is enormously influential with citizens and other stakeholders.

In conclusion, WP4, with the available experience from existing large-scale experiments in different URLs with sometimes very densely equipped monitoring instruments, provides an excellent pool of information of great value for the design of monitoring programmes related to the post-closure safety case.

2.3.4 Effectively engaging local citizen stakeholders in RD&D on monitoring for geological disposal (WP5)

The broad aim of WP5 was to put Responsible Research and Innovation (RRI) into practice in repository monitoring RD&D. RRI envisages that "societal actors […] work together during the whole research and innovation process in order to better align both the process and its outcomes with the values, needs and expectations of society" (Horizon 2020 website). Key principles are that RD&D should be anticipatory, inclusive, responsive, reflective, and sustainable. It is a relatively new approach to RD&D, so attempts to implement it necessarily involve 'learning by doing', something reflected in the work of WP5.

Involving stakeholders in the RD&D process is consistent with Responsible Research and Innovation. RRI has most often been applied to new and emerging technologies. Institutionalised policy commitments and legal frameworks for long-term management of HLW have closed down technological options to a focus on geological disposal which achieves passive safety, thereby establishing a path-dependent technological trajectory for related RD&D. Even though there are national differences in how that goal is framed (for example, in terms of the potential reversibility of the process or the retrievability of the waste), which have implications for monitoring RD&D, it establishes a boundary condition for the scope of citizen-stakeholder engagement, in that the goal of passive safety in a GDF is not open to negotiation.

Specific aims of WP5 were (a) to develop an engagement format that can be used to integrate local public stakeholders into national monitoring programmes, and (b) to draw general lessons on how to organise EU research projects to allow for meaningful engagement of concerned local citizen-stakeholders.

To establish a basis for addressing these aims, WP5 first establishes the significance of context for stakeholder engagement with monitoring. This emphasis on the importance of context was echoed in several conference presentations by external researchers, but the approach taken in WP5 is distinctive. It develops an analytical framework that identifies four interrelated dimensions of national context which shape the conditions for citizen-stakeholder involvement in RD&D on repository monitoring. These are: the national culture of public trust in governance and nuclear sector institutions; the national history of radioactive waste policy and management; the institutional arrangements for radioactive waste management and public stakeholder involvement; and the ways in which monitoring is framed and understood by the different stakeholders. This framework will be helpful for users comparing, or considering the replication of, engagement practices from another national context. The four contrasting cases analysed provide enough illustrative substance for the framework to be applied reflexively by those developing citizen engagement in national monitoring programmes.

Whatever the national context, the design and implementation of appropriate forms of repository monitoring must be responsive to societal expectations. Policy decisions and corresponding repository licensing requirements and formal process oversight are designed to ensure that societal expectations regarding long-term safety are met. However, WP5 shows that citizen-stakeholder engagement in monitoring RD&D can perform a variety of functions that complement institutional arrangements by supporting closer alignment between the design and implementation of a geological disposal programme, and the values and expectations of citizens and their communities. Although participating stakeholders felt that the technical aspects should be left to experts, they and the researchers also gave reasons why citizen involvement in RD&D has practical value. One function, acknowledged by all, is that involvement with monitoring RD&D enables citizens to become better informed about this aspect of the repository programme, and therefore better equipped to engage with the process. A second function is that participating stakeholders can act as bridges for their communities. A third function is that opening up RD&D to stakeholder scrutiny could, particularly in contexts where there is 'healthy mistrust' of institutions, meet a perceived need for 'civic surveillance' of the experts. A fourth function is to enable stakeholders to witness RD&D activities and to interact with researchers, something that has an impact, beyond that of assimilating information, on how some stakeholders relate to geological disposal. All these can be beneficial for relationships between (local) stakeholders and WMOs (and potentially, by extension, with regulators and policy-makers) and therefore for the development and implementation of a repository programme.

Citizen-stakeholders were most closely involved in WP2. The consensus workshops on responding to monitoring results provide one example of constructive participation. This work takes forward an important aspect of the monitoring programme, but also responds to a stakeholder concern voiced during the first MoDeRn project, in which participants questioned how WMOs would respond to data that were not consistent with the safety case. Integration was also evident in the principle incorporated in the Deliverable D2.1, *Repository Monitoring Strategies and Screening Methodologies*, which states that "Engagement with public stakeholders and regulators should take place *throughout* monitoring programme development and iteration".

The stakeholder guide on monitoring and participation (D5.2), seen in draft, promises to be of practical value. The involvement of citizen-stakeholders in its production should ensure its usefulness. The guide is expected not to prescribe how stakeholder engagement should be organized but to present a series of questions, illustrated with comments from stakeholders who took part in the Modern2020 project, for stakeholders to consider in the appropriate forum, whether a specially convened citizen group or an established local partnership. In this it diverges from the original aim to develop an engagement format for use in national contexts but, given the analysis in D5.1, this is appropriate and the guide that has been developed instead is adaptable to different contexts. The use of examples drawn from the four national case studies also helps to contextualise the information about geological disposal and monitoring, making it more concrete and more likely be useful to stakeholders newly engaging with this issue. The questions about stakeholder engagement in monitoring RD&D prompt local stakeholders to consider, in the context of national repository programmes policy, their detailed expectations of involvement with monitoring RD&D and the specific nature of their involvement. Making this explicit, even where stakeholders decide that they do not wish to have close involvement in technical RD&D, will be beneficial in that it will contribute to an open and transparent relationship between WMOs, regulators/TSOs, the policy-maker and local and other stakeholders.

In conclusion, WP5 has made substantive progress on stakeholder engagement with monitoring since the first MoDeRn project. WP5 demonstrates that citizen-stakeholders can be closely and constructively involved with the RD&D process, but also highlights potential challenges and limitations. The reports and stakeholder guide will help partners in national programmes to establish contextually-appropriate citizen-stakeholder engagement with monitoring RD&D.

2.4 Overall conclusions

2.4.1 Achievements within Modern2020 and information available from elsewhere: impact and end-users

The work done in all work packages is considered to be of high-quality leading to new developments, more insight and documented experience from impressive large-scale experiments. No fundamental changes in understanding have emerged, but the work performed is an important step forward towards implementation of the first European HLW repositories in the next decade. The work covers all the topics defined in the agreement of the Modern2020 project.

It is expected that the results of Modern2020 together with the experience and information available from activities from the last 30 years will allow the development of useful monitoring programmes that can be successfully implemented. However, this still needs substantial work by each of the disposal programmes to arrive at a monitoring programme tailored to its specific needs. The technology is available that allows monitoring related to post-closure safety. In the long term, refined and new technologies will become available, first for RD&D, later as qualified instruments for repository operational monitoring. This implies that sufficient flexibility should be maintained to adapt the monitoring programmes if this is deemed to be justified. It may be worthwhile to conduct the development of refined and new technologies (including the development of qualification procedures) through cooperative projects.

The very extensive experience in URL's with large-scale experiments delivers a useful pool of information that can be directly used to provide input to the detailed design a monitoring programme related to post-closure safety. It may be useful to maintain a platform to promote future information exchanges related to large-scale experiments in URLs.

The involvement of external stakeholders is essential for the success of a repository project. Early involvement of external stakeholders, especially those from the community hosting the repository project, allows a working relationship with mutual trust and understanding to be built. The engagement of stakeholders in RD&D allows both the stakeholders and the researchers to develop a better understanding of one another’s 'way of thinking' and thereby to improve the programme.

To summarize, through the results achieved in Modern2020 a considerable impact is expected on the member states of the EU that face the implementation of geological repositories, on the project partners of Modern2020 and the affiliated project partners of Modern2020 that work on repository projects, on the stakeholders in countries with repository projects, and on interested organisations worldwide, including those in the fields of science and technology. The end-users of Modern2020 are policy-makers with responsibility for governance issues (e.g. defining the scope of stakeholder involvement), implementers (WMOs) and their support organizations, regulators and their support organizations, other stakeholders, and the broad scientific and engineering community.

2.4.2 The role of the deliverables developed within the Modern2020 project for monitoring of a GDF: a broad view

Below, the topics of the individual work packages of Modern2020 are revisited and put in the broader context of their future use. This involves some subjective judgement by the rapporteurs.

Development of a monitoring programme to support the safety case and to provide information for decision-making during the operational phase

Based on the material available at the start of Modern2020 and on the achievements within Modern2020, a consensus has been reached on the broad approach to developing a monitoring programme to support the post-closure safety case and to provide input to decision-making. The documentation produced within Modern2020 provides an excellent background for each national repository programme to develop a detailed monitoring programme taking their boundary conditions into account. By considering the guidance provided, it will be possible to develop an operational monitoring programme that is transparent and understandable both for external stakeholders and people in the future. Looking back, it is clear that coming to an understanding on how to develop a monitoring programme was an evolutionary process with continuous refinements without any dramatic changes.

Current understanding shows that a GDF project should be sufficiently advanced to develop and implement a detailed operational monitoring programme that provides input to decision-making and is able to identify deviations from expected repository evolution and to perform an in-depth assessment of the meaning of such deviations for post-closure safety to implement appropriate actions if needed. Nevertheless, also for less advanced programmes it is important to develop first ideas on a monitoring programme to get an understanding of its meaning for the overall disposal programme.

The development of a operational monitoring programme should start with listing the questions that are in the broadest sense connected to acquiring additional information for the safety case and decision-making. From all these questions, only those related to aspects with significant relevance to post-closure safety and with significant uncertainty will be further evaluated. To ensure that the limitations of operational monitoring are adequately considered, the questions are then screened to see which of them can be reasonably addressed by operational monitoring of the nearfield alone (EBS and surrounding host rock), which of them can only be partially addressed by operational monitoring of the nearfield and benefit from other activities, and which ones are addressed by other means (large-scale experiments as proxies, RD&D activities, etc.) and then those, where collection of additional information is not feasible and the corresponding uncertainties will remain integral part of the post-closure safety case. The process of developing the operational monitoring programme must ensure the capability of the monitoring systems to provide unequivocal information and unambiguous relationships between observations and important performance metrics. Longevity and survival of monitoring technologies as well as instrument drift must be considered.

The process of developing the monitoring programme and its transparent documentation is a very useful platform for stakeholder interaction, creating the opportunity for (project-specific) 'face-to-face' discussions in the early phase of development. In this process, it is important to acknowledge that information for decision-making and to support the evaluation of post-closure safety comes in parallel from several other sources (e.g. RD&D programme), and that there are inherent limitations on what monitoring can contribute to support the post-closure safety case. In the documentation it should also be mentioned that monitoring in the broader sense is also conducted for other (safety-related) aspects, e.g. for compliance with operational limits for correct emplacement of the EBS and the waste, as well as ensuring safety and protection of the environment, safeguards & security, readiness of equipment for intervention, etc. Furthermore, it should be clear which aspects of the monitoring strategy are strongly influenced by the repository concept and national context. The documentation of the monitoring programme is obligated to provide a traceable record of its development and to be understandable to the relevant external stakeholders and to future generations.

Development of monitoring technology (WP3)

The technology needed for implementing a monitoring programme for the operational phase of a repository is available. However, taking the planned duration of monitoring into account (several 10's of years up to 100 years), proven technology is for some desired applications without direct access to the sensors not yet available for all aspects. This is due to the harsh in situ conditions (which for all components present challenges for material longevity (electronics, other material)), the limitations in accessibility of the monitoring locations, and the role of induced perturbations of the EBS by the installed monitoring equipment (and the products of its degradation). Limitations also exist for some of the equipment available due to the need for maintenance (including calibration), replacement, and or cabled connections for power supply and data transmission. In the case of using wireless technology, there are limitations for power supply and storage as well as data transmission (distance). With respect to the induced perturbations by the measuring devices, the advantage of the non-intrusive nature of geophysical tomography (with all its difficulties such as the need for calibration and the interference between parameters) has to be acknowledged. The research and development of relevant monitoring technologies within Modern2020 led to a better understanding of the potential of new technologies. Promising technologies have been identified which may be worthwhile to adapt and to further develop. First work on this led to very promising results. The work also pointed out the importance of developing suitable qualification procedures for the use of new technology, where advantage can be taken from the experience elsewhere. Although this development work is considered important and valuable for specific applications, it is not indispensable for the monitoring programmes of the GDF's that start operating in the next decade as these can rely upon existing technology, e.g. by using also proxies.

Evaluation of experience from ongoing large-scale experiments in URLs (WP4)

The evaluation of experience from large-scale experiments comparable to the near field of a repository in URLs is of direct relevance for the practical implementation of monitoring programmes. It provides a pool of information that is useful for developing a monitoring programme and provides evidence on what is 'routine' and where current difficulties are. This includes the comparison of performance of different sensors, experience with longevity of sensors and other technology (functioning, correct signal) and the development of a better understanding of reasons for failure as input for improving technology. It also provides input to the importance of redundancy and diversity. Practical experience with installing equipment, managing and evaluating data and drawing conclusions is very helpful. Especially the challenges with data handling and interpretation are informative for future work although one has to acknowledge that in some of the URL experiments instrumentation is more extensive than planned for actual repository monitoring. This more extensive instrumentation, however, allows comparison of technologies to support decisions on what to use for the real monitoring.

The large-scale experiments also provide practical experience with proxies that allow dismantling after completion of the experiments with the possibility of (visual) inspection as additional source of information that also allows the comparison with the information from monitoring. Such inspections are also a valuable source of information to potentially capture the 'unexpected' because a much broader spectrum of information can be made available (full spectrum of analytical tools) than by monitoring with sensors alone.

Early involvement of stakeholders in the development of methodologies and technologies (WP5)

Involvement of, interaction with and working together with external stakeholders is essential for the success of implementing a geological repository. In many countries, it is the task of the policy-maker to ensure that all relevant issues are addressed with sufficiently broad involvement of the different stakeholders. This is part of defining adequate governance of repository implementation and involves adhering to agreed rules for stakeholder engagement to ensure a good partnership. This requires, for example, that an awareness is developed that implementation of a geological repository is a task of national importance and thus requires broad support by all stakeholders.

One important pre-requisite for direct stakeholder engagement is 'common ground' on important issues. In relation to monitoring it is essential to agree on the endpoint of waste management for HLW and long-lived waste: a geological repository with passive barriers that provides the required levels of safety without the need for any monitoring. Before this endpoint is reached, however, monitoring will play an important role in all phases of implementation up to closure of the repository, with the possibility for adaptions of the implementation plans if needed and justified. 'Oversight' and (some) surveillance of the repository will continue for some time after closure, again with the possibility to act if needed. However, it is envisaged, and is generally accepted, that sooner or later oversight and surveillance will cease. A common understanding of this process can be arrived at through constructive interaction between policy-makers, WMOs, regulators, and public stakeholders.

The Modern2020 research identifies reasons why external stakeholders find it useful to engage with specialists and see how they work. The first step in such engagement is to learn to work together; this involves agreeing the process, and giving consideration to issues such as language, behaviour (e.g. vigilance and humility of the WMO), information flow (acknowledging the role of social media), etc. In this 'working together' there will not always be consensus; disagreement should however be acknowledged. It is important to start this process early in order to develop a mutual understanding before key decisions are taken. However, stakeholder interaction is a broad endeavour; although monitoring is very important for stakeholders, looking at monitoring in isolation is not sufficient. Because of the long duration of monitoring (and some other activities), transparent and understandable documentation on monitoring (and other issues) for external stakeholders and future generations is essential. Monitoring is expected to be a continuous learning process for everybody involved and thus, it is likely that the monitoring plan will be periodically updated, potentially combined with changes in the operational procedures or in the design. In some national contexts, policy-makers may consider institutionalizing this working relationship, as proposed during the conference, e.g. by establishing an independent monitoring body on which stakeholders are represented.

Finally, the differences between countries (repository concept, legal requirements, social dynamics (trust, constructive mistrust, etc.)) highlighted in the research, may also lead to differences in monitoring and in the degree of involvement of citizens and other public stakeholders in this process. Stakeholders may therefore find it worthwhile to have the opportunity to get a broader perspective on what happens elsewhere, which will enable them to better understand the differences. The Modern2020 documentation will provide tools to support that process.

2.4.3 Current status of monitoring

Based on the information available at the start of Modern2020, the work performed within Modern2020 and the experience related to monitoring available worldwide, the status of monitoring is judged to be good – for the advanced programmes in Europe the rapporteurs feel that the information exists to develop and implement the needed monitoring programmes for HLW repositories related to post-closure safety. This is also demonstrated by existing monitoring programmes for repositories in operation (e.g. WIPP and repositories in operation for L/ILW).

The detailed content of a monitoring programme related to post-closure monitoring is strongly dependent upon the specific boundary conditions for the repository looked at. That also means that depending upon the properties of a specific repository, implementation of a monitoring programme may require additional research and development. The development and implementation of a detailed monitoring programme is in general judged to be a complex endeavour and will require significant effort.

It is expected that further development of monitoring technology will take place. Thus, when implementing a monitoring programme, it may be advisable to maintain sufficient flexibility to allow adaption of the monitoring programme to take new technological possibilities into account.

2.4.4 Work to be done in finalising Modern2020 and possible future activities

As one of the last elements to finalise Modern2020 a synthesis report will be prepared. In the view of the rapporteurs this report provides a unique opportunity to make access to the large amount of information more easy, especially for those organisations and individuals that were not part of the Modern2020 project.

Furthermore, the rapporteurs recommend that the authors consider including one or more paragraphs in one of the initial chapters of the synthesis report that put the achievements of the Modern2020 into a broader context. Such a text could start with mentioning the need to take the overall programme in support of the post-closure safety case in account when defining the monitoring programme during the operational phase of a geological repository. Such an overall programme could include, in addition to the operational EBS monitoring (subject of Modern2020), monitoring of proxies or of larger scale rock response and would most likely also encompass a RD&D programme combined with monitoring of progress in the relevant areas of science and technology, the latter often performed in coordination and cooperation with other waste disposal programmes.

Although much progress has been made within Modern2020 and a significant level of maturity has been reached, additional work is needed within the individual national programmes. Some of the RD&D might also profit from cooperative activities. The rapporteurs recommend that, while Modern2020 is still active, the project partners start to investigate the possibilities for and usefulness of future coordinated activities. Related messages heard during conference include: clarify the needs for technology (sensors (which parameters), wireless data transmission (how far? how many data? how often?) to maintain momentum for further development; continue to use existing infrastructure in Tournemire to test new technologies and compare them with existing technology; continue to share experience with demonstrators, tests, etc. and implement platforms for information exchange on technical issues but potentially also on stakeholder involvement.

2.4.5 Final remarks

In closing, a few governing issues are reiterated here.

- Monitoring of the EBS and surrounding host rock in parallel to the emplacement of the waste (subject of Modern2020) is embedded in an overall programme that provides additional information in support of the post-closure safety case and the corresponding licensing base. This fact should be made visible to all relevant stakeholders to raise their awareness of the strengths & weaknesses and inherent limitations of direct EBS monitoring and of monitoring in general in this endeavour.
- Monitoring may thus include other observations than direct measurements of EBS parameters and will be associated with ongoing research and development.
- Monitoring in some form, begins during site characterization and becomes a formal commitment when it is included in licensing the repository.
- Monitoring to evaluate and confirm performance should focus on parameters that are demonstrably linked to relevant parts of the post-closure safety case and have some relationships to regulatory performance metrics, such as release and dose.
- Monitoring must be observable, interpretable, and actionable and requires procedures to assess observations with respect to expected ranges and to act in case of significant deviations.
- External stakeholder views on monitoring should be sought and they should have the opportunity for constructive interaction and involvement.

Modern2020 embraces these issues and has advanced international awareness of monitoring development and commitment, with the first issue raised, however, requiring some additional text in the planned synthesis report.

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[6] EC (2013): MoDeRn - 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, European Commission, Brussels

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3. List of Conference Papers – Oral Presentations

This section provides the list of the papers presented under each Topic. Associated full papers can be found in Appendix C. Full Conference Papers – Oral Presentations.

3.1 Session on Monitoring Strategies

The following oral presentations were delivered during Session on Monitoring Strategies:

- Monitoring During the Operational Period to Provide Further Confidence in the Post-Closure Safety Case: Strategies and Parameters by Matt White, Galson Sciences (UK).
- Derivation of Monitoring Parameters based on the Safety Assessment as a Contribution for a Monitoring Concept until Closure of a High-Level Waste GDF by Paul Smith, SAM Ltd. (UK).
- Monitoring Concept Development for a HLW Repository in Germany in Close Relation to the Safety Case by Michael Jobmann, BGETEC (DE).
- Cigéo Project: Definition of Monitoring Strategy and Application in link with major Milestones of Development (Licensing Application, Industrial Pilot phase…) by Sylvie Voinis, Andra (FR).
- Monitoring Programme for the Olkiluoto Repository, Finland by Tuomas Pere, Posiva (FI).
- SKB Monitoring Strategy by David Luterkort, SKB (SE).

Full papers associated to this session can be found in C.a – Session on Monitoring strategies.

3.2 Session on Citizen Stakeholder Participation

The following oral presentations were delivered during on Citizen Stakeholder Participation:

- Building Trust and Improving Safety? A Four-Nation Comparison of Public Participation in Monitoring of Nuclear Waste by Axelle Meyermans, Antwerpen University (BE).
- Trust, Mistrust and Citizen Vigilance in Radioactive Waste Management Policies: a Historical Analysis of Four Forerunner Countries by Markku Lehtonen, Universitat, Pompeu Fabra, Barcelona (SP).
- Nuclear Culture and Citizen Participation: Networked and distributed artworks by Ele Carpenter, Goldsmiths, University of London (UK).

- Learning from Socio-Technical Analogues for Monitoring of DGD. A Comparative Perspective on Wind Power, Fracking, Carbon Capture and Storage (CCS) and Deep Geological Nuclear Waste Disposal by Dörte Themann, Freie Universität, Berlin (DE).

Full papers associated to this session can be found in C.b – Session on Citizen Stakeholder Participation.

3.3 Session on Summaries of Monitoring Technologies

The following oral presentations were delivered during the Session on Monitoring Technologies:

- Current State of the Art of Wireless Data Transmission Systems for Repository Monitoring by Thomas Schröder, NRG (NL).

- Electric Power Sourcing of Wireless Repository Monitoring Sensors by Esko Strömmer, VTT (FI).

- Overview of Optical Fiber Technologies for Radioactive Waste Disposal Site Monitoring by Patrice Mégret, University of Mons (BE).

- Geophysical Monitoring of High-Level Radioactive Waste Repositories by Hansruedi Maurer, ETH Zurich (CH).

- Methodology for Qualifying the Monitoring Components by Jean-Michel Matray, IRSN (FR).

Full papers associated to this session can be found in C.c – Session on Summaries of Monitoring Technologies.

3.4 Parallel Session on New Developments in Repository Monitoring Technologies

The following oral presentations were delivered during the Session on New Developments in Repository Monitoring Technologies:

- Application of Ultrasonic Techniques for Quality Assurance of Salt Concrete Engineered Barriers: Shape, Cracks and Delamination by Ernst Niederleithinger, BAM (DE).

- The Long Term Rock Buffer Monitoring in Situ Test, Assessing under Realistic Conditions the Performances of Monitoring Devices Developed in Modern2020 Pierre Dick, IRSN (FR).

- Non-intrusive Geo-electrical ERT Monitoring of High-Level Radioactive Waste Experiments in Tournemire URL Bruna De Carvalho, University of Strathclyde (UK).

- What We Can Learn from a Full-Scale Demonstration Experiment after 4 Years of DTS Monitoring – the FE Experiment Tobias Vogt, NAGRA (CH).

- Niches of Fibreoptic Sensing: From LargeStrain Applications to Acoustic Emission Monitoring by Pavol Stajanca, BAM (DE).

Full papers associated to this session can be found in C.d – Parallel Session on New Developments in Repository Monitoring Technologies.

3.5 Session on Long-term Integrated Monitoring System

The following oral presentations were delivered during the Session on Long-term Integrated Monitoring System:

- Monitoring the Full Scale Emplacement Experiment (FEBEX) over 18 Years: Lessons Learned for Future Repository Monitoring Florian Kober, NAGRA (CH).

- Lessons Learnt after more than 7 Years of Monitoring the Full-Scale Emplacement Experiment at the Mont Terri URL Herwig Müller, NAGRA (CH).

- Feedback from more than 20 years of Monitoring of Underground Research Laboratory, Site and Experiments Emilia Huret, Andra (FR).

- Difficulties of Monitoring in the Rock Formations Vsevolod Igin, NORAO (RU).

- Rock Mechanics Monitoring Programme at Olkiluoto Repository Site, Finland Sophie Haapalehto, Posiva (FI).

Full papers associated to this session can be found in C.e – Session on Long-term Integrated Monitoring System.

3.6 Session on Decision Making Process

The following oral presentations were delivered during the Session Decision Making Process:

- Planning for Evaluating and Responding to Monitoring Results, and Use of Monitoring in Decision Making by Matt White, Galson Sciences (UK).

- The IAEA Prospective on Use of the Monitoring Programmes in the Safe Development of Geological Disposal Facilities for Radioactive Waste Gerard Bruno, AIEA.

- Passive Trust or Active Mistrust? The Finnish and French Approaches to Monitoring of Radioactive Waste Repositories by Matti Kojo and , Tampere University (FI)and Markku Lehtonen, Universitat, Pompeu Fabra, Barcelona (SP).

- Do We Need a Nuclear Steward? Monitoring as Task for a Long-Term Governance Institution by Peter Hocke, Karlsruhe Institute of Technology (DE).

- Community Modelling making Sense of Monitoring Data by Catharina Landström, Chalmers University of Technology (SE).

- Strategic Monitoring - a Proposal for the Institutional Surveillance of Complex and Long-term Disposal Systems by Thomas Flüeler, ETH Zurich (CH).

Full papers associated to this session can be found in C.f – Session on Decision Making Process.

3.7 Closing session

The following oral presentations were delivered during the Closing Session:

- Regulatory perspective about monitoring dedicated to geological disposal facilities for radioactive waste in Finland by Jaakko Leino, STUK (FI).

- Regulatory Perspective about Monitoring dedicated to Geological Disposal Facilities for Radioactive Waste in Switzerland Thomas van Stiphout, ENSI (CH).

Full papers associated to this session can be found in C.g – Closing Session.

4. List of Conference Papers – Poster Presentations

This section provides the list of the papers presented for a poster presentation under each Topic. Associated full papers can be found in Appendix D. Full Conference Papers – Poster Presentations.

4.1 Topic on Monitoring Technologies

The following poster presentations were delivered under Topic 1 Monitoring Technologies:

- Development of thermocouple psychrometers for water content measurement by Héctor Abos, Arquimea (ES).
- Techniques for non-contact displacement measurement by Mauro Cappelli, ENEA (IT).
- Range-resolved optical remote sensing of hydrogen gas by Raman Lidar by Agnès Dolfi-Bouteyre and Nicolas Cezard, ONERA (FR).
- Development of a wireless relay system for monitoring of geological disposal using low-frequency electromagnetic waves by Jiro Eto, RWMC (JP).
- Estimation of the initial dry density distribution of granulated bentonite mixtures in the Full-scale Emplacement experiment by means of active distributed temperature sensing by Berrak Firat Lüthi, NAGRA (CH).
- Hybrid seismic surveying for detailed characterization of the shallow and intermediate depths subsurface by Walter Frei, GeoExpert AG (CH).
- Toward long-term hydrogen monitoring with specialty optical fibers by Georges Humbert, XLIM Research Institute (FR).
- Online monitoring system for measurement concentration changes of underground water in fracture by Jaroslav Kotowski, Research Centre Řež (CZ).
- Pore-Water Pressure Monitoring by Minipiezometers by Michael Kröhn, GRS GmbH (DE).
- Qualifying distributed strain sensing systems based on optical fiber for the monitoring of radioactive waste repository by Arianna Piccolo, Andra (FR).
- Xe radioisotopes measurement as monitoring tool for transuranic radioactive wastes by Antonietta Rizzo, ENEA (IT).

- Calibration of heated fiber-optic cable for monitoring dry density and water content in granulated bentonite mixture in the Full-scale Emplacement experiment by Toshiro Sakaki, NAGRA (CH).

- Demonstration of a two-staged, wireless transmission chain out of the LTRBM borehole to the surface of the Tournemire plateau by Thomas Schröder, NRG (NL).

- Long distance data transmission through the underground: lessons learned from two demonstrators, by Thomas Schröder, NRG (NL).

- Wireless energy transmission through electrical conductive media by Thomas Schröder, NRG (NL).

- Thermal energy harvesting from High-Level Waste by Thomas Schröder, NRG (NL).

- Wireless energy transfer with data transfer add-on through low-conductivity host rocks by Esko Strömmer, VTT (FI).

- SmartCell – Pressure and Humidity measurementfor EBS by Jiri Svoboda, CTU (CZ).

Full papers associated to this session can be found in D.a – Session on Monitoring Technologies.

4.2 Topic on Citizen Stakeholder Participation

The following poster presentation was delivered under Topic 2 Citizen Stakeholder Participation:

- Nuclear Culture and Citizen Participation: Networked and distributed artworks by Ele Carpenter, Goldsmiths University of London (UK).

Full paper associated to this session can be found in D.b – Session on Citizen Stakeholder Participation.

4.3 Topic on Post Closure Safety Cases and Monitoring Strategies

The following poster presentation was delivered under Topic 3 Post Closure Safety Cases and Monitoring Strategies:

- Screening of monitoring parameters for the Dutch OPERA disposal concept by Jaap Hart, NRG (NL).

- Qualification of diameter change monitoring system of inaccessible steel tube by Radwan Farhoud, Andra (FR).

Full papers associated to this session can be found in D.c – Session on Post Closure Safety Cases and Monitoring Strategies.

4.4 Topic on Long-term Integrated Monitoring Programmes

The following poster presentations were delivered under Topic 5 Long-term Integrated Monitoring Programmes:

- Hydrogeological Monitoring in Long and Deep Tunnel Projects – A Perspective of Austrian Base Tunnels by Giorgio Höfer-Öllinger; Geoconsult ZT Gmbh (AU).
- Multi-Parametric Devices with Innovative Solid Electrodes for Long-Term Monitoring of pH, Redox-Potential and Conductivity of the actual pore water of COx formation in a future Nuclear Waste Repository by Ioannis Ignatiadis, BRGM (FR).
- 3D Overarching Scientific Information System for the FE experiment by Robert Yeatman, Enviro-Sys.com (CH).

5. Stakeholders Roundtable

Chair of the roundtable:	Ele Carpenter, Reader in Curating at Goldsmiths University of London
Participants in the roundtable:	Vesa Jalonen, Citizen stakeholder (FIN)
	Marie Berggren, Citizen stakeholder (SE)
	Anne Bergmans, Social scientist (WP5)
	Johan Bertrand, Scientist of NWMO (Modern2020)
	Michael Egan, Regulator (SSM)
	Christophe Depaus, Scientist of NWMO
	Andy Weir, Artist working on radioactive waste

As Modern2020 Work Package 5 focuses on the involvement of citizen stakeholders and dialogue between different perspectives on repository monitoring and nuclear waste management, the Modern2020 Final Conference provided us with the opportunity of organizing a roundtable discussion with various stakeholders to further deepen out these topics. Nine panel lists representing different positions within nuclear waste management were invited to discuss a variety of questions related to embedding knowledge of underground sites within cultures and communities. These participants included artists working on geological disposal of nuclear waste, along with citizen stakeholders, a social scientist and representatives of NWMOs and a regulator. The discussion was chaired by curator Ele Carpenter to consider how the panel works differently to make public issues of site marking and monitoring from the visual arts to local community engagement.

The main topics through which we sought to discuss different stakeholder perspectives on monitoring in geological disposal were transparency and vigilance (including knowledge preservation as well as the challenges of deep time and intergenerational communication). Thus, the main questions asked during the roundtable were: ‘How to make the underground known: through data, over time and in the present? Who should be watching?’ The participants discussed these topics as well as a set of sub-questions in a dynamic way with room for the audience to intervene with comments and questions.

During the roundtable discussion various topics were addressed. The participants discussed why monitoring is important to them and how it can and should work for them in terms of transparency and vigilance. This led to a discussion on how monitoring can, on the one hand, bring about humility in repository governance by opening up debate on uncertainty and long term vigilance, and, on the other hand, might contain certain elements of hubris as it assumes that memory transfer over different generations is possible. In this regards, we could also interpret passive safety as humility since it shows that we cannot solve all the involved remaining problems of repository governance. This argument was further discussed by other participants who stated that monitoring could rather be viewed as a research undertaking instead of a technological solution aimed at solving all remaining problems. Interpreted as a research activity, the focus of monitoring turns towards development, improvement and curiosity and not on the aim of constructing a ready-made technological solution. Monitoring as a tool for memory preservation and transfer was also addressed during the roundtable. Here, it became clear that we should not have too high expectations of monitoring in this regard and that we should first open up a discussion on why and how much we would like to remember from the repository process.

Appendix A. Detailed Conference Programme

Development and Demonstration of monitoring strategies and technologies for geological disposal

2nd International Conference on Monitoring in Geological Disposal of Radioactive Waste

9-11 April 2019

Cité Universitaire (Espace Adenauer), 17 boulevard Jourdan, 75014 Paris, France

AGENDA

DAY 1 – 9 April 2019		
Session 1: Opening Session (Chair: Johan Bertrand)		
09:30	Arrival & Registration	
10:00	Welcome & Opening ceremony	Frédéric Plas, Andra (FR)
10:15	EURATOM Programme	Christophe Davies, DG-RTD, EC
10:30	Overview of the Modern2020 Project	Johan Bertrand, Andra (FR)
Session 2: Key Conclusion from the Modern2020 Project (Chair: Johan Bertrand)		
10:50	Monitoring Strategies (WP2) - Approach and Key Messages	Mansueto Morosini, SKB (SE)
11:10	Monitoring Technologies (WP3) - Approach and Key Messages	José Luis García-Siñeriz, Amberg (SP)
11:35	Demonstration (WP4) - Approach and Key Messages	Jan Verstricht, Euridice GIE (BE)
11:55	Engaging Local Citizens (WP5) - Approach and Key Messages	Anne Bergmans, Antwerpen University (BE)
12:15	Discussion	All
12:30	Lunch (90 minutes)	
Session 3: Monitoring Strategies (Chair: Bernd Frieg)		
14:00	Monitoring During the Operational Period to Provide Further Confidence in the Post-Closure Safety Case: Strategies and Parameters	Matt White, Galson Sciences (UK)
14:20	Derivation of Monitoring Parameters based on the Safety Assessment as a Contribution for a Monitoring Concept until Closure of a High-Level Waste GDF	Paul Smith, SAM Ltd. (UK)
14:40	Monitoring Concept Development for a HLW Repository in Germany in Close Relation to the Safety Case	Michael Jobmann, BGETEC (DE)
15:00	Cigéo Project: Definition of Monitoring Strategy and Application in link with major Milestones of Development (Licensing Application, Industrial Pilot phase…)	Sylvie Voinis, Andra (FR)
15:20	Break (30 minutes)	
15:50	Monitoring Programme for the Olkiluoto Repository, Finland	Tuomas Pere, Posiva (FI)
16:10	SKB Monitoring Strategy	David Luterkort, SKB (SE)
16:30	Discussion	All
17:00	Break (30 minutes)	
Session 4: Poster session		
17:30	Poster Session	
19:00	Cocktail	

DAY 2 – 10 April 2019

Time	Session 5: Citizen Stakeholder Participation (Chair: Anne Bergmans)	Speaker
09:00	Building Trust and Improving Safety? A Four-Nation Comparison of Public Participation in Monitoring of Nuclear Waste	Axelle Meyermans, Antwerpen University (BE)
09:20	Trust, Mistrust and Citizen Vigilance in Radioactive Waste Management Policies: a Historical Analysis of Four Forerunner Countries	Markku Lehtonen, Universitat Pompeu Fabra, Barcelona (SP)
09:40	Nuclear Culture and Citizen Participation: Networked and distributed artworks	Ele Carpenter, Goldsmiths University of London (UK)
10:00	Learning from Socio-Technical Analogues for Monitoring of DGD. A Comparative Perspective on Wind Power, Fracking, Carbon Capture and Storage (CCS) and Deep Geological Nuclear Waste Disposal	Dörte Themann, Freie Universität Berlin (DE)
10:20	Discussion	All
10:35	Break (25 minutes)	

Time	Session 6: Summaries of Monitoring Technologies (Chair: Juan Carlos Mayor)	Speaker
11:00	Current State of the Art of Wireless Data Transmission Systems for Repository Monitoring	Thomas Schröder, NRG (NL)
11:15	Electric Power Sourcing of Wireless Repository Monitoring Sensors	Esko Strömmer, VTT (FI)
11:30	Overview of Optical Fiber Technologies for Radioactive Waste Disposal Site Monitoring	Patrice Mégret, University of Mons(BE)
11:45	Geophysical Monitoring of High-Level Radioactive Waste Repositories	Hansruedi Maurer, ETH Zurich (CH)
12:00	Methodology for Qualifying the Monitoring Components	Jean-Michel Matray, IRSN (FR)
12:15	Discussion	All
12:30	Lunch (90 minutes)	

Time	Session 7a: Stakeholders Roundtable (Chair: Ele Carpenter)	Time	Session 7b: New Developments in Repository Monitoring Technologies (Chair: José Luis García-Siñeriz)	Speaker
14:00	How to Reveal the Underground: through Data, over Time and in the Present?	14:00	Application of Ultrasonic Techniques for Quality Assurance of Salt Concrete Engineered Barriers: Shape, Cracks and Delamination	Ernst Niederleithinger, BAM (DE)
		14:20	The Long Term Rock Buffer Monitoring in Situ Test, Assessing under Realistic Conditions the Performances of Monitoring Devices Developed in Modern2020	Pierre Dick, IRSN (FR)
		14:40	Non-intrusive Geo-electrical ERT Monitoring of High-Level Radioactive Waste Experiments in Tournemire URL	Bruna De Carvalho, University of Strathclyde (UK)
		15:00	What We Can Learn from a Full-Scale Demonstration Experiment after 4 Years of DTS Monitoring – the FE Experiment	Tobias Vogt, NAGRA (CH)
		15:20	Niches of Fibreoptic Sensing: From Large-Strain Applications to Acoustic Emission Monitoring	Pavol Stajanca, BAM (DE)
15:40	Break (30 minutes)			

Time	Session 8: Long-term Integrated Monitoring System (Chair: Jan Verstricht)	Speaker
16:10	Monitoring the Full Scale Emplacement Experiment (FEBEX) over 18 Years: Lessons Learned for Future Repository Monitoring	Florian Kober, NAGRA (CH)
16:30	Lessons Learnt after more than 7 Years of Monitoring the Full-Scale Emplacement Experiment at the Mont Terri URL	Herwig Müller, NAGRA (CH)
16:50	Feedback from more than 20 years of Monitoring of Underground Research Laboratory, Site and Experiments	Emilia Huret, Andra (FR)
17:10	Difficulties of Monitoring in the Rock Formations	Vsevolod Igin, NORAO (RU)
17:30	Rock Mechanics Monitoring Programme at Olkiluoto Repository Site, Finland	Sophie Haapalehto, Posiva (FI)
17:50	Discussion	All
18:10	End of Day 2	

DAY 3 – 11 April 2019		
Session 9: Decision Making Process (Chair: Mansueto Morosini)		
09:00	**Planning for Evaluating and Responding to Monitoring Results, and Use of Monitoring in Decision Making**	Matt White, Galson Sciences (UK)
09:20	**The IAEA Prospective on Use of the Monitoring Programmes in the Safe Development of Geological Disposal Facilities for Radioactive Waste**	Gerard Bruno, AIEA (AU)
09:40	**Passive Trust or Active Mistrust? The Finnish and French Approaches to Monitoring of Radioactive Waste Repositories**	Matti Kojo, Tampere University (FI)
10:00	**Do We Need a Nuclear Steward? Monitoring as Task for a Long-Term Governance Institution**	Peter Hocke, Karlsruhe Institute of Technology (DE)
10:20	**Community Modelling making Sense of Monitoring Data**	Catharina Landström, Chalmers University of Technology (SE)
10:40	**Strategic Monitoring - a Proposal for the Institutional Surveillance of Complex and Long-term Disposal Systems**	Thomas Flüeler, ETH Zurich (CH)
11:00	**Discussion**	All
11:20	Break (30 minutes)	
Session 10: Closing Session (Chair: Johan Bertrand)		
11:50	**Regulatory perspective about monitoring dedicated to geological disposal facilities for radioactive waste in Finland**	Jaakko Leino, STUK (FI)
12:05	**Regulatory Perspective about Monitoring dedicated to Geological Disposal Facilities for Radioactive Waste in Switzerland**	Thomas van Stiphout, ENSI (CH)
12:20	**Rapporteur on Strategies and Technologies**	Frank Hansen, independent (US)
12:35	**Rapporteur on Stakeholder Involvement**	Peter Simmons, University of East Anglia (UK)
12:50	**Rapporteur on the Overall Modern2020 Conference**	Piet Zuidema, Zuidema Consult GmbH (CH)
13:20	**Closure of the Meeting**	Johan Bertrand, Andra (FR)
13:30	**Lunch - End of Day 3**	

Appendix B. List of Participants

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Appendix C. Full Conference Papers – Oral Presentations

C.a – Session on Monitoring strategies

Monitoring During the Operational Period to Provide further Confidence in the Post-Closure Safety Case: Strategies and Parameters

Matt White[1], Jo Farrow[1] & Mansueto Morosini[2]

[1] Galson Sciences Limited, UK
[2] SKB, Sweden

1. Summary

This paper provides a summary of the development of detailed methodologies for screening safety cases to identify needs-driven repository monitoring strategies. It considers the role of monitoring in the post-closure safety case, high-level monitoring programme strategies, and a generic methodology for screening lists of parameters to identify parameters to be monitored during the operational period in order to build further confidence in the post-closure safety case.

2. Introduction

Long-term safety following repository closure is demonstrated through multiple lines of reasoning, including conduct of a safety assessment and comparison of the results with safety criteria. Residual uncertainties in the post-closure performance of a repository will be managed in the safety case, both by applying specific approaches to the safety assessment and through other means. Uncertainty can be addressed through the design of the repository, and does not rely on monitoring. Furthermore, the development of design requirements, and demonstration of compliance with these through limits, controls (including quality control) and conditions, is used to verify that the as-built repository is consistent with the safety case.

Monitoring has the potential to affect the passive safety of the disposal system by providing pathways for groundwater flow and radionuclide migration, or by introducing materials that could negatively affect the post-closure performance of the system. However, the repository will be partially open and accessible for monitoring for several decades during the operational period and this provides an opportunity for gathering information on the performance of the disposal system following emplacement of the waste and the engineered barrier system (EBS). Consistent with stepwise implementation of geological disposal, periodic updates to the safety case will be produced during the operational period, and information from monitoring could be one input to these periodic updates. In certain cases, information from repository monitoring could be compared with the arguments used to build the safety case to check whether the parameters of the repository system are evolving in a domain that is consistent with the safety case. The results from such monitoring could also form part of an ongoing stakeholder engagement plan and form part of stakeholder dialogue during repository operation.

3. Monitoring Programme Strategies

Monitoring programmes must be developed with respect to the relevant national context. This includes the programme-specific legislation and regulatory guidance, the nature of the waste, the geological environment, the disposal concept upon which the repository design is based, and consideration of stakeholder views. A monitoring programme might adopt different strategies dependent upon this national context, which will include consideration of where, what, when and how to monitor:

- Where: the extent to which the programme would be undertaken in the main repository (in situ), either with or without retrieval of monitored components at the end of the monitoring period; in a pilot facility; or in an on-site underground rock characterisation facility.
- What: the extent to which the programme would focus on waste packages (and surrounding EBS and near-field rock); dummy packages (and surrounding EBS and near-field rock); specific elements of the EBS (e.g. small-scale batch tests); the geological barrier (near-field rock and far-field rock); and the biosphere.
- When: the interplay between monitoring prior to operations and during construction (e.g. to establish baseline conditions); monitoring during operations; monitoring during closure; and, monitoring after closure (including the different elements of the repository system that would be monitored at each stage.
- How: The technologies that could be used for such monitoring.

4. Safety Assessment and the Role of Monitoring

Safety assessment is founded on an understanding of the performance of the barriers with respect to the safety functions they are designed to meet, but does not predict the detailed evolution of the disposal system. In addition, safety assessment calculations are typically undertaken with conceptual and mathematical models that combine multiple processes, making pessimistic assumptions, which typically do not address all sub-system behaviour and hence are usually not good for comparing with monitoring results. Therefore, care is needed when comparing monitoring results with quantitative safety assessments. To demonstrate system understanding, and thereby to support further confidence building, a predictive model of the performance of the repository would be required. This predictive model must include parameters that are monitored during the operational period to ensure there is an expectation against which to compare the monitoring results.

For some disposal concepts, building further confidence in the understanding of repository-derived impacts on the rock mass (e.g. recovery of groundwater pressures in response to backfilling), might contribute to ongoing licensing and periodic review. Although such monitoring might not provide direct information on post-closure safety, it might provide an opportunity for a waste management organisation to build further confidence in its capability to model phenomena over longer periods, and thereby also to demonstrate organisational competency.

In addition to monitoring to build further confidence in the post-closure safety case, repository monitoring may be required to address regulator and other stakeholder concerns. At this early stage in the development of repository monitoring programmes it is not possible to define these concerns, but potential examples can be identified. For example, treatment of uncertainty in the safety case may be difficult to communicate to some stakeholders, and there may be a concern that the safety case has missed a feature, event or process (or made an error) that is significant to safety. There may be a concern that the disposal system is not implemented as assumed in the safety case, for example because quality control is not comprehensive enough to be sure that no elements are faulty and nothing unexpected has happened during implementation. For some disposal concepts, if these concerns arise, they will have to dealt with through other parts of the safety case as no amount of repository monitoring during the operational period would be able to demonstrate safety. This is the case where changes to barriers providing safety functions will only occur over much longer periods and/or relevant components will not be accessible without disturbing the EBS. However, it is possible that, for some elements of the disposal system, in some disposal concepts and for some monitoring strategies, such concerns may be more readily resolved through monitoring than additional dialogue, explanation, calculation and/or research, development and demonstration. However, such concerns need to be explicitly and specifically stated to allow an adequate response to be formulated.

5. The Modern2020 Screening Metholology

Overall, deciding what to monitor is largely a process of expert judgement that will involve comparing and contrasting the benefits and disbenefits of any proposed monitoring activity, and considering the potential benefits to the safety case, especially the periodic update of the safety case during the operational period and in support of closure. Monitoring can be undertaken to increase confidence in the safety case further and to check concerns of third parties (award of an operational licence requires confidence in repository safety on behalf of both the implementer and the regulator).

In order to formalise how such expert judgement might be undertaken in practice, the Modern2020 Project developed a structured approach to the identification of monitoring parameters, referred to as the Modern2020 Screening Methodology (Figure 1). The Methodology builds additional detail to the MoDeRn Monitoring Workflow developed during a previous European Commission project [1]. The Modern2020 Screening Methodology considers the steps followed in a monitoring programme between identification of possible processes to monitor and detailed design of the monitoring system. The Methodology includes the following steps:

- Consideration of the value in monitoring a process and translation of processes into parameters.
- Identification of combined strategy and technology options for monitoring each parameter and developing a predicted parameter evolution for each option.
- Consideration of the feasibility of monitoring each combined strategy and technology option.
- Ensuring that each process has been adequately considered within the Screening Methodology.
- Cross-comparing the feasible parameters to decide on a final list of parameters.

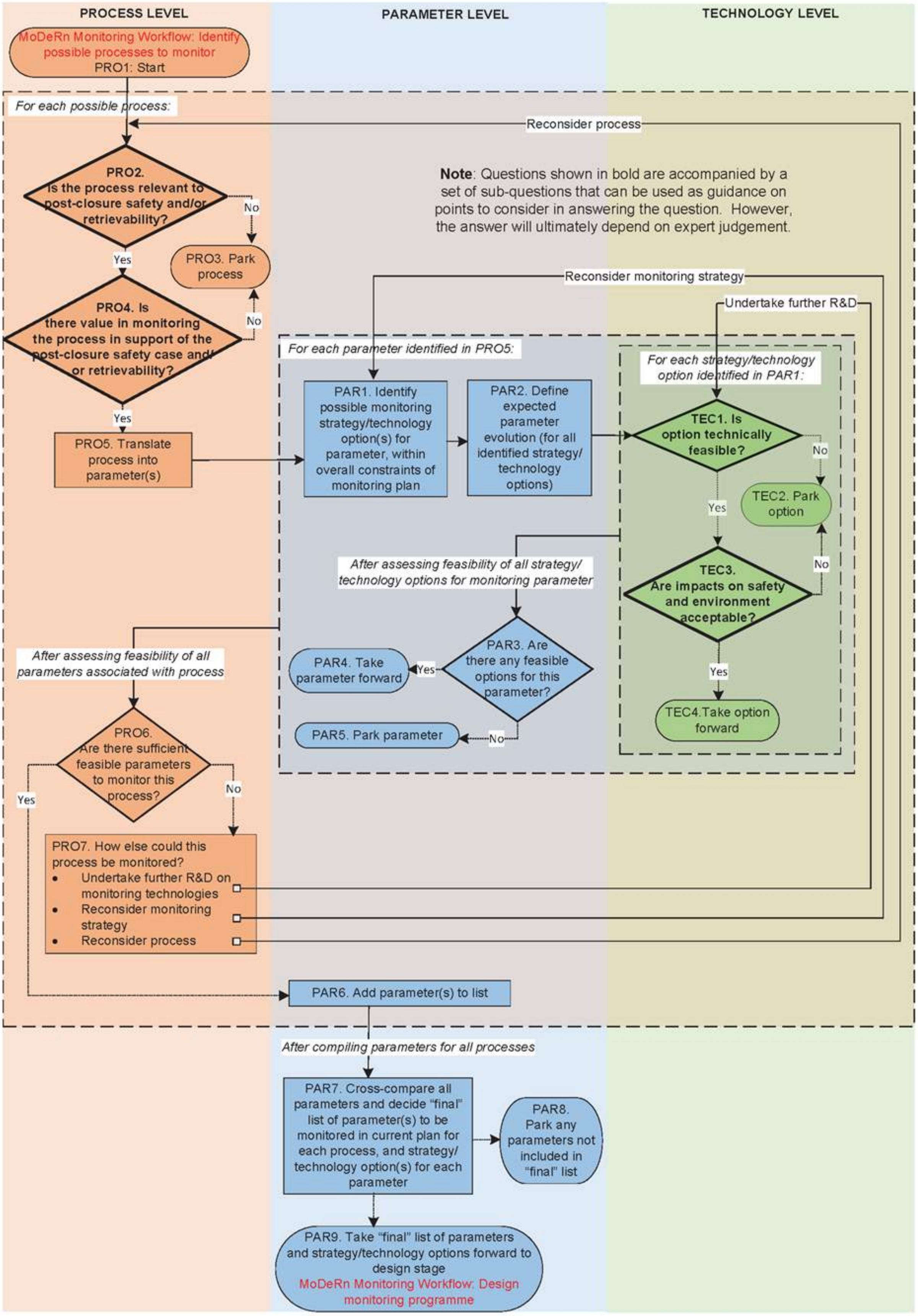

Figure 1: The Modern2020 Screening Methodology.

The Modern2020 Screening Methodology was tested in the Modern2020 Project through conduct of seven test cases, each focused on a recent programme-specific safety case:

- Cigéo test case: The safety assessment for the planned repository for high-level waste (HLW) and long-lived intermediate-level waste (ILW-LL) in the Callovo-Oxfordian Clay in France.
- ANSICHT test case: The new safety assessment concept developed for a repository sited in clay in Germany.
- Opalinus Clay test case: The demonstration of disposal feasibility for spent fuel, HLW and ILW-LL in a clay host rock in Switzerland.
- OPERA test case: An evaluation of the technical feasibility and safety performance of a repository for low and intermediate-level waste (L/ILW) and HLW in the Boom Clay, in the Netherlands.
- TURVA 2012 test case: Posiva's 2012 safety case for disposal of spent fuel in crystalline rock in Olkiluoto, Finland.
- SR-Site test case: Long-term safety case for the final repository for spent nuclear fuel at Forsmark, Sweden.
- Reference Project 2011 test case: Update of the reference project of a deep geological repository in granite at a hypothetical locality, Czech Republic.

6. Conclusions

The following conclusions were drawn from the development and results of the test cases regarding the identification and screening of repository monitoring parameters:

- Determining parameters to be monitored in an implementable and logical repository monitoring programme for the engineered barrier system (EBS) and near field is challenging but achievable. Finding a balance (appropriate to the national context and drivers) between monitoring everything possible and monitoring only what is valuable is a key challenge. Consistent with IAEA and NEA guidance, a repository should be passively safe without relying on monitoring, and so it is important that all monitoring activities are carefully considered and their need justified.
- Two principal justifications are possible: Firstly, that parameters are relevant to post-closure safety and/or retrievability, for example through being directly linked to safety functions. However, monitoring during the operational phase to build further confidence in the safety case may include demonstrating general thermal, hydraulic, mechanical, chemical and radiological (THMCR) understanding as well as validating performance (for some WMO's), so a direct link to safety is not necessarily required for there to be value in monitoring a parameter.
- Further work on developing implementable monitoring programmes is ongoing for all WMO's. Activities undertaken in the test cases need to be extended to all relevant components of the underground repository system. There is also a need, in most programmes, to focus on more detailed aspects of monitoring programme design, such as selection of sensor type, number and location. Detailed assessments of the impact of the monitoring system on the post-closure safety case (such as including sensors in models) will also need to be carried out, especially in cases where sensors are installed inside EBS components.
- There is no common set of parameters that should be monitored in every repository monitoring programme. Instead, the parameters to be monitored in each programme will depend strongly on the specific drivers, constraints and objectives identified in the national and repository-specific context.
- To be useful and traceable in the future, the screening process and its results must be transparent and understandable to future generations and external stakeholders. Therefore,

WMO's must give thought to both the format and the level of detail of how results and their underpinning justification will be presented.

- Decisions on parameter screening are more readily undertaken by programmes with detailed safety case approaches and repository performance models, and a more developed understanding of stakeholder expectations regarding monitoring. However, there are advantages to planning repository monitoring at an early stage, such as allowing sufficient time for technology development, ensuring design takes account of monitoring needs, building stakeholder confidence, and enabling some information/confidence requirements to be addressed through long-term experiments instead of or in addition to monitoring. Early thinking about monitoring also ensures that aspects of monitoring relevant to different stages (e.g. siting, construction, commissioning and operation) can be developed and implemented at the appropriate time.

The Modern2020 Screening Methodology was shown to be useful across a wide range of programmes, to be flexible and to be adaptable to the needs of individual programmes. At the current stage in the development of repository-specific monitoring programmes, no programme has identified parameters that will be monitored during the operational period to build further confidence in the safety case, but lists of possible monitoring parameters have been identified. As implied earlier, parameters must be linked to specific strategies and repository components, not considered as isolated entities.

Acknowledgements

The Modern2020 Project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 662177.

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Derivation of Monitoring Parameters Based on Safety Assessment as a Contribution to a Monitoring Concept until Closure of a High-level Waste GDF

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1. Summary

Nagra has developed its own preliminary methodology for the identification of candidate monitoring parameters related to long-term safety, including an assessment of how and where these parameters could be monitored, in the framework of the Modern2020 project. The methodology has been implemented as a database tool and applied using information from Nagra's high-level waste program. The information comes in part from Nagra's Project Opalinus Clay, which presented a comprehensive description of the post-closure radiological safety assessment of a repository for spent fuel (SF), vitrified high-level waste (HLW) from the reprocessing of spent fuel and long-lived intermediate-level waste (ILW), sited in the Opalinus Clay formation in northern Switzerland. Additional information is included from more recent material published in support of the ongoing site selection process.

The methodology consists of five steps:

1) Identify key, safety-relevant parameters;

2) Consider (without consideration of technical feasibility) whether monitoring of these parameters would be of interest, and set priorities;

3) Consider the technical practicability of monitoring those parameters identified as being or first and secondary priority;

4) Identify whether models exist for the evolution of those parameters that can be monitored and whether safety-relevant criteria exist that the parameters should meet, and;

5) Assess the overall rationale for monitoring those parameters identified in Steps 1 - 4.

The primary focus of monitoring activities is currently planned to be on the pilot facility being considered in the Swiss disposal concept. The key decision is that this monitoring activities will support the decision to proceed with backfill of the main access tunnels and the repository closure.

2. Introduction

Swiss Nuclear Energy Law requires that the disposal of radioactive waste takes place in one or more geological repositories, and that repositories are monitored for a given period of time before final closure [1]. It is however, expected that some types of monitoring will also take place prior to the monitoring phase, including baseline monitoring at the site before construction begins. The present paper discusses monitoring in the context of the Swiss geological disposal programme and presents an approach to identify parameters that would be both technically feasible to monitor, and useful from the point of view of demonstrating long-term safety.

The geological disposal strategy that Nagra has refined over the years is based on the concept of monitored long-term geological disposal, which involves an extended period of monitoring, during which retrieval of the waste is relatively easy, and a representative fraction of the waste is emplaced in a pilot facility which:

- Serves as a demonstration facility for emplacement technology;
- Provides information to better understand the behaviour of the barrier system and to check predictive models;
- Allows early detection of any unexpected and undesirable system evolution; and
- Provides input for decisions regarding the commencement of operations and eventually the closure of the entire facility.

In addition to monitoring of the pilot facility, the disposal rooms of the main facility and the access tunnels can be monitored if needed, at least until they are backfilled and sealed, and only in a more limited manner thereafter. Furthermore, a test facility - or facility for underground geological investigations - will provide additional information in support of decision making, and some of this information can be classified as "monitoring", i.e. continuous, in-situ measurements of parameters. The main function of the test facility is to provide the information required before the main facility can start operation, in so far as this information is not already available from site investigations. The test facility is not necessarily a single facility, but rather it is a series of experiments at different locations and may be regarded as a site-specific underground rock laboratory (URL).

The current Swiss concept for the disposal of spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) in the Opalinus Clay host rock is illustrated in Fig. 1. The currently selected host rock for the repository is Opalinus Clay (OPA).

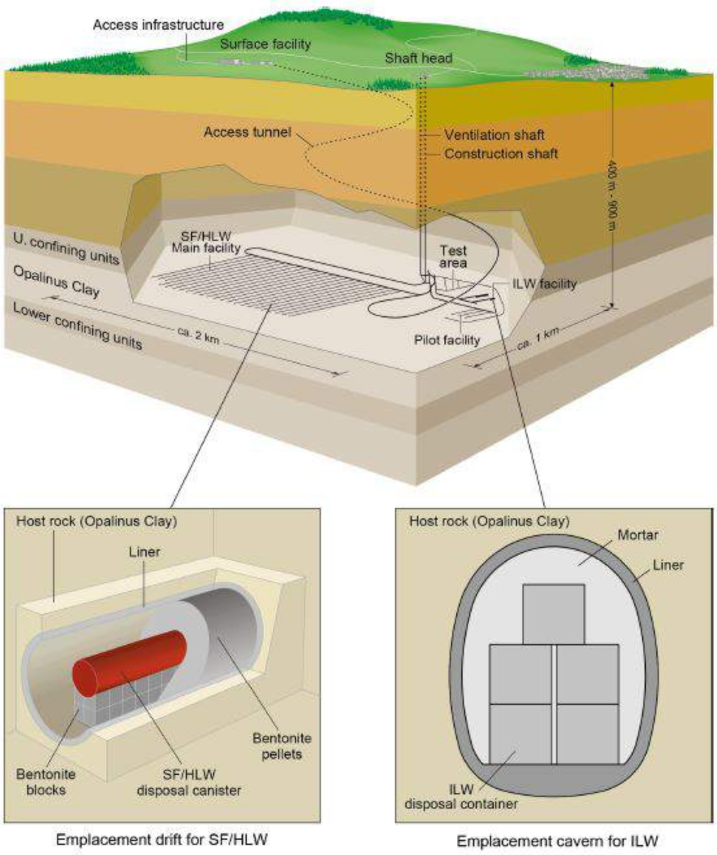

Figure 1: Example layout of Swiss repository concept with its main features (Status 2016; not drawn to scale).

3. Description of methodology

Nagra's proposed methodology for the identification of potential monitoring parameters relevant to long-term safety consists of the workflow depicted in Fig. 2. The methodology consists of five steps (also shown in Fig. 2). These steps are described in the following sections.

Step 1: Identification of key safety-relevant parameters

The first step in the methodology is the identification of key, safety-relevant parameters. The parameters are identified, at this stage, without regard on whether or not they can, or should, be monitored in practice. The following categories of safety-relevant parameters are identified:

1. *Safety-related requirements on the overall system and on sub-system components (in particular, the canister, buffer and host rock) and/or reference assumptions for safety assessment, which can be expressed by means of one or more parameters.*
   For example, there is a requirement on the SF/HLW disposal canisters (Fig. 1) that the radiation dose at the outer surface should be < 1'000 mSv/hr to preclude radiation-induced corrosion [2]. Radiation dose at the canister surface is thus defined as a key safety-relevant parameter and 1'000 mSv/hr is the associated criterion.

2. *Potentially (safety) detrimental phenomena are quantified, influenced, or their occurrence indicated, by the parameter.*
   A set of potentially detrimental phenomena has been compiled for the trial application of the methodology by considering:
   - phenomena that might compromise the ability of the system to meet the safety-related requirements or conform with the reference assumptions for safety assessment, and/or
   - phenomena that are present in Nagra's FEP List [3] and are clearly detrimental.

   Of course, phenomena may fall into both categories, and indeed it is a test of the comprehensiveness of the FEP database if all the phenomena identified under the first of these points are also identified under the second. Canister corrosion is an example of one such phenomenon and, as mentioned above, radiation dose at the outer canister surface is an example of a parameter that influences this phenomenon

3. *The parameter is needed for the evaluation of other key parameters that cannot be measured or monitored directly.*
   Not all parameters are amenable to monitoring. In some instances, the necessary monitoring technology either does not exist, or applying the available technology would cause unacceptable disturbances to the repository system. Such parameters are generally evaluated from other parameters, usually by means of a model. When Step 1 in the methodology is first carried out, no assessment is made of whether parameters can be measured or monitored in practice; this assessment falls within the scope of Step 3. Thus, there is a feedback from this later step to Step 1 (see Fig. 2) and the full set of key safety-relevant parameters is developed iteratively.

Step 2: Consideration of whether monitoring is of interest

The second step in the methodology is to consider whether or not monitoring the key, safety-relevant parameters identified in Step 1, assuming it could be undertaken in practice, would yield information that is of interest with regard to long-term safety. Such information is of high priority if significant changes are expected in the value of a safety-relevant parameter during the pre-closure monitoring period of around 100 years, especially if there are significant uncertainties associated with those changes. In the case that significant changes in a parameter are not expected but are also not completely excluded, such a parameter would be assigned secondary priority with regard to monitoring. Finally, if significant changes in a parameter can be confidently ruled out, then the parameter is excluded from further consideration.

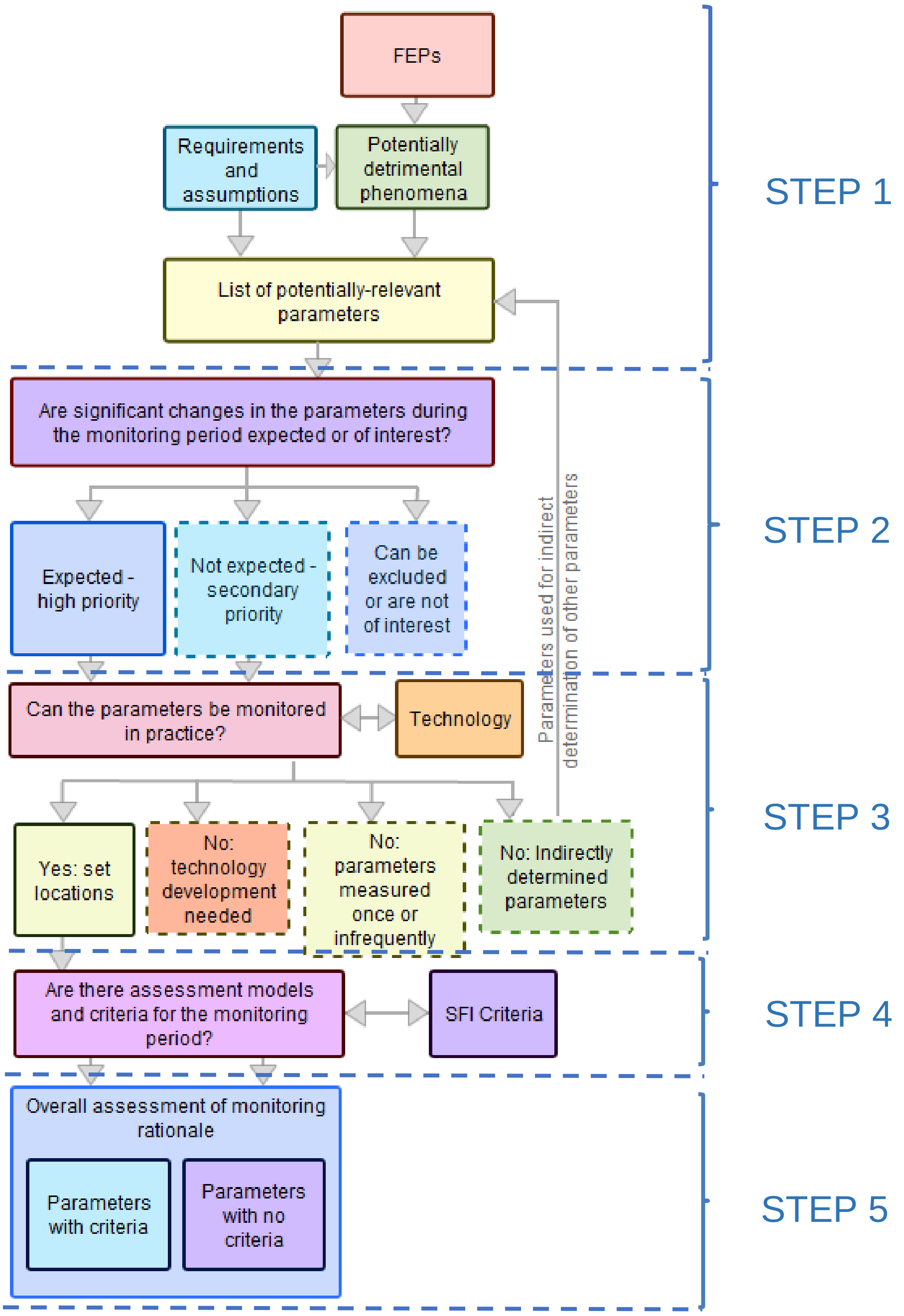

Figure 2: The five steps in Nagra's preliminary methodology for the identification of candidate monitoring parameters related to long-term safety.

Step 3: Consideration of the practicability of monitoring

The third step in the methodology is to consider whether or not monitoring the high and secondary priority parameters identified in Step 2 could be undertaken in practice.

To implement this step, the technologies that are currently available to monitor these parameters have been reviewed in terms of their technological readiness level. The parameters identified in Step 2 are then further categorised as:

- Amenable to monitoring in practice, regularly and continuously,
- Not yet amenable to monitoring – further technology development is needed and should be consider in RD&D planning,

- Not amenable to monitoring – rather, the parameter is obtained by measuring it once or infrequently, or
- Not amenable to monitoring – the parameter is obtained indirectly from other parameters.

Only those parameters that are amenable to monitoring in practice are then carried through to Step 4 of the methodology, which concerns models and criteria. Parameters in the second and third categories are not considered any further (the parameters are "parked"). Parameters in the fourth category are used to identify additional safety-relevant parameters that are needed for their evaluation; this is the feedback loop to Step 1 already noted above.

As part of Step 3, it is also considered where in the repository and its surroundings monitoring should be undertaken. Potential locations in the present Swiss concept include:

- Open emplacement rooms (Note: Monitoring in the closed rooms is not considered to be an option),
- Operations tunnels before backfilling,
- Operations tunnels after backfilling,
- Access structures before backfilling,
- Access structures after backfilling,
- Pilot facility before backfilling,
- Pilot facility after backfilling,
- Test facility (facility for underground geological investigations),
- Boreholes in the rock and
- Surface.

As an example, the saturation of the buffer around the SF/HLW canisters has been judged to be amenable to monitoring via a range of technologies, including psychrometers, time-domain reflectometers (TDR) and geophysical radar, in the closed pilot facility and also in the test facility.

A key consideration is avoiding any detrimental impact on long-term safety due to the monitoring equipment/sensors and associated cables, boreholes, etc. Hence, the test facility or pilot facility are monitored in preference to the open emplacement rooms, unless there are good reasons otherwise. Note that any monitoring of the underground infrastructures after backfilling and sealing of the access tunnels, ramp and shafts will have to take place remotely from the surface, presumably via wireless transmission if this is technically feasible.

Step 4: Consideration of models and criteria for parameters

One of the motivations for monitoring is to build confidence in models used to describe the evolution of safety-relevant parameters and confirm their adherence to specific criteria. The fourth step in the methodology is to identify which of the parameters identified in Step 3 as being potentially monitorable can be described by available models and are associated with specific criteria.

There are currently two high priority parameters that are associated with numerical criteria (or for which it is planned to develop criteria) considered in the application of the methodology. These are:

- Temperature in the host rock, for which the current criterion is that it should not exceed the maximum paleotemperature, to avoid the possibility of detrimental mineralogical alteration,
- Fluid pressure, also in the host rock, for which it is planned to develop criteria related to mechanical failure of the rock, which could occur if fluid pressures are too high.

For each of these parameters, if the corresponding criterion is violated, then either a system requirement is not met and/or a safety function may be significantly perturbed, although, in the case of secondary priority parameters, this is judged to be highly unlikely (which is why the parameter is classified as secondary priority). Violation of a criterion means that possible further actions needed to be considered.

The capacity of the current repository concepts to meet these and other criteria has been tested in qualitative and quantitative assessments [see e.g. 4]. Note that a number of additional parameters have no specific numerical criteria associated with them, examples being the buffer saturation and the pH of the buffer porewater. However, they may be modelled and it could be valuable to monitor them, e.g. to build confidence in the models and in support of decision making, as discussed in the following sections.

Step 5: Overall assessment of monitoring rationale

The fifth and final step in the methodology is to carry out an overall assessment of the rationale for monitoring the parameters that remain after Step 4.

The various possible reasons for monitoring a parameter can be divided into three main categories, reflecting those in Step 1:

1. *Build confidence that the requirements on overall system and on sub-system components are met and/or reference assumptions for safety assessment are valid.*
2. *Build confidence that potentially (safety) detrimental phenomena do not compromise safety.* Within this category, three subcategories can be identified:
   a) confidence in general understanding of the phenomena,
   b) confidence in input parameters used for modelling the phenomena, and
   c) confidence in model predictions, including adherence to criteria.
3. *Build confidence in the parameter values used for the evaluation of other key parameters that cannot be directly measured or monitored.*

There may also be other reasons to monitor a parameter, not directly related to long-term safety, for example:

- Stakeholder demands or reassurance, and
- Support for decision making (e.g. when to backfill a section of repository).

The role of monitoring in the confidence building and decision-making process is discussed further in the following section.

4. Discussion

Although monitoring of conditions in the host rock will take place in the facility for underground geological investigations prior to, as well as during, repository construction, the primary focus of monitoring activities will be on the pilot facility (and to some extent the main facility and access structures) during the monitoring phase. The key timing decision that monitoring during this phase will support is the decision to backfill the main access tunnels and close the repository. There are, however, other timing decisions that could also be affected by monitoring outcomes. An example is the decision on when to backfill the ventilation of access, operations, and ventilation tunnels (there is a legal requirement to backfill the emplacement tunnels immediately after canister emplacement). There are essentially two bounding options in this regard:

- Backfill these tunnels as soon as emplacement operations are over (in accordance with the scheme presented above);
- Delay backfilling until the decision has been taken to close the whole facility.

Monitoring for example creep in the access structures and ventilation tunnels could support a decision on which of these options to adopt, or whether to adopt some option in between. In particular, if creep is found to be low, it could be beneficial to delay their backfilling. Delayed backfilling gives more flexibility by providing continuing easy access to the emplacement area. This is consistent with the observational method in geotechnical engineering, whereby, during the construction of a tunnel or other structure, a continuous, managed and integrated process of design, construction control, monitoring and review is adopted, enabling appropriate, previously-defined modifications to be incorporated during (or after) construction.

Unexpected monitoring outcomes, including non-conformance with model predictions, will require an appropriate response, which may involve decisions, for example, to develop further R&D, to modify engineered design or even to retrieve waste packages.

5. Conclusions

This paper has presented a methodology to identify parameters that would be both technically feasible to monitor, and useful from the point of view of demonstrating long-term safety. Key candidate parameters for monitoring provisionally identified by applying the methodology and that have associated criteria include:

- Temperature in the Opalinus Clay host rock, and
- Fluid pressure, also in the Opalinus Clay host rock.

It should be noted that, in Nagra’s safety concept, the Opalinus Clay host rock is a key “pillar of safety”. It has a low hydraulic conductivity, a fine, homogeneous pore structure and a self-sealing capacity, thus providing a strong barrier to radionuclide transport and a suitable environment for the engineered barrier system. Emphasis in the safety case, and in the monitoring programme, is thus on phenomena that could potentially damage or by-pass the host rock as a safety barrier, rather than on extensive and detailed monitoring of the engineered barrier system.

In Nagra’s programme, the primary focus of monitoring activities will be on a pilot facility during the monitoring phase. The key timing decision that monitoring during this phase will support is the decision to backfill the main access tunnels and close the repository. Other timing decisions could, however, also benefit, in terms of flexibility, from the monitoring outcomes, e.g. the decision on when to backfill the ventilation of access, operations, and ventilation tunnels.

Unexpected monitoring outcomes, including non-conformance with model predictions, will require an appropriate response, which may involve decisions, for example, to develop further R&D, to modify engineered design or even to retrieve waste packages. A tentative generic response plan has been presented in this paper, but it is expected to undergo further discussion and development before it is finalised.

The methodology presented in this paper serves as a contribution to the EC project on Development & Demonstration of monitoring strategies and technologies for geological disposal - Modern2020. The methodology, as well as its trial application, are to be regarded as first iterations, and are likely to be refined over the forthcoming years as experience is gained.

Acknowledgements

This work was funded by the Swiss State Secretariat for Education, Research and Innovation (SERI) as part of the Modern2020 project (Euratom research and training programme 2014 – 2018 under the grant Grant agreement No. 662177 / European Atomic Energy Community represented by European Commission).

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Development of a Monitoring Concept for a HLW Repository in Germany tailored to the Safety Case

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1. Summary

Within the scope of MODERN2020, a strategic monitoring concept for repositories in clay formations in Germany has been developed. The focus of this concept was set on the engineered barrier system that is necessary to seal the man-made access routes to the underground facilities in a suitable manner. A balance was found in space and time between information requirements about the seal's proper perfomance and the fact that monitoring equipment implemented in the seal components may weaken the seal's barrier function. This balance relies on the selection of representative areas and seal components for monitoring and the use of wireless technology.

2. Introduction

With the restart of the site selection process for a high-level waste (HLW) repository in Germany, different types of host rock (e. g. clay) are in the focus. In recent years, the research activities in argillaceous rocks in Germany have been significantly intensified. In the framework of the ANSICHT project, a safety assessment methodology for a high-level waste repository in clay formations in Germany was developed [1]. Exemplarily, two generic geological models, typical for potential clay sites in Northern (Model North) and Southern Germany (Model South), were developed. The repository concept and especially the sealing concept of Model North have been taken as basis for the development of a suitable monitoring concept, especially for the engineered barrier system (EBS).

The motivation of repository monitoring and in particular of the EBS is to get continuous information about the evolution of important repository components. The clay host rock is assumed to be the main barrier for radionuclide migration. But even the best host rock cannot fulfil the containment requirements if the man-made access routes to the underground facilities are not sealed properly. Engineered barriers need to be installed in the underground drifts and shafts and have to be able to fulfil the containment requirements in a similar quality as the host rock itself. Repository monitoring is seen as a tool that is to provide information whether the containment requirements can be met.

3. Strategy for repository monitoring

The repository layout of Model North consists of 45 emplacement fields and an infrastructure part with two shafts (Fig. 1). Each emplacement field comprises 9 emplacement drifts with 11 vertical emplacement boreholes each. According to the backfilling and closure concept, emplacement starts in the field farthest from the shaft. When a borehole is completely filled, it will be sealed with a plug that consists of a sealing element and an abutment to keep the sealing element in place. The part of the emplacement drift above the borehole will be backfilled (Fig. 2). This corresponds to a repository design where repository backfilling and sealing takes places continuously and successively during the entire operating phase of the repository. The monitoring concept has to be adjusted to the operating processes.

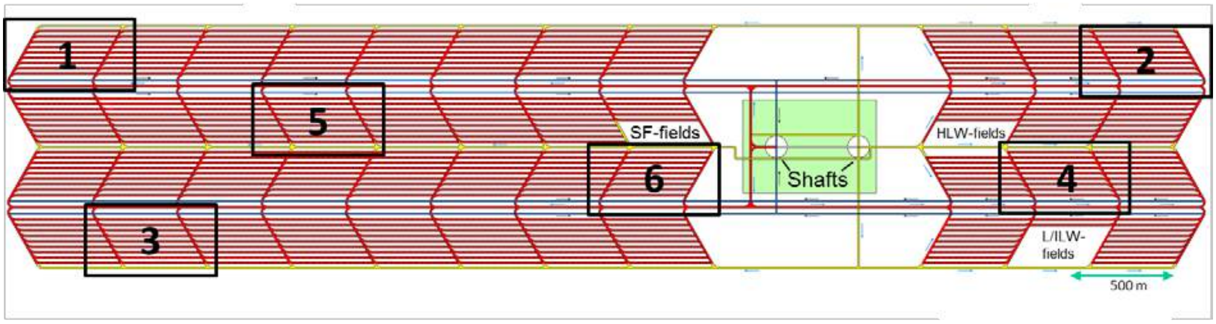

Figure 1: Repository design and potential arrangement of monitoring fields (the number assigned indicates the order in which the monitoring activities will be implemented).

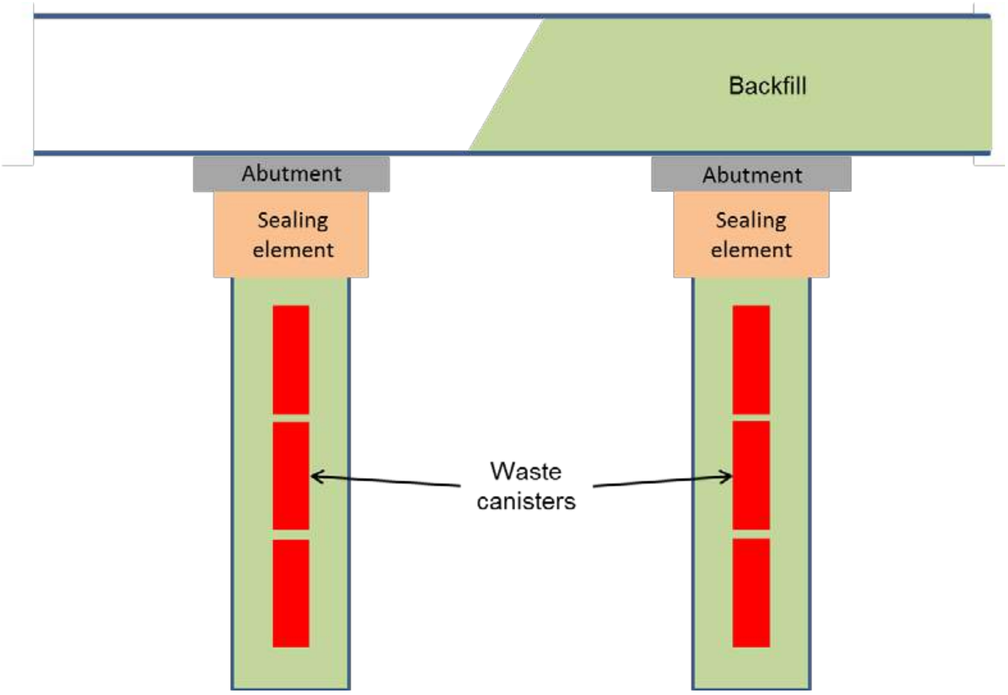

Figure 2: Sketch of the operational procedure of backfilling the emplacement drifts.

One specific aspect that has to be considered in order to determine the duration of the monitoring activities is the evolution of the repository. The monitoring programme is to be understood as a continuous learning process that is to be used to gather information that may help the repository operator, the regulator, and future generations to make decisions in the course of the repository evolution. In order to successfully implement a monitoring programme in a repository, a learning or process concept that consists of all measures necessary to collect, evaluate, transfer, and implement lessons learned related to the monitoring activities has to be defined and developed as part of the monitoring programme.

These specific components will be referred to as 'Monitoring Fields' (MF), 'Monitoring Boreholes' (MB) and 'Monitoring Seals' (MS). The experience gained from the initial monitoring activities in the first MF, MB, and MS will refine the knowledge of the operator about implementing and evaluating the monitoring systems (e.g. durability, adequate measurement locations, reliability etc.), about analysing and interpreting the data obtained, and about understanding the behaviour of the repository and its barriers. The results are to be collected continuously and analysed regularly by the responsible staff and institutions including the regulator. The evaluation results are intended to be used to increase the quality of the monitoring systems and of their implementation in the repository components selected next for monitoring, in order to improve the monitoring efficiency and thus, the monitoring concept in general. As a first approach and taking into account the repository concept and facility design, six emplacement fields have been selected as representative (Fig. 1).

In order to benefit from the experience gained in previous monitoring activities, the process will start with installing the monitoring equipment at the first monitoring field MF-1. This monitoring field will be the outermost one in the emplacement area planned for the disposal of spent fuel canisters. This field will be the first one to be filled and thus offers the possibility of maximising the time available for monitoring during the operating period of the repository. The same argument is valid for monitoring field MF-2. This field is the outermost emplacement field in the area planned for the disposal of waste from reprocessing. According to the safety requirements, each emplacement field has to be sealed against the rest of the underground openings as soon as possible. This allows obtaining monitoring data from an already backfilled and sealed emplacement field during the operating period of the repository and thus, getting something like “post-closure” information.

During the monitoring activities, the results will be recorded properly, and before starting the monitoring activities at the next monitoring field MF-3, a standardised review statement of the monitoring activities implemented at MF-1 and MF-2 will be prepared and evaluated. This evaluation point is seen as a milestone. The results of this evaluation will be used to decide whether the monitoring concept needs to be updated and/or improved, thus determining the monitoring strategy and approach to be followed in the next disposal field. This approach allows minimising errors and increasing the knowledge of the operator and the regulator. Currently, it is being discussed whether an involvement of the public/lay stakeholders in the evaluation process at this milestone would help getting acceptance and increasing the confidence of the stakeholders.

After the monitoring activities at MF-3 have started, the monitoring activities at field MF-1 and MF-2 will continue. It is important to implement continuous long-term monitoring activities and to collect long-term monitoring data, which can be helpful to better understand the long-term behaviour of the barriers of the repository and, thus, to determine the most suitable monitoring strategy to be followed during the post-closure phase of the repository. If the lessons learned from monitoring during several decades in the operating phase of the repository show that further monitoring would not provide significant added value, the monitoring activities may be stopped. Figure 3 gives an overview of the arrangement of monitoring boreholes in monitoring field MF-1, together with the first drift seals called ‘migration barriers’, which are to be monitored as well.

Monitoring fields MF-4 and MF-5 are located in the central parts of the two emplacement areas for spent fuel and high-level waste from reprocessing. They will be exposed to the highest temperature and thus the highest relevance for the monitoring of THM processes are expected in these areas. Monitoring field MF-6 is assumed to be the last one to be filled, and the distance to one of the shafts is the shortest, which represents the critical path when it comes to the evaluation of the tightness of the backfilled and sealed underground openings.

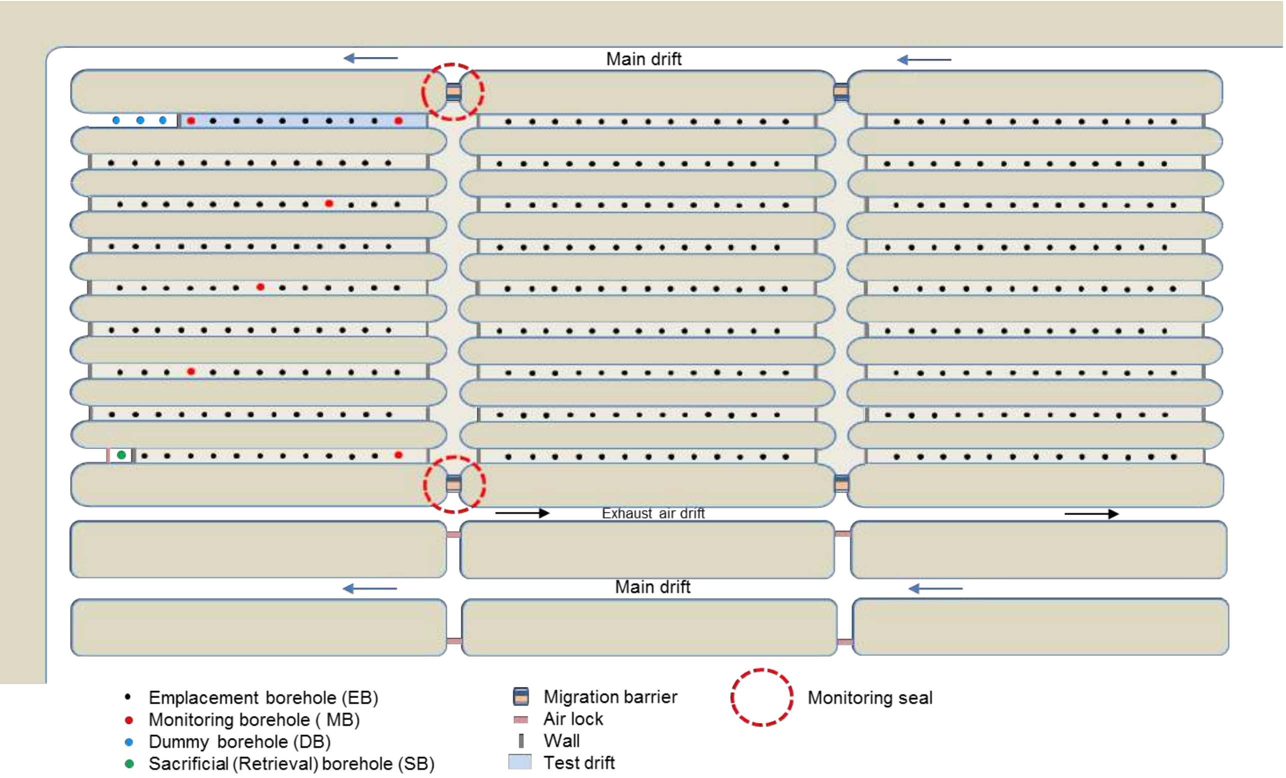

Figure 3: Potential arrangement of monitoring boreholes in monitoring field MF-1 and the first monitoring seals

Currently, the implementation of so-called "Dummy Boreholes (DB)" is being discussed. The idea is to implement three dummy boreholes in the very first monitoring field (MF-1) (indicated in Fig. 3 by the three blue dots in the outermost drift). The use of electrical heaters in the first three boreholes, as shown in Figure 4, would allow testing the complete emplacement procedure, especially the plug implementation, without risk of exposure to radiation. The three plugs will be instrumented to monitor the plugs' long-term behaviour under thermal load, the fluid inflow, and the rock convergence. Easy access to the monitoring equipment to check or update sensing and/or transmission units used for data acquisition will be possible. These dummy systems can be used to evaluate the monitoring system and the plug evolution and to develop improvements for future installations in plugs of boreholes filled with real waste.

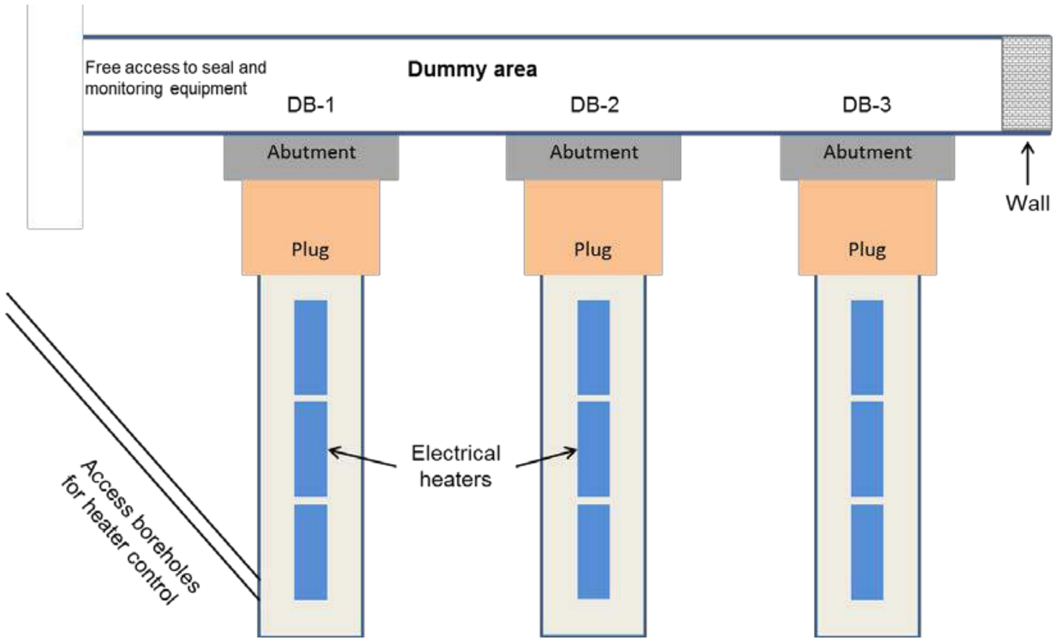

Figure 4: Dummy boreholes for plug monitoring purposes

After it has been decided to finish the test phase in the three test boreholes, emplacement of the real waste can be started. With regard to the statements given in the report of the German Repository Commission [2] concerning a "hot" test phase, it is proposed that the remaining part of the first emplacement drift will be used as a test drift.

After the first emplacement boreholes in this part of the drift have been filled with real waste and sealed, monitoring systems are to be installed successively during the backfilling operation in order to monitor the evolution of the backfill, the conditions at the contact zone between backfill and rock, and the host rock behaviour in the near field of the test drift. In addition, the last emplacement borehole will be used as a monitoring borehole and its seal will be monitored similar to the seals in the three test boreholes. Figure 5 shows an example of the preliminary technical concept for borehole plug monitoring.

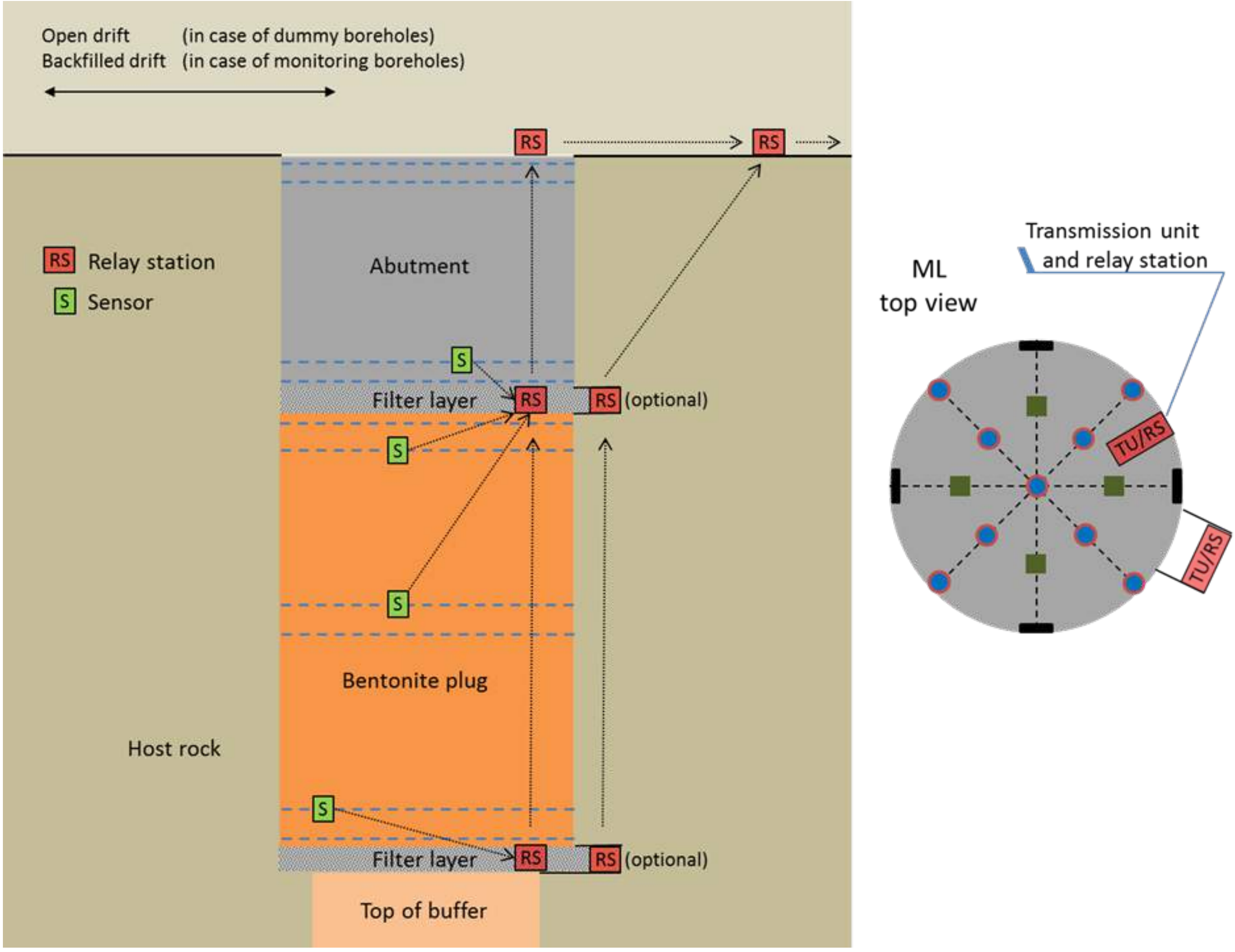

Figure 5: Principle design for plug monitoring

During the former MoDeRn project, multiple-parameter sensors were developed, including small data transmission units. These sensors are able to send their recordings to a nearby receiver [3]. Using such autonomous sensors, relay stations could be implemented in the sealing system to form a so-called 'data hopping system'.

This way, recordings of the individual sensors can be transmitted for further interpretation via several relay stations to a central receiving unit.

After final closure of this test drift, a "waiting period" may follow, during the monitoring results are to be continuously evaluated. As a first approach, a period of one year seems reasonable. The monitoring results obtained during this "waiting period" are assumed to be a fundamental input for the decision to give the go-ahead for continuous waste emplacement.

In MF-1, five boreholes (marked with red dots) have been selected as monitoring boreholes for borehole seal monitoring in five different emplacement drifts (Fig. 3). They are arranged in a line through the monitoring field. This configuration starts at the outer boundary of the emplacement field where the first boreholes have been filled and goes to the other outer boundary where the last boreholes will be filled. It is also possible to cover the location with the most intensive heat input in the central part of the monitoring field. Thus, the whole THM evolution in the first emplacement field can be monitored.

Another option currently under discussion is the use of a so-called "sacrificial borehole" (Fig. 6). This borehole could be the last one to be filled in the last emplacement drift in the first emplacement field, as shown by the green dot in Figure 3. The idea behind this is that the waste canisters in this borehole are intended to be retrieved prior to final closure of the repository and disposed of in another, already prepared, emplacement borehole in a reserved area.

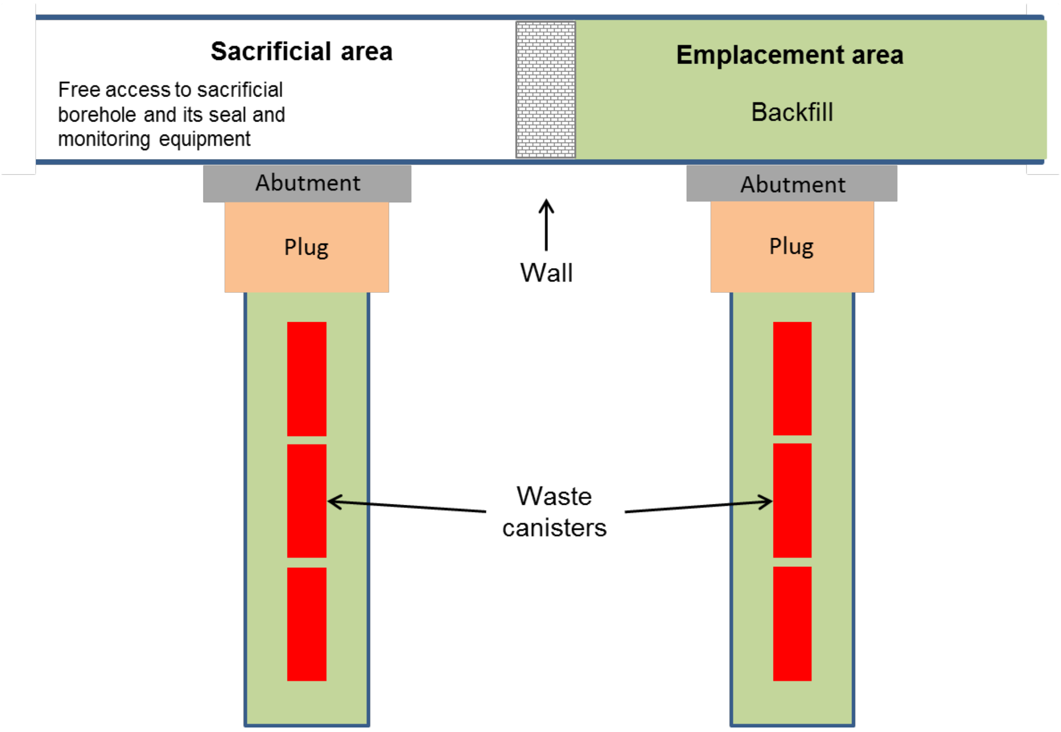

Figure 6: Sketch of the sacrificial borehole area

This borehole will be heavily instrumented for monitoring not only the seal but the canister environment as well. In this case, wired monitoring equipment could be used because the systems will be completely recovered after waste retrieval. A weakening of any barrier function is not to be considered.

The complete recovery of the monitoring equipment, which would (hopefully) have been under operation for several decades, would allow investigating the aging of the system components and thus, information about their durability could be obtained. This information will be helpful to estimate the expected lifetime of the sensing systems still in operation at the other monitoring locations.

When the access drift between the first two emplacement fields is not needed any longer, migration barriers are to be built at both its ends in order to seal the access to the emplacement field against the rest of the underground facilities (Fig. 3 and Fig. 7), as stipulated by the Safety Requirements. These very first seals are intended to be used as 'monitoring seals'. This means that monitoring systems are to be installed to monitor the evolution of these very first seals. The monitoring results can be used to evaluate whether the performance targets defined for these seals can be met or if changes of the barrier design or the monitoring system itself would be necessary. Each emplacement field will be sealed by four migration barriers in the two access drifts. At each of the identified six monitoring fields, two of these barriers are planned as monitoring seals.

After all emplacement fields have been filled and sealed against the remaining underground facilities, an observation phase may follow. During this phase, the shafts and the main drifts, which allow access to the individual emplacement fields and the migration barriers, are to be kept open for a time span to be defined. The monitoring results obtained during this pre-closure phase are assumed to be a fundamental input for the decision for final closure of the repository.

At the end of the pre-closure phase, when the decision for final closure has been made, the main drifts are to be backfilled, and the eight main drift seals at the interfaces between the infrastructural area and the emplacement areas for spent nuclear fuel and high-level waste from reprocessing are to be built (Fig. 7, left). The two seals closest to each emplacement area, i.e., the outermost left and outermost right seal shown in Figure 7 (left), are to act as 'monitoring seals'. Both seals have the most direct connection to the shafts and monitoring them is considered to be essential. All lessons learned during several decades of monitoring the migration barriers at the end of the access drifts to the emplacement fields will be available and will form a sound basis for the installation of the monitoring system at these two seals.

After filling the infrastructural area with gravel with high porosity, which can act as a temporal gas and water storage medium, the two shafts will be closed by using two separate sealing modules in each shaft. The preliminary sealing concept is shown in Figure 7 (right). As the two shafts represent the main access to the earth's surface, all of the four sealing modules are to be monitored.

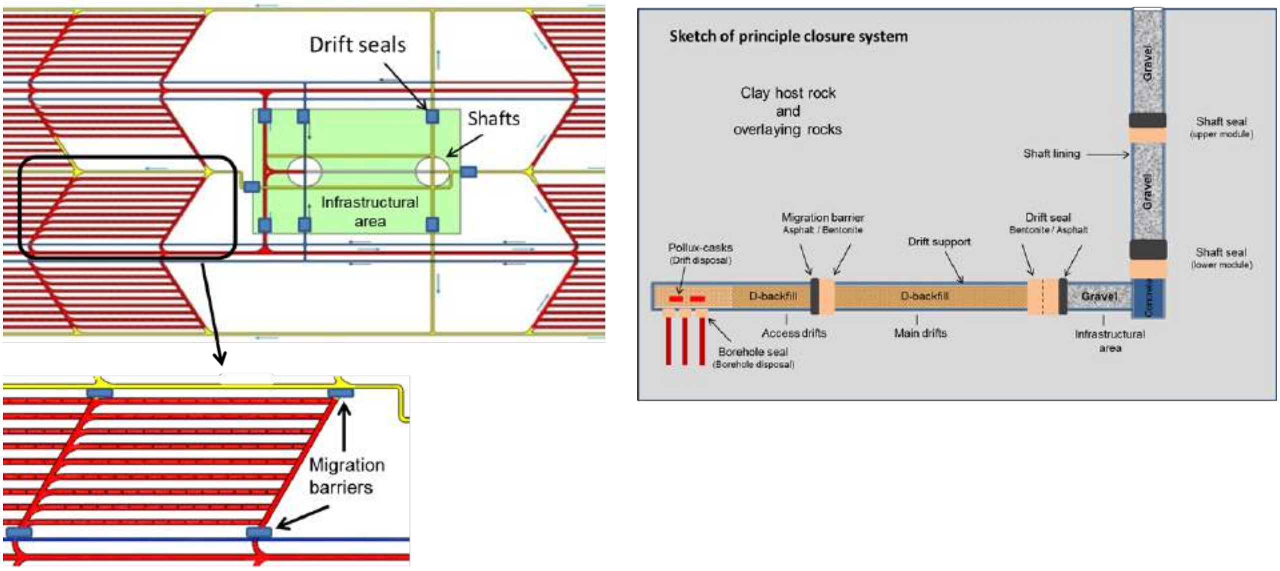

Figure 7: Schematic overview of the principle sealing system [1]

4. Conclusion

Within the scope of MODERN2020, a strategic monitoring concept for repositories in clay formations in Germany, especially for the EBS, has been developed, taking into account the German regulatory framework and the European view on repository monitoring established during several European projects. The strategic monitoring concept explicitly considers the learning effects monitoring results may provide during the entire lifetime of the repository, especially with regard to seal design improvements. At the same time, the strategic concept provides a sound input for decisions to be made during the stepwise approach to the disposal programme.

Acknowledgements

The author would like to thank the Federal Ministry for Economic Affairs and Energy (BMWi = Bundesministerium für Wirtschaft und Energie) represented by the Project Management Agency Karlsruhe (Karlsruhe Institute of Technology, KIT) for funding the research work carried out within the scope of this project.

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Cigéo project: Definition and status of Andra's monitoring strategy

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[1] Andra, France

1. Summary

Andra is currently in the license application process of the for a deep geological disposal facility for HLW and ILLW in a clay formation in the eastern part of France. This process started in 2011 by the development of an industrial design phase that consists in the proposal of an overall underground architecture for the repository and the definition of the operating principles and the name given to the projet was defined: the "Centre industriel de stockage en milieu géologique" (Cigéo, Industrial Center for Geological Disposal). As a response to the public debate of 2013, Andra has published the Safety Options reports "Cigéo 2015" in early 2016 to precede the license application. The "Cigéo 2015" set of reports aimed at presenting the safety strategy, the safety requirements, the safety methods, the key safety and design options; the list of safety scenarios, their classification, and a preliminary impact of selected key safety scenarios were defined to include margins. They did not aim to present or demonstrate the overall safety, which will be in the safety case report supporting the licensing application. In that frame, Andra started to provide preliminary elements about the monitoring strategy in different parts of the "Cigéo 2015" reports without providing the overall strategy and its application to the key milestones of the Cigéo project development. This abstract provides an overview on the current regulatory framework regarding monitoring and the approach on monitoring activities by Andra.

2. National framework

Andra is currently in the license application process of the for a deep geological disposal facility for HLW and ILLW in a clay formation, The Callovo-Oxfordian, in the eastern part of France. This process started in 2011 by the development of an industrial design phase that consists in the proposal of an overall underground architecture for the repository and the definition of the operating principles and the name given to the projet was defined: the "Centre industriel de stockage en milieu géologique" (Cigéo, Industrial Center for Geological Disposal). Given by the type of the waste it will house, Cigeo will be classed as a basic nuclear installation (INB). The Order of 7 February 2012 [1] has set the general rules relative to basic nuclear installations. According to the article 3.1 the aim is *"to detect the incidents and to implement the actions allowing, on one hand, to prevent these from leading to an accident and, on the other hand, to restore a situation of normal functioning or in the case failing, to reach then to maintain the installation in a safe state"*.

According to the French ASN-2008 Geological Disposal Safety Guide, Andra has to develop a monitoring program, which intends to track the evolution of parameters characterizing the condition/state of components of the disposal facility and its geological environment, as well as the main driving processes of the further evolution of the repository. The monitoring program has to be implemented in the phase before operation (monitoring of the baseline conditions). During the operational phase, monitoring of the repository is required as well. Such monitoring is described as including systematic measurements in order to control the construction, the operational safety, to provide inputs for retrievability and to assess that the repository evolves in accordance with post-closure safety requirements and that the defined monitoring parameters remain in the limits as defined in the safety case. The monitoring program must show that the main processes are well anticipated and remain under control.

In 2015, Andra submitted the “Cigéo 2015” reports (DOS) to the French Nuclear Safety Authority (“ASN”). The review was conducted from mid-2016 to mid-2017. This regulatory process gave the possibility for Andra to get advices from “ASN” in advance to the licensing application in view of the safety demonstration and the detailed development of the technical design solutions. Those advices are compiled in an “opinion report”. Results from reviews by the French TSO “IRSN” and an international review organised by the IAEA are addressed. Both reviewers provide on ASN request a technical review of the safety options reports. Finally, ASN stated the necessity for Andra to present the monitoring strategy together with the license application and its application to Cigéo project.

3. Requirement for a industrial pilot phase

The Cigéo project was opened to public debate between 15 May and 15 December 2013, and the review and report were published on 12 February 2014. To take the opinions and expectations raised during the public debate into account and to stick with the step-by-step approach adopted by the Law of 1991, Andra has decided to pursue the Cigéo project but with four changes, specifying its proposal with regard to reversibility and making commitments moving forward. The industrial pilot phase is one of the four changes. The aim of this industrial pilot phase will be to improve the following under real-life conditions:

- the technical measures and provisions taken to manage operating risks,
- the performance of industrial equipment,
- the ability to withdraw waste packages that have been disposed of,
- the methods and sensors used to monitor the disposal facility,
- the techniques for sealing off the disposal cells, tunnels and access (shafts and ramps).

The monitoring programme of the industrial pilot phase will be a key step for the establishement of the Cigéo monitoring plan

4. Key milestones of Cigéo project

The Cigéo monitoring program will start with the construction of Cigéo (and partly before) and will continue during the operating phase and after closure. It will evolve according to feedback and technological progress. Andra will ensure that this program does not disrupt the operation of Cigéo in a passive mode.

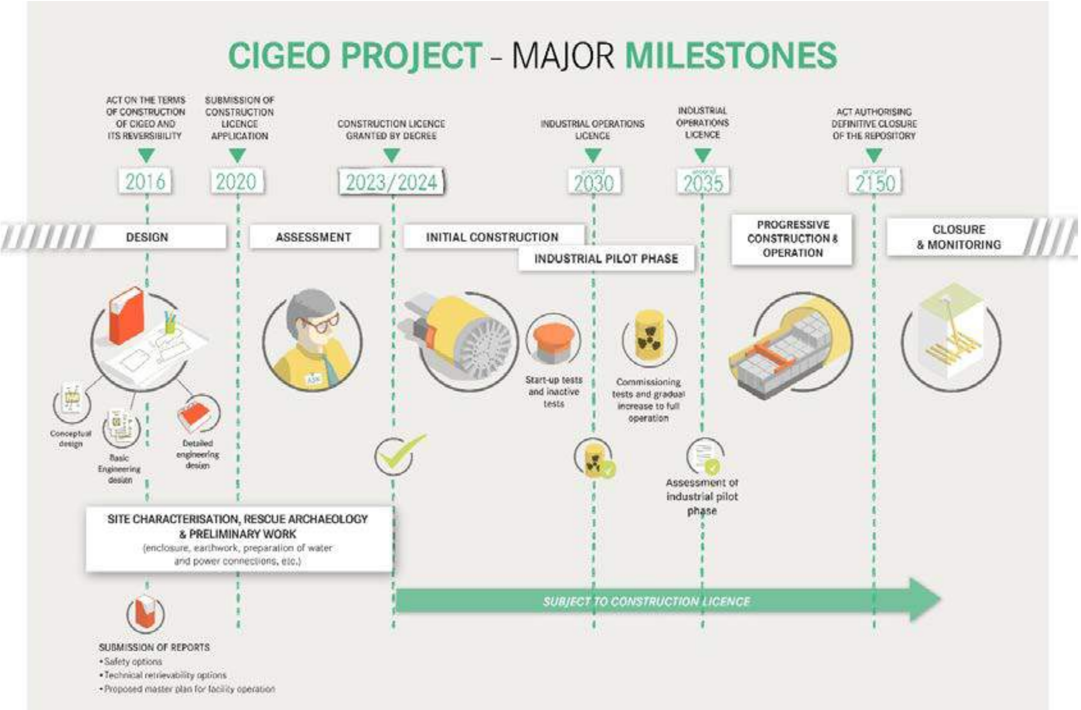

Figure 1: The key milestones of Cigéo project

5. Safety Options reports “Cigéo 2015”

In 1991, the French Act [1] on management of high-level and Intermediate long-lived radioactive waste (HLW-ILLW) tasked Andra, the French National Radioactive Waste Management Agency, with assessing the possibility of disposing of waste in a deep geological formation, primarily by means of developing underground laboratories (section 2 of the Act). According to the 2006 French Act [2], studies and investigations for a reversible deep geological disposal shall be conducted with a view to select a suitable site and to desing the facility. Cigéo Center comprises both nuclear surface and underground facilities (see figure below).

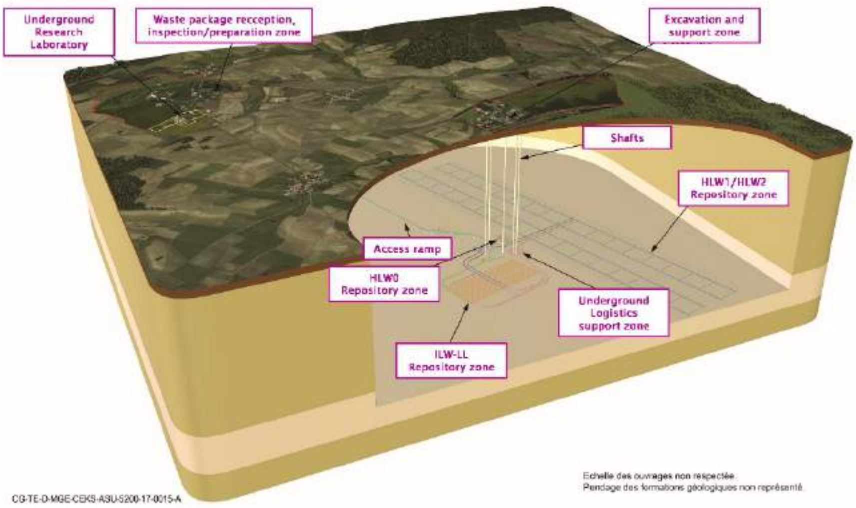

Figure 2: Surface and underground facilities at Cigéo (extract of references 6 & 7)

Andra submitted in 2016 the Safety Options files (DOS) to the Nuclear Safety Authority (ASN). These files correspond to a preliminary safety case but do not present the overall safety demonstration to support future licensing application of Cigéo. It aims to:

Stabilize the safety standards reference documents, approaches, and input data, particularly the package design assumptions used;

Stabilize the design and safety options and identify potential evolutions of the design;

Stabilize the various scenario categories (encompassing those used as the basis of design calculations, those not included in DOS-example, normal evolution scenarios and "what-if" scenarios);

Present an initial "bounding scenarios" impact assessment.

At the request of the nuclear safety authority, the Safety Options report underwent a review by the technical support organization as well as international experts from regulatory bodies from other countries, conducted under the auspices of the IAEA. The nuclear safety authority considered that at the stage of the Safety Options reports, "the project has reached an overall level of technical maturity that is satisfactory" and "constituted significant progress with respect to the previous dossiers".

Regarding monitoring aspects, the peer review report mentioned that "*Andra should further address in the development of its monitoring plan implemented during the operational phase:*

- *the relationship between the monitoring parameter(s) and post-closure safety;*
- *the feasibility of the monitoring activities planned to function over the operational period including equipment maintenance or replacement and potential detrimental impact on post-closure safety barrier performance.* "

The ASN has issued an opinion underlining the fact that the monitoring of the facility must be addressed in the licensing application. Detailed information is available here [10].

6. Main purposes of monitoring

The main purposes of monitoring are:

- During construction of the repository: geological survey and some parameters related to pos-closure safety;
- During operating: operational safety as well as parameters related to post-closure safety.

The main aims are to:

- Check that the construction of the repository will be as defined in the licensing application;
- Check that the installation remains in the operating area as defined in the General Operating Rules Report;
- Identify any possible deviation in the construction and operation of the installation, which will conduct the facility to get out of this area in the absence of corrective action, before the installation does not come out of its normal operating range.

At first, the monitoring program is established in response to the operational risks as for nuclear facilities (radioprotection, dissemination of radioactive particles …). It also integrates Cigéo specificity, particularly the underground facility and its geological environment related to the post-closure safety objective. As an illustration, the Callovo-Oxfordian being the central pillar of the post-closure safety (see figure 3), one aim of the monitoring program is to identify the potential disturbances of the key characteristics of the Callovo-Oxfordian (e.g. mechanical behavior, extension, structure and permeability of the damaged zone around the structures). It also aims to monitor the evolution of the surrounding ambiance of the engineered barrier system components important for post-closure safety that will be installed during operation (e.g. hydraulic, mechanical surrounding of the HLW disposal packages).

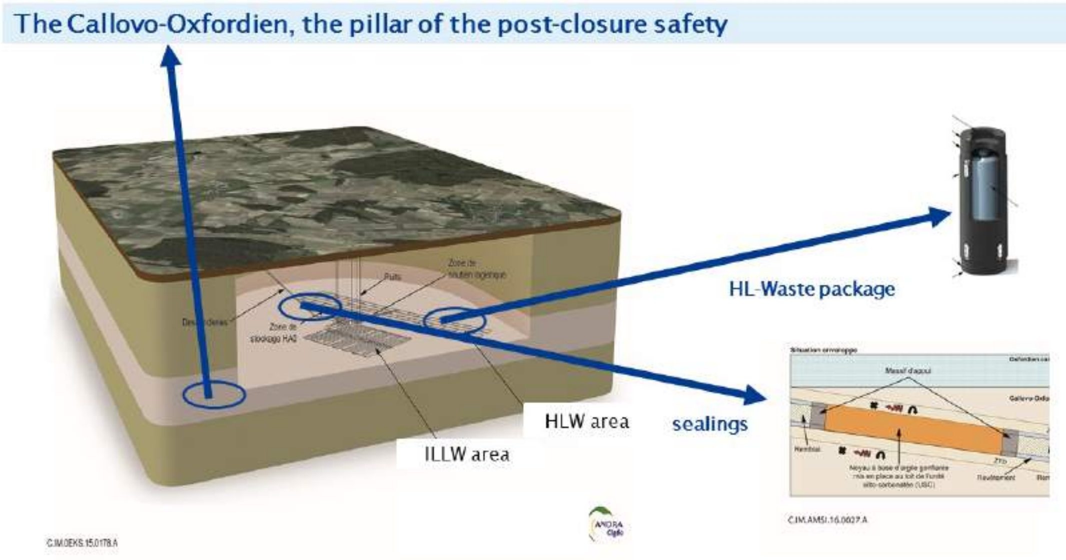

Figure 3: The key components for post-closure safety [7]

Figure 4: The key components for post-closure safety [7]

The monitoring program implements proven technical monitoring solutions from other areas than geological disposal (e.g. underground structures, extractive industries ...) in the Meuse / Haute-Marne Underground Laboratory or other underground research laboratories abroad for several years or decades and nuclear installations, which are transposable also in the context of Cigeo.

The choice of the technical solutions selected for the monitoring must take into account the following aims i) respect the passive safety requirement after closure as such ii) minimize the disturbance of the key components for post-closure safety and iii) provide the ability to monitor installation in relation to operational risks.

7. A stepwise development of the monitoring program

A preliminary monitoring program of Cigéo will be presented in the reports supporting the license application for authorization of the repository construction. It will present the roles of the specific measures put in place in the specific parts of the underground installation (HLW and ILLW cells, sections of ramps, wells, sections of gallery or intersections) chosen for their representativity or for their particular positioning (for example at the location of a future sealing).

The Cigéo monitoring program starts with the construction of Cigéo and partly already before. Based on lessons learnt during the operation (see figure below), it will continue, if needed, with necessary adaptations. It will be detailed for the authorization of commissioning of Cigéo, in connection with the general operating rules (cf. above), in particular on lessons learnt during the initial construction as well as the additional safety and design studies needed towards the commissioning.

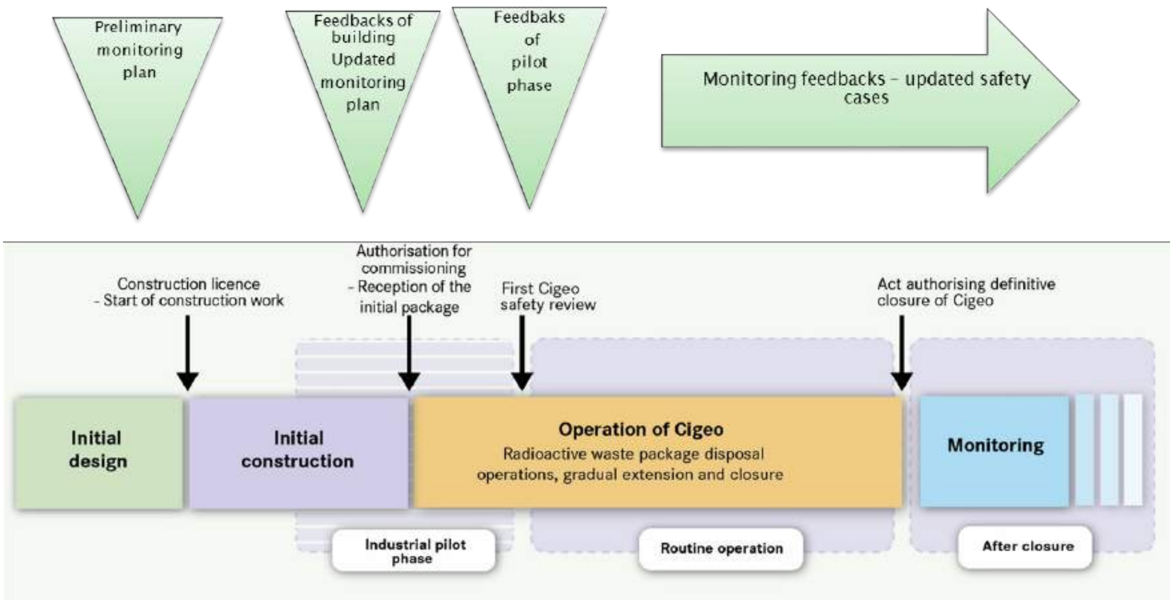

Figure 5: Successive monitoring plans and relation with the step-by-step development of Cigéo

Within this general framework, the industrial pilot phase is an important step towards Cigéo monitoring. It is part of the incremental development of the project, which includes the confirmation of the actual operating environment and of the assumptions made during the design phase. In this context, it is possible to consolidate the forecasts of the subsequent evolution of the disposal in particular by the implementation of demonstrators (closure works, test cells, etc.) that will focus in particular on the verification of the ability to monitor specific parameters.

During the industrial pilot phase:

- The monitoring plan will include the measurements of operating parameters such as temperature, radiological atmosphere, position of packages, especially after waste packages have been disposed.
- The monitoring plan will also include parameters related to the design and the behavior of structures with time considering the limited duration of the operational phase, such as the preservation of geometry of the disposal cells.
- Moreover, the verification of the important characteristics of the host rock such as mechanical behavior, extension, structure and permeability of the damaged area around the structures will be included in the monitoring plan;
- The monitoring plan will specifically address the objective of the feasibility of retrieval of the waste packages by for instance verifying the preservation of geometry of the disposal cells (cf above).

A synthesis report with the lessons learnt of the performed monitoring during the idnustriel pilot phase will assess its relevance, the quality of its implementation by the operator. This assessment will help to consolidate the monitoring plan and, where appropriate, imply adaptation for the subsequent phases.

Surveillance activities will continue along the operating period. A review of lessons learnt of the operation and its monitoring will be submitted at periodic safety reviews in accordance with French regulatory framework [3].

Periodic safety reviews will include lessons learnt of the operation and monitoring of the Cigéo facility and will check that the planned closing process of the repository is still compatible with the objectives and the preservation of the needed safety functions for the period after the closure of the disposal facility.

8. Ongoing work on monitoring program

Currently work is ongoing to map parameters to be monitored in line with the safety functions to be satisfy by the Callovo-Oxfordian and the engineered componants. The work was initiated during the establishement of the safety options and the development of the design. This work needs technical views from design, science and safety fields, such as within Modern2020.

The monitoring programme will relate in particular to the key parameters of the underground architecture's design that will be defined at the forthcoming stage corresponding to the detailed engineering design phase of the project. Some portions of the underground facility (HLW and ILLW-LL disposal cells, ramp and shaft sections, gallery sections or intersections) selected for their representativeness of a set of structures or for their specific position (e.g. at the location of a future seal) will be the subject of specific monitoring measures.

The following table lists a preliminary list of operational monitoring requirements in conjunction with post-closure safety functions identified at this stage [7]. This list of parameters may change depending on the studies currently being conducted for the purposes of the construction licence application.

Example of Post-closure safety functions	Underground facility component examined	Estimated monitoring requirements over time
Restrict the release of radionuclides and toxic elements and immobilise them in the repository	ILLW disposal cell	Environmental conditions within the disposal cell: temperature, relative humidity, and the presence of liquid water Deformations, movements Disposal cell deformations
Delay and mitigate the migration of radioactive substances and toxic elements	Underground facility	Characteristics of the near-field argillites, in particular the damaged argillites (permeability, porosity, fracture, spatial extension, deformation, desaturation) Hydraulic head fields in the calcareous Oxfordian rock (porous horizons)
	Callovo-Oxfordian formation	
Protect the favourable properties of the argillites	Drifts	Characteristics of the near-field argillites, in particular the damaged argillites (permeability, porosity, fracture, spatial extension, deformation, oxidation, temperatures)
	ILLW disposal cells	
	HLW disposal cells	
	Geological medium	Hydraulic head fields in the calcareous Oxfordian rock (upper surrounding formation of Callovo-Oxfordian) around the surface-bottom connection structures and at the repository Pore water pressure fields in the Callovo-Oxfordian formation near the surface-bottom connection structures and the underground facility structures Temperature fields in the Callovo-Oxfordian formation near the HLW section structures

9. Outlook

Andra submitted a "safety options dossier" for the Cigéo project to the ASN in April 2016. This sets out the chosen objectives, concepts and principles for ensuring the safety of the facility. A monitoring program is ongoing to consider the monitoring strategies in the different repository phases, to develop and adapt monitoring technologies/system to Cigeo compound. The monitoring approach is currently assessed at the Andra underground research laboratory in Bure.

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Monitoring programme for the Olkiluoto repository, Finland

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[1] Posiva Oy, Finland

1. Summary

Posiva Oy is preparing to start the geological disposal of used nuclear fuel in the 2020's. The disposal site ONKALO® is located on the island of Olkiluoto, which is located in the municipality of Eurajoki, South-Western Finland. For final disposal Posiva utilizes the KBS-3V- concept in the Precambrian crystalline bedrock of Olkiluoto. In 2015 Posiva was granted the licence for constructing the repository and the construction works are currently ongoing.

A multidisciplinary monitoring programme has been running at the site since the early 2000's. In Finland, a multidisciplinary monitoring programme is required for nuclear waste repositories by different laws, decrees, regulations, licenses as well as nuclear safety guidance. The monitored processes and parameters have been selected in a way that they either provide data on processes and parameters related to different requirements set for the disposal system and the environment or provide background data for the site description and different models of the site. The most important task of the monitoring programme is to provide data on long-term safety related processes. Posiva's monitoring programme comprises five sub-sections: i) rock mechanics, ii) hydrology and hydrogeology, iii) hydrogeochemistry, iv) surface environment and v) the monitoring of engineered barriers. Based on requirements, for the closure of the repository at the end of operation, a summary and interpretation of the data provided by the monitoring programme during the operation of the repository shall be presented in the application for closure.

During its course, the monitoring programme has already been able to detect effects in the groundwater and the bedrock, caused by the excavation- and construction activities. These observations have helped in further developing the safety case and the procedures related to excavation and grouting of the tunnels.

2. Background

2.1 General

Posiva Oy is a private company established and owned by the Finnish energy companies Teollisuuden Voima Oyj and Fortum Oy for the purpose of safe disposal of their high-level nuclear waste. Posiva is constructing facilities for geological disposal of high-level nuclear waste in Olkiluoto, South-Western Finland. The underground research and disposal facility ONKALO® being the most widely known of the facilities at the site. The construction works at the site started in 2003 and in 2015 based on nuclear energy act [8] and nuclear energy decree [9], Posiva was admitted the construction license for the actual disposal facilities by the Finnish Government [4]. Posiva has since shifted from the research facility construction to the construction of the nuclear facilities. The operation of the repository is to be started in 2024.

For final disposal Posiva utilizes the KBS-3V- concept, where the used nuclear fuel assemblies are packed inside copper-overpacked graphite-iron canisters. The canisters are emplaced within crystalline bedrock, to the depth of -420 m. Through a network of tunnels forming disposal panels, the canisters are emplaced in deposition holes, where the canisters are surrounded by a buffer made of bentonite. The disposal tunnels are eventually backfilled with bentonite and a concrete plug is constructed at the entrance to each tunnel. All other underground spaces, including the central tunnels, shafts and the access tunnel will also be backfilled at the end of the operational period which is planned to last for ~100 years.

Related to the final disposal activities at the site, a multidisciplinary monitoring programme has been running from the early 2000's. The latest version publicly available is the one compiled for the construction license application and released as a Posiva report [12]. The programme was initiated before the construction and excavation activities at the site were started, thus allowing comparison of construction- and operation-related data to undisturbed baseline data. In addition, extensive site investigation studies have been carried out at the site since the early 1980's, also adding up to the set of baseline data and understanding of the processes in the site.

Monitoring is continuous work and the monitoring programme has been and will be updated when needed, also during the operational phase in order to enable the programme to react to possibly different or new monitoring needs indicated by the observations or changes in internal or external requirements. The first version of the programme was published in 2003 [11], then updated in 2012 [12] and several internal updates to the programme have been carried out between 2012 and present due to aforementioned needs.

2.2. Geological setting

Geologically, the crystalline bedrock of Olkiluoto consists mainly of Precambrian gneisses and migmatites with occasional pegmatites, also related to migmatization. The migmatites were formed between 1.9-1.8 Ga [1]. In addition, single younger subjotnian diabase veins cross-cut the island in places, based on current understanding, these are related to rapakivi magmatism, which occurred in south-western Finland at 1.6-1.5 Ga [1], [7]. The western contact of the Eurajoki rapakivi granite stock is located ~4 kilometers east from Olkiluoto. The hydrothermal phenomena related to rapakivi magmatism have also resulted in hydrothermal fracture fillings in Olkiluoto [10]. Postjotnian diabase dykes, aged 1.27-1.25 Ga [18] are also present in the vicinity of Olkiluoto.

2.3. Groundwater conditions

In the otherwise very dry crystalline bedrock of Olkiluoto, the highest water conductivities are found in fractures and fracture zones. The hydrogeochemical baseline conditions of this bedrock groundwater in Olkiluoto have been described in Fig. 1. Different, vertically layered groundwater types can be distinguished and their distribution is monitored within the monitoring programme.

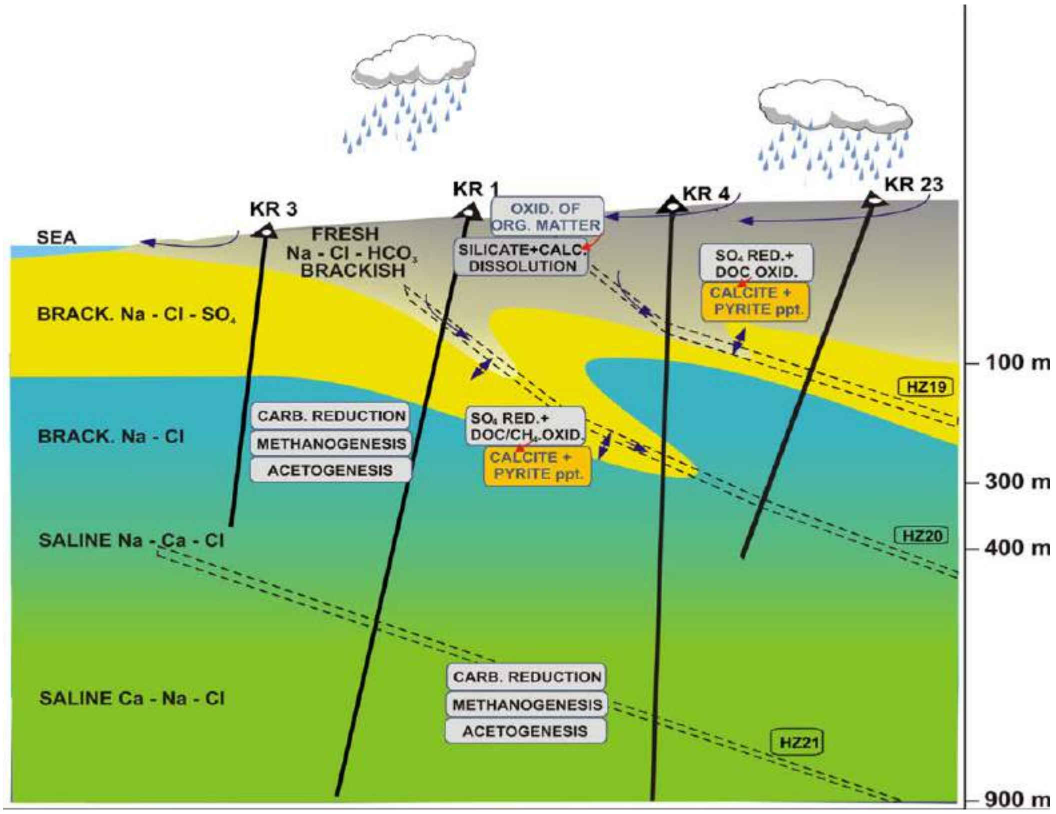

Figure 1: Illustrated hydrogeochemical site model of the baseline groundwater conditions with main water-rock interactions at Olkiluoto. Changes in colour describe alteration in the water type. The hydrogeologically most dominant zones are also presented with indications of groundwater flow (→) and mixing/diffusion (↔) with groundwater in less transmissive fractures. Rounded rectangles contain the main source and sink reactions controlling pH and redox conditions. Enhanced chemical reactions dominate in the infiltration zone at shallow depths, and at the interface between the Na-Cl-SO4 and Na-Cl groundwater types. Note that the illustration depicts hydrogeochemical conditions in variably conductive fracture system (Figure 7-86 in [13]).

3. Regulatory requirements

In Finland, regarding geological disposal, a monitoring programme for the site is either directly or indirectly required by several national laws, decrees, regulations and guides as well as in international guidance. Selected examples are given below.

STUK regulation Y/4/2018 [14] requires e.g. that in order to confirm the performance of the release barriers, a research- and monitoring programme must be established for the operational phase of the repository. The nuclear safety guides YVL D.5 "Disposal of nuclear waste" [15] and YVL D.7 "Release barriers of spent nuclear fuel disposal facility" [16] include several detailed requirements related to monitoring.

The environmental protection act [3] requires that the operators shall have sufficient knowledge of the environmental (not radiation-related) impacts and risks of their operations, and of the management of these impacts and risks and ways to reduce adverse impacts (knowledge requirement). Monitoring is one action to comply with this knowledge requirement. Based on the environmental protection act, Posiva has also been admitted an environmental licence regarding the environmental effects of excavation, rock transport, piling and crushing activities [21].

In addition to the monitoring during construction- and operational phases and based on requirementsfor the closure of the repository at the end of operation, a summary and interpretation of the data provided by the monitoring programme during the operation of the repository shall also be presented in the application for closure [15].

4. Monitored parameters and processes

The monitored processes and parameters have been selected in a way that they either provide data on processes and parameters that relate to different requirements set for the disposal system and the environment or provide background data for site description and different models of the site. Monitoring also provides data for rock suitability classification (RSC) [6], however, the most important task of the monitoring programme is to provide data on long-term safety related processes [12].

Five main objectives have been set for the programme: 1) to demonstrate that the conditions in the repository and its surroundings remain favorable for long-term safety despite repository construction and operation; 2) to collect additional information regarding long-term safety critical properties of the site, which is done for ensuring the suitability of the site and for developing site models; 3) to monitor the environmental impacts of the project; 4) to gather data and provide feedback for construction and design on the impact of construction on the geosphere and surface environment; and 5) to monitor the function of the engineered barriers for ensuring that they function as planned and expected.

5. Structure of the monitoring programme

Posiva's multidisciplinary monitoring programme comprises five sub-sections: i) rock mechanics, ii) hydrology and hydrogeology, iii) hydrogeochemistry, iv) surface environment and v) the monitoring of engineered barriers.

5.1 Rock mechanics

Rock mechanical monitoring concentrates on monitoring the rock mechanical stability of the site, including e.g. rock stresses, rock displacements and seismicity of the site. Seismicity is monitored by using a microseismic network consisting of 18 stations. The microseismic network can detect the excavation-related blasts as well as microearthquakes related to stress field redistribution around the excavated openings. The network also detects possible natural microearthquakes or earthquakes occurring in the area or its vicinity. The microseismic monitoring network is also used for safeguards-purposes in order to confirm the locations of excavations done in the disposal area and its surroundings by Posiva and possible other companies or land owners operating in the vicinity. In addition to the microseismic network, tunnel stability is monitored with extensometers and visual/auditory observations. Extensometers are used for measuring displacements in the tunnel walls or roof, these can be used for monitoring locations in the tunnel which have been identified to be prone for instability or displacements. However, microseismic monitoring is the primary method for confirming the stability of the site. GPS-measurement network and precise leveling are used for monitoring glacio-isostatic land uplift and possible block movements. The GPS-network includes 17 stations, 16 of which are operating continuously. The precise levelling campaigns are done annually or in certain intervals, depending on the levelling loop. The most recent results regarding rock mechanical monitoring have been published in [5].

5.2 Hydrology and hydrogeology

Monitoring of hydrology and hydrogeology provides data on the groundwater surface levels and groundwater pressure gradients as well as groundwater flow and interaction within and around the repository site. The monitoring networks for hydrogeology are largely the same as used for the monitoring of hydrogeochemistry. Posiva uses packers in the drillholes, these allow monitoring of deep groundwater pressure head in each packer-isolated interval in the hole. The water inflow into the underground facilities is measured monthly, the measurement is done mainly by using measuring weirs located in the tunnel. Visual water leakage mapping in the underground openings is done annually. Groundwater surface variation in the overburden is monitored by using a network of groundwater tubes. The most recent results regarding hydrogeological monitoring have been published in [19].

5.3 Hydrogeochemistry

With the hydrogeochemistry- sub-section of the programme, the groundwater composition at the site is monitored. This includes the composition of deep groundwater in the bedrock as well as composition of shallow groundwater in the soil close to the surface. The most important monitoring target in hydrogeochemistry is to monitor the changes in distribution of different compositional layers in the groundwater, especially with regard to the repository host rock. As in hydrogeological monitoring, also in hydrogeochemistry the main monitoring network is Posiva's extensive network of deep drillholes (58 in total) complemented by numerous shallow drillholes, groundwater tubes in overburden as well as underground pilot holes, measuring weirs and groundwater stations drilled in the water-conducting structures of the bedrock, not to forget the ONKALO access tunnel and shafts. Packed drillholes are also used for the hydrogeochemical sampling of the groundwater and in addition, Posiva has continuous monitoring of certain parameters from the packed drillhole intervals. The most recent results regarding hydrogeochemical monitoring have been published in [20].

5.4 Surface environment

Environmental monitoring concentrates on monitoring the traditional environmental effects of the construction, excavation, rock piling, rock crushing and water handling activities at the site. These are monitored by following the composition and flow of surface waters, noise monitoring and land use. The monitoring is complemented by periodical surveys regarding biodiversity. Seawater is sampled in certain intervals. The water levels and groundwater compositions in local private wells are also monitored. For the operational licence application safety case, extensive monitoring networks of the surface environment were used for collecting biosphere modelling data [2]. These included data on transfer of elements and nutrients in different aquatic and terrestrial ecosystems around the island. The most recent results regarding environmental monitoring have been published in [17].

5.5. EBS-monitoring

Monitoring of engineered barrier systems (EBS) will provide data on the evolution of the engineered barrier systems. EBS-monitoring is currently under development and will be implemented at the time of operation. The results of Posiva's own EBS-monitoring development works, Posiva's Full-Scale In-Situ System Test (FISST) as well as results from international projects such as Modern2020 will be utilized when the operational monitoring programme is complilied.

6. Action limits

In the monitoring programme, action limits have been set for the key parameters [12]. The action limits have been either directly or indirectly derived from requirements and are typically placed in between the range of natural fluctuation and requirements set for the system. The purpose of the action limits is to inform that the need of actions needs to be assessed in order to prevent the actual requirements from not being fulfilled. They thus act as warning signs informing if processes possibly unfavorable for long-term safety or environmental safety are going on. If the action limits are exceeded, an administrative handling process is started in Posiva in order to assess the significance of the issue and a decision is made on possible actions according to internal guidance. The action limit exceedings are also reported to the Radiation and Nuclear Safety Authority (STUK). The process for setting limits for monitored parameters and having an administrative process for assessing and deciding on the significance of the exceedings is formally required in national nuclear safety guidance [15] & [16].

7. Conclusions and main results up to date

During its course, the monitoring programme has produced an extensive set of data regarding different processes and phenomena occurring at the disposal site. This data has confirmed many of the preceeding assumptions related to site conditions but at the same time new processes and phenomena have been identified. In general, the monitoring activities have shown that the site is seismically stable and confirmed many of the assumptions related to hydrogeological and hydrogeochemical conditions. In addition monitoring has provided new information regarding the effects and disturbances in groundwater and bedrock, caused by the excavation- and construction activities. Environmental monitoring has shown that Posiva's activities have not had adverse effects to the environment. It can be seen that the monitoring programme in general has fulfilled and continues to fulfill its objectives in producing data which can be utilized for confirming whether the disposal system performs as predicted and planned. The monitoring observations related to groundwater disturbances caused by underground openings have helped in further developing the safety case and the procedures related to excavation and grouting of the tunnels.

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SKB Monitoring Strategy

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1. Summary

Currently SKB is developing an overarching monitoring program for the final repository for spent nuclear fuel. The need was identified during SKB's application process and the program will be delivered to the authorities as part of the application to start construction of the repository. The objectives of the SKB monitoring program related to post closure safety are to check that the basic assumptions made for the assessment of post closure safety are not challenged, to further increase the confidence in SKB's handling and understanding of repository evolution and to contribute to the search for earlier unknown features, events and processes. Monitoring of the repository site has been ongoing since the conclusion of the site investigations, forming a baseline of understanding the temporal variation of e.g, groundwater pressure and hydrogeochemistry for conditions undisturbed by construction activities. Furthermore SKB has a long experience of conducting experiments where monitoring methods have been developed and utilized. Currently work is ongoing to map parameters that can be monitored and that are linked to the safety functions of the KBS-3 concept. The purpose of this approach is to in an effective manner identify the most important processes and parameters that can be monitored based on current expert knowledge. Experts are asked to describe the expected evolution of the parameters suggested for monitoring, to elaborate on different alternative evolutions, explain why these may occur and to state if these could affect the safety functions. In the monitoring program suitable methods for collecting data together with related uncertainties and challenges are also discussed. If applicable analyses necessary to derive the monitoring parameters are described.

2. Introduction

SKB has applied to construct a repository for Sweden's spent nuclear fuel in the crystalline bedrock at the Forsmark site. Licensing is ongoing and a construction permit may be obtained within a few years, as a part of preparation for the next step SKB is developing an overarching monitoring program for the repository to be applied during underground construction and operation. The need was identified during SKB's application process and the program will be delivered to the authorities as part of the application to start construction of the repository. During the initiation of the work it became evident that there was a need to describe different monitoring purposes and how monitoring data are utilized for the different purposes. At the same time the work within the Modern2020 project spurred important discussions on monitoring of EBS related to post closure safety. The work was conducted as meetings and workshops within SKB taking discussions within Modern2020 and with Posiva into account. Also discussions within the IAEA project "Use of Monitoring Programmes in the Safe Development of Geological Disposal Facilities for Radioactive Waste" contributed to the process.

The Swedish concept of spent-fuel repository is KBS-3 (i.e. copper canisters containing the spent fuel emplaced in vertical deposition holes surrounded by a high-compacted bentonite buffer, in crystalline basement granite rock at about -500 m level). The overlying deposition tunnel will be backfilled with bentonite. A concrete plug will be installed at the entrance of each deposition tunnel to control the amount of water seeping out into the main tunnels and to ensure that the backfill stays in place. Eventually the entire repository will be backfilled, the backfill material needs to be tight up to about 100 m above the deposition area.

3. Monitoring purposes

As a result of the work the following three main monitoring cathagories were defined:

a) Monitoring program related to post closure safety

b) Environmental monitoring program

c) Design and construction of the repository

Apart from this, monitoring data can also be used for safeguards and workers safety but this is not discussed in the overarching monitoring program.

Regarding 2) and 3) structured work has been conducted by SKB during the last decades and this will of course continue. However a need for a common description of how monitoring data are collected and analyzed for different purposes was identified. This also requires using common nomenclature and definitions that are clear to the different involved stakeholders. Work to map data collection and utilization was performed and is presented in Figure 1. The Figure includes data from Quality Control and Quality Assurance and illustrates the complexity of how different collected data are analyzed and utilized. The need for this type of overview for data and information flow was also identified in the discussions within Modern 2020 and the ongoing IAEA project to facilitate the scope and limitations of different national monitoring programs.

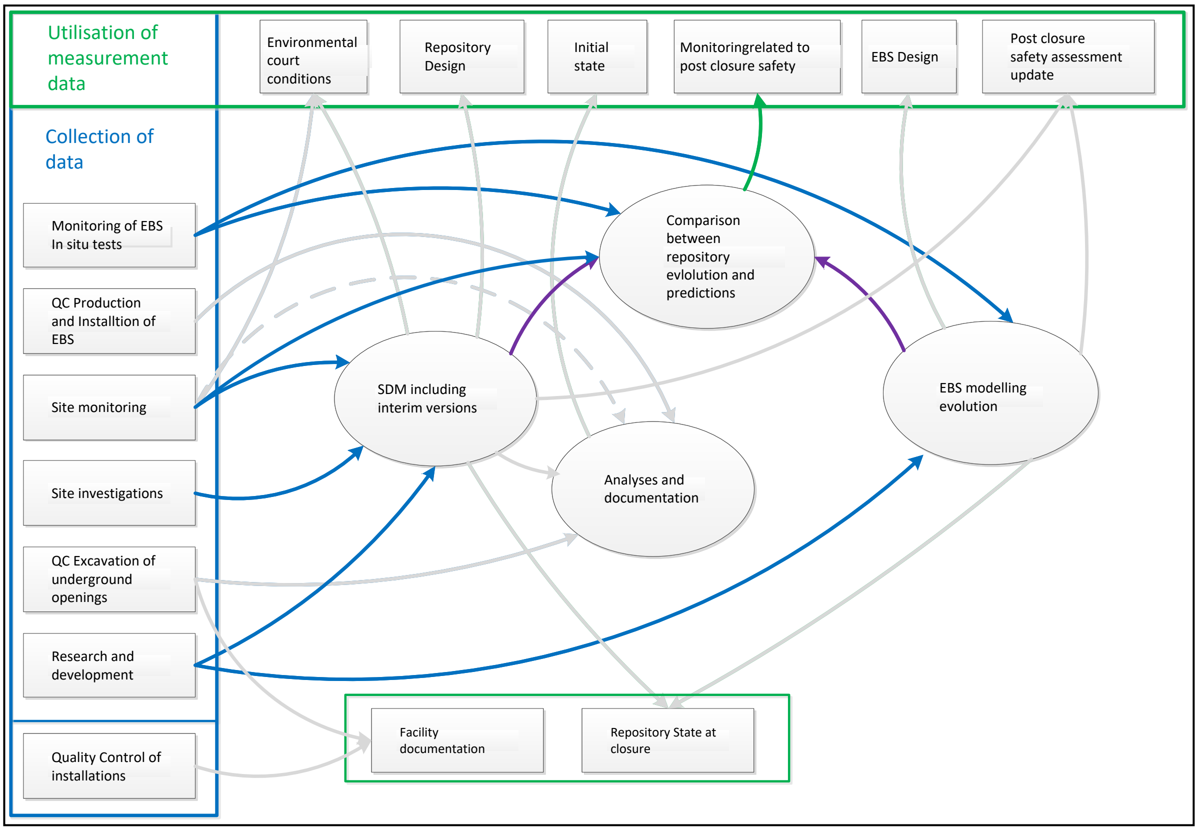

Figure 1: Purposes of Data and Information collection during repository construction and operation. Monitoring data related to post closure safety are illustrated with arrows in blue (from collection to analyses), purple (from one step in the analyses to the next) and green (from analyses to the final utilization of information). The gray arrows illustrate data and information utilized for other purposes

4. Monitoring related to post closure safety

4.1 Objectives

Confidence in the post-closure safety assessment rests upon:

- a sufficient understanding of the THMCB processes determining the evolution of the repository system, thereby providing a necessary basis for demonstrating the repository's ability to provide adequate containment and retention, and
- demonstration that the installed engineered barriers and the underground construction work conforms to stated technical design requirements.

For the former, the thorough process understanding achieved by decades of research will be complemented by a research program tailored to the specific conditions at the chosen site and to the need to analyse the wealth of high resolution rock data expected from the underground site characterisation. For the latter a Quality Control programme is being developed. This implies possibilities to find potential manufacturing or installation errors or other deviations in material, equipment and handling. Before and during waste emplacement, quality control provides the main source for ensuring that the as-built stage complies with stated design requirements.

In addition, monitoring aspects of the evolution during operation may provide further insights. While monitoring results essentially never can relate to direct safety impacts, a management structure will be developed to handle situations when monitoring results deviate from expectations.

Hence the objectives of the SKB monitoring program related to post closure safety are:

- Check that the basic assumptions made for the assessment of post closure safety are not challenged
- Further increase the confidence in SKB:s handling and understanding of repository evolution.
- Contribute to the search for earlier unknown features, events and processes

4.2 Overarching monitoring programme

Currently a draft program is being compiled and work for the different monitoring disciplines is carried out. The program comprises an introduction describing scope, purpose, background, international work and an overview of purposes of data and information collection. The program describes monitoring related to post closure safety and includes statements from the authorities. Follow up of monitoring data, compilation of decision bases and response plans are also described. The site descriptive model that is the starting point for monitoring of hydrology, geochemistry, mechanical and thermal behaviour is described.

The monitoring of buffer, backfill and plugs is described and so is monitoring of copper corrosion. Considering the EBS, the work is currently aimed at designing single or multiple barrier component tests that can focus on processes that are relevant to post closure safety. Work is also directed at developing models to increase the accuracy for predictions of parameter evolution. In some cases the transients during construction and operation of the repository has been assessed to have no or very marginal influence on the post closure safety. Hence little effort has earlier been put into modelling and predicting the parameter evolution for these short transients. This work is now ongoing.

Long-term tests in the repository to monitor the evolution of EBS components will be carried out. The design and planning for such tests has recently been initiated based on SKB’s comprehensive experience of in situ tests. SKB do not intend to apply monitoring that could disturb or jeopardize the EBS function. Hence neither emplaced waste nor EBS components (canister, buffer and backfill) will be directly monitored.

The water flow passing the deposition tunnel plugs will be monitored. As for the host rock, the surface based monitoring activities at Forsmark will continue complemented with monitoring of hydrogeological, geochemical , thermal and rock mechanics parameters from boreholes or other installations underground.

The overarching monitoringprogram also considers monitoring programs related to the environment and to the design and construction of the repository. In the program these detailed programs are generally described in order to provide the overall picture, explain important aspects and to provide references to where the work is described in greater detail.

The resulting monitoring activities focusing on what will be done during the different phases of repository construction, operations and preparations for closure are described. The program also includes a description of how the monitoring program is planned to evolve and become more detailed during the time up so start of operations.

4.3 Developing the monitoring programme

Monitoring of the repository site has been ongoing since the conclusion of the site investigations [1] at Forsmark, forming a baseline of understanding the temporal variation of e.g groundwater pressure and hydrogeochemistry for conditions undisturbed by construction activities. Furthermore SKB has a long experience of conducting experiments where monitoring methods have been developed and utilized. The purpose of these experiments was to increase the knowledge of the host-rock and barriers as input to barrier design, repository design, barrier installation method and to the assessment of post closure safety. This knowledge and experience is essential for planning the specifics of the monitoring programme for the construction and operational phase of the final repository.

Currently work is ongoing to map parameters that can be monitored and that are linked to the safety functions of the KBS-3 concept. The work was initiated by a simple approach where a set of questions and instructions for experts within the different fields were formulated. The purpose of this approach is to in an effective manner identify the most important processes and parameters that can be monitored based on current expert knowledge. A purpose was also to raise the issue within SKB and create commitment and engagement for the coming work where the Modern2020 screening methodology will be used for structuring the findings and for checking that no parameters have been missed.

The experts were asked to describe the expected evolution of the parameters suggested for monitoring. It comprises qualitative descriptions of expected reference evolution that are supported by quantitative examples from models, lab or field data if applicable. The experts were also asked to elaborate on different alternative evolutions and explain why these may occur and to state if these could affect the safety functions of the KBS-3. The experts were also asked to identify need for further development of models and understanding.

It is important to stress that SKB´ss work for the safety case has been directed at processes that have been important for the safety functions for the entire post closure assessment period. However, the work with the monitoring program has also resulted in a need to be able to predict processes that are not necessarily important for the post closure safety. The main purpose of predicting these processes are to show that the understanding of system development is good to further increase the confidence in the KBS-3 and in the safety case.

The experts were also asked to discuss and recommend location and frequency of measurements. Suitable methods for collecting data are discussed. Uncertainties and challenges considering the measurement methods are also discussed. If applicable analyses necessary to derive the monitoring parameters are described. Work needed to develop monitoring program, methods for measurements and analyses are also described.

5. Example of ongoing work for buffer and backfill monitoring

5.1. Parameters and processes suitable for monitoring

As buffer and backfill have been installed these componeents will be saturated with groundwater from the rock. Subsequently the bentonite develops a swelling pressure and homogenizes. The initial state (defined as the properties of the buffer and backfill bentonite together with the density of the installed blocks and pellets) and the degree of homogenization governs the variation in density and hydraulic conductivity at the steady state after homogenization. For a specific bentonite there is a correlation between density, swelling pressure and hydraulic conductivity. The safety functions of the buffer are stated as swelling pressure, density and hydraulic conductivity and the monitoring of water saturation and homogenization are hence directly linked to the safety functions.

The relative humidity in the pores of the bentonite is a suitable parameter to monitor that can be directly correlated to the water ratio of the bentonite. The swelling pressure is a suitable parameter to monitor since it is a safety function, it is also a suitable parameter to follow the homogenization process. However, measuring these parameters alone in a limited number of locations is not sufficient fully understand the evolution. Hence the direct determination of water ratio and density at dismantling of dedicated tests in the repository environment give a more detailed picture. Furthermore, installation of monitoring equipment in the buffer may detrimentally affect its safety functions.

5.2 Expected parameter evolution

The inflow to the buffer and backfill will vary considerably with in the individual deposition hole as well as between the different deposition holes due to the heterogeneous nature of the crystalline rock. Because of this the saturation times will vary between a few years up to several thousand years. Based on results from laboratory tests, field test and modeling the influence on the density after saturation will be marginal. A sensitivity analyses for variations in initial state and water saturation cases are presented in [2] and a comparison of modeling tools and a full scale test of backfill deformation is given by [3].

5.3 Work to develop models to enhance prediction of parameter evolution

An extensive work to enhance the understanding of bentonite saturation and homogenization of bentonite is currently ongoing within the European Union project BEACON. SKB are also conducting work for improving the modelling tools for buffer and backfill homogenization. These models will be used for updating design to fulfill requirements from post closure assessment while creating good possibilities to achieve a robust and efficient production and deposition process in the repository facility.

5.4 Plans for monitoring program

Field tests for monitoring buffer saturation and homogenization will be carried out at repository depth in Forsmark. The tests will be designed based on SKB experience from field tests in different scales in Äspö HRL. The current plan is that the test will be downscaled to make it easier to focus on the parameter evolution for monitoring. This makes it possible to create a larger test matrix to monitor. The monitoring will be based both on results from sensors during the running of the tests and on results from the dismantling that will be performed according to pre-set intervals. Using this approach no monitoring equipment that may detrimentally affect its safety functions is installed in the active buffer barrier. The data from dismantling of tests is also more reliable than data from long term measurements with sensors and greatly reduces the risks of misinterpretion.

6. Conclusions

Currently SKB is developing an overarching monitoring program for the final repository for spent nuclear fuel.The objectives of the SKB monitoring program related to post closure safety are to check that the basic assumptions made for the assessment of post closure safety are not challenged, to further increase the confidence in SKB’s handling and understanding of repository evolution and to contribute to the search for earlier unknown features, events and processes.

Monitoring of the repository site has been ongoing since the conclusion of the site investigations, forming a baseline of understanding the temporal variation of e.g, groundwater pressure and hydrogeochemistry for conditions undisturbed by construction activities. Currently work is ongoing to map parameters that can be monitored and that are linked to the safety functions of the KBS-3 concept. Experts are asked to describe the expected evolution of the parameters suggested for monitoring and to elaborate on different alternative evolutions and explain why these may occur and to state if these could affect the safety functions. Suitable methods for collecting data are assessed.

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C.b – Session on Citizen Stakeholder Participation

Building Trust and Improving Safety? A Four-Nation Comparison of Public Participation in Monitoring of Nuclear Waste

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1. Summary

In this paper we present how monitoring is assessed in four European national nuclear waste programmes in order to improve safety, Belgium, Finland, France and Sweden, and also in the EU ambition to reconcile the national differences by efforts of collaboration and coordination, i.e. to establish consensus on the role of monitoring for improving safety.

The paper is developed in three steps. First, we present the differences and similarities between the four European nations on how to understand the role of monitoring. Secondly, we analyse how trust is connected to the way monitoring is assessed. Thirdly, we discuss the role of public participation when developing monitoring programmes.

To conclude we highlight some key points for guidance on how to implement public participation in relation to technical programmes (trying to combine the issues of consensus, trust and participation):

- Be sensitive towards consensus. What are agreed technical solutions and agreed political projects, and what is not agreed upon? Consensus is something good but should never be intertwined with coercion.

- Be sensitive towards processes which delegate decision power to technical experts. Delegation to experts could be something good, especially when there are, for good reasons, high trust in expert knowledge and experts. But this must build on lack of controversial issues and major uncertainties. If there is lack of consensus and trust, delegation to experts must be conditional.

- Be sensitive towards what is open for discussions when citizen stakeholders are invited to discuss so-called technical issues. There must be something important to negotiate about, otherwise participation become 'tokenistic'.

2. Introduction

Geological disposal (GD) is today an internationally agreed solution for managing nuclear waste. The Implementing Geological Disposal Technology Platform (IGD-TP), initiated by the European Commission in 2009, states that time has come to implement this agreed solution [1]. Part of this is the aim of passive safety, i.e. disposal without intention of maintenance or retrieval [2]. However, the clear distinction between storage and disposal has gradually become blurred, partly due to long time delay in planning processes but also to development of monitoring technologies, opening up for continuous vigilance, which could be viewed as in conflict with the aim of disposal and passive safety. In relation to monitoring, the IGD-TP concludes that “a license application is not received favourably, if it does not include a monitoring programme” [3].

Interestingly, we find important differences concerning monitoring among European nuclear nations most close to implement their waste programmes. Some assess monitoring as a way to improve or confirm safety, while others consider it a threat to safety. These differences could be explained by specific national trajectories deriving from political conflicts.

In this paper, which has been developed by the social science part of the Modern2020 programme, we present how monitoring is assessed in four European national nuclear waste programmes in order to improve safety, Belgium, Finland, France and Sweden, and also in the EU ambition to reconcile the national differences by efforts of collaboration and coordination, i.e. to establish consensus on the role of monitoring for improving safety. This paper on the development of monitoring programmes in European nuclear nations, and who should be involved and responsible for this work and for what reasons, is developed in three steps:

The first is about the differences and similarities between the four European nations on how to understand the role of monitoring. Is monitoring important or not, and is a consensual view on this issue important?

The second is about the role of trust, and how this is connected to the way monitoring is assessed. Is monitoring a way to increase public trust in nuclear waste management or not, and what explains the possible existence of trust or distrust?

The third is about public participation when developing monitoring programmes. What is the role of citizen stakeholders, living in the vicinity of a planned nuclear waste repository, in this work? What is meaningful participation?

In order to analyse this situation, ideas from science and technology studies (STS) are utilized, and we especially focus on the role of consensus as a political goal, trust as strongly dependent on context, and public participation as something in need of topics open for discussion in order to become meaningful. As part of our empirical data we will use the reports published by the Modern2020 programme and also the surveys we have carried out, in which both technical experts and local citizen stakeholders in the four nations have answered questions on monitoring and safety.

3. Consensus, Trust and Participation

In relation to the first step, we argue that technical *consensus*, such as about GD and monitoring, can only be explained as a result of political ambitions, which these technological solutions also reinforce. Our analysis tries to improve the understanding of consensus: why it is strongly pushed for by leading nuclear actors, such as the EU IGD-TP and the Modern2020 programme; the latter understood as a programme for facilitating and ordering the different national views on monitoring into one coherent understanding, i.e. a protocol. We argue that political and technical consensus are mutually supporting each other. Therefore, the political push on technology development should become more visible and better understood, and an alternative view on consensus is proposed, which not conceal the political choices involved when trying to establish agreements on technical solutions.

According to STS scholars, there is much to gain from consensus. When there is agreement, the fact or the artefact becomes ‘natural’, i.e. immutable and inevitable [4]. There are no longer possible alternatives, and there is no need for alternatives since the working, or the safety, is taken for granted. When there is no consensus on what makes an artefact, such as a nuclear waste repository, working or safe, the ‘working’ and ‘nonworking’ of the artefact become seen as something in need of explanation instead of seen as “intrinsic properties of the artifact” [5]. “When a scientific controversy is closed by the participants reaching consensus, scientific facts are created” [5].

However, and this is the important and classical position taken by STS scholars, to “assume that such consensus exists, and act as if it did, is a form of political coercion” [6]. This means that consensus conceals political interests, and accordingly the STS ambition is to describe and analyse how political interests are important drivers behind consensus, being it social or technical consensus, and also show how these interests become hidden when consensus is established and just the facts remain.

Results from our survey show that both technical experts and local citizen stakeholders disagree about the statement that “repository monitoring makes the repository safer”; the results were quite evenly spread between disagree and agree (both for technical experts and local stakeholders). This means that consensus is quite far from being “natural” concerning how monitoring could improve safety.

In relation to the second step, we argue that GD of nuclear waste gives an exceptional case of societal *trust* in science and technology, which means delegation of both trust and safety to geology. While the principle of passive safety remains at the core of all GD concepts, over the past two decades influential international bodies have raised the issue of integrating monitoring activities in some phases of the disposal process as it would hold potential to confirm safety case assumptions and build stakeholder confidence. Interestingly, it appears that monitoring is welcomed as a tool for trust building in some countries while being discarded for being superfluous and undermining trust in other countries, particularly those characterized by high level of trust in science and institutions, i.e. Finland and Sweden. Drawing from participatory observation and field research, part of the Modern2002 programme, we explore and compare the different discussions and strategies regarding monitoring in the four nations. Doing so we disclose the different ways in which monitoring strategies reflect how national GD programmes deal with uncertainties, trust building and the delegation of societal responsibilities in the context of nuclear waste management.

In relation to the third step, we present some data from our studies on how citizen stakeholders, waste management organisations and technical experts discuss monitoring and *who should be involved* and responsible on what topics in relation to developing monitoring programmes. We also present some thoughts on meaningful participation and try to summarize this in some practical guidance for other R&D programmes, which plan to integrate local stakeholders at an early stage. In this we try to focus on the role of consensus, trust and what meaningful participation is and could be.

An agreed starting for participants in the Modern2020 programme discussing meaningful participation is that all stakeholders (including implementers, regulators, and local publics) should be asked the same question, i.e. what do you expect from monitoring? Furthermore, all stakeholders should be involved from the beginning of the process, which in STS is called upstream engagement [7]. The output from the process could be the screening of parameters, i.e. what to monitor and what not to monitor and give reasons for these choices.

However, according to results from our survey, there exists a large discrepancy between local stakeholders and technical experts with regards to the extent to which local stakeholders should be involved on the technical/engineering level of a specific R&D project. 85 per cent of technical experts does not think that local stakeholders should be involved in these matters (such as repository design or design of monitoring systems), whilst 44 per cent of local stakeholders do see a role for themselves here. A significant part of the local stakeholders (35.5%) are, moreover, convinced that local stakeholder involvement in the R&D of monitoring has the potential to improve the design of the monitoring system, whilst only 9.1% of the technical experts shares this opinion.

Citizen stakeholders consider themselves to be watchdogs over the development of monitoring, also with regard to the wellbeing of future generations. As being informed, knowledgeable bridge-builders and watchdogs, they see themselves as possible brokers between technical expertise and broader public groups. However, citizens are aware of that much of this topic is beyond their knowledge, but also that experts lack knowledge and often frame risk issues as being just about technical details.

These results mean that it is of great importance to carefully assess on what topics in what phases of the development process, and for what reasons, citizen stakeholders should be engaged.

Finally, we conclude from our studies that there must be something to negotiate in order to establish meaningful participation, and we should always ask what is open for negotiation and what is not, and for what reasons. This also connects to the issue of consensus: what do we agree on and what do we disagree on? If there are no issues open for discussion, participation becomes ‘tokenistic’.

4. Conclusions

To conclude we want to highlight some key points for guidance on how to implement public participation in relation to technical programmes (trying to combine the issues of consensus, trust and participation):

- Be sensitive towards consensus. What are agreed technical solutions and agreed political projects, and what is not agreed upon? Consensus is something good but should never be intertwined with coercion.

- Be sensitive towards processes which delegate decision power to technical experts. Delegation to experts could be something good, especially when there are, for good reasons, high trust in expert knowledge and experts. But this must build on lack of controversial issues and major uncertainties. If there is lack of consensus and trust, delegation to experts must be conditional.

- Be sensitive towards what is open for discussions when citizen stakeholders are invited to discuss so-called technical issues. There must be something important to negotiate about, otherwise participation become ‘tokenistic’.

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Trust, mistrust and citizen vigilance in radioactive waste management policies: a historical analysis of four forerunner countries

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1. Summary

Trust-building has become somewhat of a 'magic bullet' supposed to solve the problems of local citizen acceptance of radioactive waste repositories. National and subnational governments as well as industry actors have sought to build trust, e.g. via partnership approaches, supported by capacity-building and exchange of 'best practice' in international forums. Building on research conducted within the EU-funded HoNESt project (History of Nuclear Energy and Society), we analyse trust-building in RWM policy from a historical cross-country perspective. The paper focuses on two hitherto largely overlooked aspects in literature on trust and RWM policy: 1) the interaction between various dimensions of trust in shaping RWM policy, and 2) the potential downsides of trust and the corresponding virtues of mistrust, especially in the form of 'civic vigilance'. To illustrate our arguments, we analyse the RWM policy experience of four key European forerunner countries – Finland, France, Sweden and the UK. Our case studies contrast the experience of the two Nordic 'high-trust societies' with those of France and the UK, characterised by far lower levels of interpersonal and institutional trust. We examine role of trust in explaining the contrast between the relative ease in Finland and Sweden, and the corresponding difficulties in France and the UK in advancing repository projects. We also explore the differences between two Nordic cases, which illustrate the virtues of mistrust as 'civic vigilance' and the downsides of "overtrust" and excessive deference to authorities. Efforts to improve citizen participation and monitoring of RWM projects should take into account and draw upon the specific ways in which trust and mistrust exhibit themselves in any given policy context.

2. Introduction

Spurred by repeated failures to gain public acceptance for high-level radioactive waste repositories across a number of Western countries, and in the context of concerns for a long-term decline of trust in state institutions, radioactive waste management (RWM) emerged, since the 1990s, as a forerunner in participatory governance approaches. As part of these efforts, trust-building has become somewhat of a 'magic bullet' supposed to solve the problems of local citizen acceptance of waste repositories. Because of the long-term, multilevel and sociotechnical character of RWM, the role of institutional trust has been seen as primordial – in particular, public trust in safety experts and the institutions responsible for planning and implementing RWM solutions. In consequence, national and subnational governments as well as industry actors have sought to build trust, e.g. via partnership approaches, and, to a lesser extent, through the concept of Social Licence to Operate – SLO [1]. These have been accompanied by trust-building efforts at the international level, with the Forum on Stakeholder

Confidence (FSC) within the OECD Nuclear Energy Agency as a key example of attempts to facilitate cross-country learning via exchange of information, experience, and 'best practice' [2].

3. Research questions, data and methods

Building on the three and a half years (2015-2019) of research conducted within the EU-funded HoNESt project (History of Nuclear Energy and Society), which analysed the evolution of the interaction between the nuclear sector and society in Europe, this paper suggests a novel historical and cross-country perspective to trust-building in RWM policy. In doing so, the paper focuses on two hitherto largely overlooked aspects in literature on trust and RWM policy: 1) the interaction between various dimensions of trust in shaping RWM policy, and 2) the potential downsides of trust and the corresponding virtues of mistrust, especially in the form of 'civic vigilance' [3]. To illustrate our arguments, we analyse the RWM policy experience in four key European countries – Finland, France, Sweden and the UK. We examine in particular the evolution of the efforts to build institutional trust, from the purely technical to more participatory arrangements since the 1990s. The selection of these case study countries allowed us to contrast the experience of Finland and Sweden as 'high-trust societies' – where both generalised social trust and institutional trust are exceptionally high – with those of France and the UK, where both types of trust are at low or medium European level [4, 5, 6, 7, 8]. We examine the degree to which the historically high levels of trust in Finland and Sweden help explain the relatively smooth advancement of these countries' deep geological repository projects on one hand, and the continuing difficulties of France and the UK in their respective RWM policies, on the other. Moreover, while Finland, France and Sweden, are forerunners in that all have identified a host site for their far-advanced nuclear waste repository projects, the UK provides an illustrative contrasting case: it has a long history of unsuccessful to reach consensus on RWM policy and find a willing host community, despite innovative experiments in deliberative decision-making especially in the early 2000s. We also seek to understand the differences between two Nordic cases: the Swedish project has experienced delays caused by scientific controversies that have been debated in public (incl. in the Environmental Court), while this kind of a debate has hitherto been largely absent in Finland.

In addition to research on the history of nuclear energy and society conducted as part of the HoNESt project, the paper draws on existing literature concerning nuclear waste policy and community benefits; on semi-structured interviews carried out with key actors involved in the nuclear waste policy of the four countries at the national, regional and local levels (e.g. local politicians, civil society, departmental authorities, state representatives at the departmental level, the nuclear industry and waste management organisations, the central government, and academic researchers); and on the authors' earlier work on the subject [9-15]. On all four countries, informal discussions conducted over the years with stakeholders and experts provided further inputs.

4. Conceptual framework

Drawing on social science literature on the various types and roles of trust and mistrust, we distinguish between social (interpersonal) trust on one hand, and institutional trust on the other. To complement this conceptualisation often adopted in research on trust, we build on Tait [16], who called for greater attention to the ideological dimension of trust on one hand, and to the dynamic interaction between the three dimensions of trust – social, institutional, and ideological – on the other. Lastly, we draw on recent literature [e.g. 17] specifically focused on mistrust as a central variable and as a possible asset, rather than as a mere reverse side of trust. For the sake of simplicity, we use the term trust to encompass both its traditional meaning as a normative judgement concerning an individual or entity, and *confidence*, that is, a belief based on earlier experience that certain events will occur as predicted [18, 27, 19].

Social trust is interpersonal, and can be divided into **generalised** trust in other, unknown, members of society [20] – the 'cultural glue' of society – and **particularised (specific)** trust in people we already know, with whom we interact regularly, for example in our own social or demographic group [21]. Research and practice in the area of RWM policy has often focused on **institutional trust** – the public trust in key actors involved in RWM, such as nuclear safety authorities, the government, nuclear operators, and environmental organisations. Following Hodgson [22], we define institutions broadly, as "systems of established and embedded social rules that structure social interactions". Organisations, in turn, are a specific type of institution. Also this type of trust can be divided into two categories. What we here call **specific** institutional trust reflects an individual's support to a given organisation or entity (e.g. the present government or parliament, a specific industry enterprise). **Diffuse** trust, in turn, relies on more general, diffuse support to an institution, regardless of its current composition. While the former is typically based on judgements concerning the performance of an institution (what the institution *does*), diffuse institutional trust relies on what the institution represents to the trusting individual (what the institution *is*). By enhancing the legitimacy of institutions [23], this type of trust is expected to improve governance. Finally, **ideological trust** [16] relates to more abstract institutions, such as democracy, the state, market, and planning. In our case, it concerns the general perceptions concerning the appropriate roles and legitimacy of, for example, government, industry, and NGOs in shaping and implementing RWM policies. As a more abstract form of trust, difficult to capture via quantitative surveys, ideological trust has received far less attention than the two first dimensions of trust.

Mistrust[1] can entail on the one hand doubt, fear, even paranoia, but on the other hand also suspicion, prudence, cunning and vigilance [17]. It can present itself as conditional trust entailing the idea that under certain conditions and circumstances, one might trust the 'trustee'. As 'healthy suspicion', mistrust constitutes the very foundation of liberal democracy, by ensuring that citizens can control and hold accountable the powers that be [17, 24-26]. It can help anticipate the future [27], deal with complexity and uncertainty, and facilitate cooperation in situations that entail asymmetries of power [17]. We draw attention to 'vigilant mistrust', which can be either institutionalised in regulatory agencies and in systems of monitoring and accountability – variously referred to as 'due diligence' or 'checks and balances' [24, 28, 29], or take the form of 'civic vigilance' via the activities of NGOs or civil society organisations [16]. We also highlight the multiple ambiguities and paradoxes of trust and vigilant mistrust, and illustrate the reciprocal, asymmetric and self-reinforcing nature of trust and mistrust [30, 31, 32].

Sources of trust and mistrust vary. Sincerity and competence are often highlighted as the fundamental characteristics that an entity must be seen to possess, in order to be trusted [3, 33]. Institutional trust feeds on attributes such as integrity, empathy, transparency, common values, and proximity [34]. Trust and mistrust can rely on a normative predisposition in relation to an individual or an institution, but it can also draw on past experience concerning the trustworthiness of the individual or institution. Finally, ideological trust has its basis in broader visions and worldviews.

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[1] While a distinction is sometimes made between mistrust and distrust (e.g. 45, 46), these concepts are here used as synonyms.

5. Virtues and vices of trust and mistrust

Trust has its incontestable virtues. It has been described as an essential element of social life [17], and as a foundation for interpersonal relations, economic exchange [35], societal and economic development [8, 36], and legitimacy of political power. Empirical analysis has associated trust with such benefits as economic growth, innovation, rule of law, good governance, low levels of corruption, education, absence of violence, subjective well-being [26, 37], environmental performance [38, 39], and acceptance of industrial installations entailing potential health and environmental risks.

However, excessive and unwarranted trust can be detrimental. In particular, it can foster complicit acceptance of harm or wrongdoing, and it may incite people to delegate decision-making to trusted experts and institutions rather than to participate in governance [40]. The strong 'particularised' social trust – often seen as an element of 'bonding' social capital – can feed exclusion, homogeneous social networks, potentially dysfunctional norms of reciprocity [41, 42], groupthink, and the exclusion of different yet competent others [43] – phenomena familiar also for various RWM communities.

While demonstrating the safety of the waste disposal solution constitutes the most fundamental trust-building measure [e.g. 44], our focus in this article is on **measures to strengthen trust in institutions**, as a foundation for trust in the viability and safety of the disposal concept: given that few citizens have the requisite expertise to judge the technical aspects of a repository project, trusting a disposal concept actually translates into trusting in the implementing and regulating bodies. Trust-building measures include notably the creation of independent bodies of control and oversight; participatory governance arrangements; stepwise decision-making; the principle of voluntary engagement by the community and the possibility to withdraw from the siting process; partnerships between the RWM policy implementers and local communities; community benefit schemes; and the extension of the conventional one-way communication concerning the RWM activities to a broader strategic questions relating for instance to energy policy [14, 47]. Obviously, trust-building measures can fail or even backfire. This can happen when deliberative and participatory processes are motivated by purely instrumental rationales – the desire to gain the trust of key community actors in order to ensure the acceptance and legitimacy of a project in question [44, 49]. In situations of longstanding institutional mistrust, attempts by the project developer to enhance participation and openness can initially undermine trust [3, 50].

Table 1 summarises the typology of trust and mistrust that guides our analysis of the RWM policies of the four case study countries.

Table 1. Summary of the key concepts relating to trust, mistrust, and trust-building.

Type of trust/mistrust	**Social**	**Institutional**	**Ideological**
Description	Generalised Particularised	Diffuse support Specific support	Legitimacy of and support to meta-level institutions
Sources of trust	Competence Sincerity		Worldviews, visions
	Normative predisposition in relation to an institution or an individual (trust)		
	Predictability, based on previous experience (confidence)		
Trust-building	Independent bodies of control and oversight Participatory governance Stepwise decision-making Voluntary opt-in and opt-out Partnerships Community benefit schemes Broadening of debate to strategic questions (e.g. energy policy)		

In this paper, we will not conduct a rigorous comparative analysis of the four cases, but rather seek to illustrate, via an empirical analysis of four case studies, the complex dynamics of trust and mistrust in the four countries. To structure the analysis, we explore three concrete aspects in each case:

1) How have the key trust and mistrust relationships evolved over the years?
2) Which measures have been implemented to build trust?
3) Which measures have worked, which have failed, and why?

6. Discussion

Each of the four case studies allows us to illustrate a specific aspect of trust and mistrust related to RWM policy. We summarise our findings by describing the Finnish case as an example of *'pragmatic' or 'resigned' trust*, in which the repository project appears somewhat of an inevitability, albeit an outcome of a legally correct and therefore legitimate process. Despite the strongly contrasting conditions of institutional trust in the two countries, the French case of *'resigned' trust* exhibits similarities with the Finnish one. Despite the burgeoning and sometimes radical activism against the project – activism that is also national and internationally networked – the French local-level situation is characterised by a combination of ideological trust in the state; deep-seated reciprocal relations of institutional mistrust; attitudes of resignation and powerlessness amongst the local municipal leaders and officials in the face of government decisions; and perception of the repository project as the 'only hope' in an economically declining region. The Swedish example stands out as the purest example of *'genuine trust via constructive mistrust'*, based on dialogue and counter-expertise, and backed up by strong national-level social and institutional trust, as well as ideological trust in representative politics. Lastly, the UK case could be described as one of *'ambiguous mistrust'*. It underscores the ambiguities in the simultaneous growing institutional mistrust of the 'Big Six' energy companies [51] and the long-standing ideological trust in market-based policy solutions, manifested in the energy policy "market fundamentalism" [52] or "pro-market energy policy paradigm" [53]. The UK case further underscores the coexistence of trust in markets with trust in "community" [54], and the contrasting discourses of 'technocratic' trust in government scientists, and anti-nuclear discourses of mistrust in government scientists [13].

7. Conclusions

Our cases demonstrate how, in order to succeed, trust-building efforts must link and hold together trust-relationships at the three levels – social, institutional and ideological. We conclude by exploring the role of different regulatory styles on the operation of varying forms of ‘civic vigilance’, which we consider as one of the possible manifestations of ‘virtuous mistrust’. The sharp differences between the Finnish and Swedish RWM policies with regard to ‘civic vigilance’ calls into question the idea of a ‘Nordic model’: in Sweden, ‘civic vigilance’ is an integral part of the regulatory model, whereas in Finland, its absence evokes the danger of institutional ‘overtrust’ – excessive deference to authorities. Recent Swedish experience carries traits of a mistrust-based regulatory style – which is arguably making inroads to Nordic administration more broadly [55, 56], but does not seem to have yet affected the Finnish RWM policy. Civic vigilance appears to more naturally fit within the mistrust-based democracies of France and the UK than in the Nordic countries, whose democracies have historically been built upon trust rather than mistrust of state institutions. However, conditions for civic vigilance differ also between France and the UK, notably for reasons related to differences in ideological trust in the state, market, and community in the two countries. The varying degrees of ideological trust – in state, market, community, and representative democracy – crucially shape the institutional trust relations, conditions of ‘civic vigilance’, and success of trust-building efforts.

We further underline the mistrust based on ***historical legacies,*** which weighed particularly heavily in the UK and in France. These cases also illustrated the ***reciprocity and asymmetry of trust and mistrust***, including notably the ways in which mistrust on the part of waste management experts and authorities towards the citizens fed institutional mistrust. The relative successes of the Finnish and Swedish repository projects owe not only to generally high trust in institutions, but also to the long-established ***social trust relationships***. In France, social trust relations consolidated the “nucleocracy” – a central target of criticism and mistrust, and a source of “us vs. them” perceptions at the local level. In the UK, reciprocal social mistrust was evident in the 1990s between the waste management experts and local citizens.

Our analysis underscores the importance of the initial conditions of institutional and ideological trust as crucial determinants of the success of local-level trust-building efforts. Among such background conditions, the familiarity or not of the host community with nuclear industry, as well as the constant spill-overs from nuclear energy policy appear as the most crucial. Our examples contrast the relative ease of trust-building in the Nordic ‘nuclear communities’ as opposed to the French region without experience of nuclear power, yet as the UK case shows, previous experience of nuclear installations does not guarantee trust. Finally, our case studies highlight the potential and limits of constructive mistrust, especially via citizen vigilance, in strengthening the social robustness of a repository project. It appears that the preconditions for full exploitation of the virtues of mistrust are complex: while our two Nordic case study countries present equally high levels of generalised social trust, institutional trust, and ideological trust in representative democracy, the trust in dialogical and more direct forms of democracy appears to make a vital difference. Further research would be needed to explore the conditions under which citizen vigilance could best operate in conditions of strong institutional mistrust as in France and the UK.

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Nuclear Culture and Citizen Participation: Networked and distributed artworks

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1. Summary

This presentation introduces the Nuclear Culture project's artistic and curatorial strategies for engaging citizens in an interdisciplinary and indepth discourse about long-term radioactive waste management through networked and distributed artworks.

There is an established humanities discourse on the relationship between social and technical challenges of long-term radioactive waste siting, monitoring and site marking, to which the visual arts can make a valuable contribution. Although there is a significant volume of contemporary visual art produced about this topic, there is a severe lack of curatorial work to establish its contribution to the wider arts, humanities and Radioactive Waste Management (RWM) discourse. The Nuclear Culture project aims to readdress this balance, enabling curatorial and artistic research to contribute new knowledge to the field of nuclear arts and humanities, and to be embedded in nuclear sites and museums around the world.

At the same time RWM is interested in the role that visual artists and their work can play in the public consultation and stakeholder engagement around geologic storage of high-level radioactive waste. Government directives encourage wide ranging forms of public engagement with the issues, hoping to establish public acceptance. However, the instrumentalisation of art for political ends will always be resisted by contemporary art. Instead the visual arts can provide a more complex and nuanced form of citizen participation, to establish social and technical networks for contemporary art where creative partnerships across sectors and disciplines build new knowledge within the deep time politics of the nuclear. In this way, art can create a space for a wider cultural debate, which includes voices of protest and dissent within the framework of nuclear heritage, present and futures.

In this presentation, curator Ele Carpenter and artists Andy Weir, Jon Thomson and Alison Craighead argue that the only way to commission contemporary art in response to the nuclear is to fully understand the cultural and artistic context, as well as the social and technical challenges of RWM. They argue that this can only be achieved through working in partnership with professional curators, arts organisations, galleries and museums to ensure that the work can productively contribute to public cultural discourse and archives. These partnerships require long-term strategic commitments from the industry, university and art museum sectors.

2. Introduction

The Nuclear Culture project, curated by Ele Carpenter, has successfully engaged over 100,000 people with artworks investigating radiological deep time and nuclear aesthetics by commissioning new artwork, curating exhibitions, organising site visits and roundtable discussions in partnership with arts organisations and nuclear agencies. The project has an ongoing impact on the contemporary debate about long-term storage of radioactive waste through publishing, reviews, book chapters, journal papers and touring films and artworks. The findings of the project are regularly presented at conferences on nuclear culture, nuclear history, nuclear humanities and European research programmes on art, archives, and site markers.[1]

Following the success of the 'Perpetual Uncertainty' exhibition[2] and The Nuclear Culture Source Book[3], Carpenter's curatorial research in Nuclear Culture is now focusing on articulating a range of curatorial methodologies for commissioning artwork in nuclear contexts. Whilst there is a significant body of artwork being produced in response to deep time aesthetics, there is an important need for curatorial frameworks to enable artwork to contribute to the production of knowledge in the field through academic, social, public and artistic discourses and contexts. This abstract and presentation focuses on the curatorial methodology of commissioning networked and distributed artworks through consultation with the Records, Knowledge & Memory (RK&M) project.[4]

The aim of commissioning artwork that has 'distributed' characteristics is to enable it to exist in many places at once, forming a network between sites, communities, digital and physical platforms. A distributed network was Paul Baran's proposal for an indestructible communications system in the event of a nuclear war (Fig.1). Ele Carpenter applies the internet logic of Baran's distributed network topology to socially engaged and new media artworks that can function on an international scale across public and archival platforms. These artworks include: Thomson & Craighead's Temporary Index, currently being commissioned by the NDA for the Nucleus Archive at Wick, Scotland; and Andy Weir's Pazugoo figures which are being modified for nuclear sites and museum collections around the world.

3. Methodology

The Nuclear Culture Research group employs a range of visual art and curatorial practice based research methods. These include situated field research, unstructured interviews, materials testing, and the iterative conceptual development of the relationship between theory and practice in the process of making. Collaborative methodologies for inter-disciplinary, multi-disciplinary and socially engaged practice are used to engage exhibition audiences, stakeholders and cross-sector agencies in indepth dialogue. Pedagogic workshops enable young people to participate in the creative development and production of the artwork. The public engagement with the work is an essential part of its iterative development and dissemination, and includes academic seminars, doctoral research, artistic production and curatorial production. Artworks are developed through testing the concept in nuclear and museum sites, drawing on the specific local context and issues. Artists and curators regularly consult with nuclear scientists, anthropologists, ethnographers, materials scientists and radiation protection advisors in the planning and implementation of their work.

The curatorial methodology to commission artwork that has 'distributed' characteristics enables it to exist in many places at once, forming a network between sites, communities and platforms. Influenced by Paul Baran's network topologies for an indestructible communications system in the event of a nuclear war (Fig 1). Ele Carpenter considers the open source logic of Baran's distributed network as a way of mapping socially engaged and new media artworks that operate across multiple digital, analogue and physical platforms.

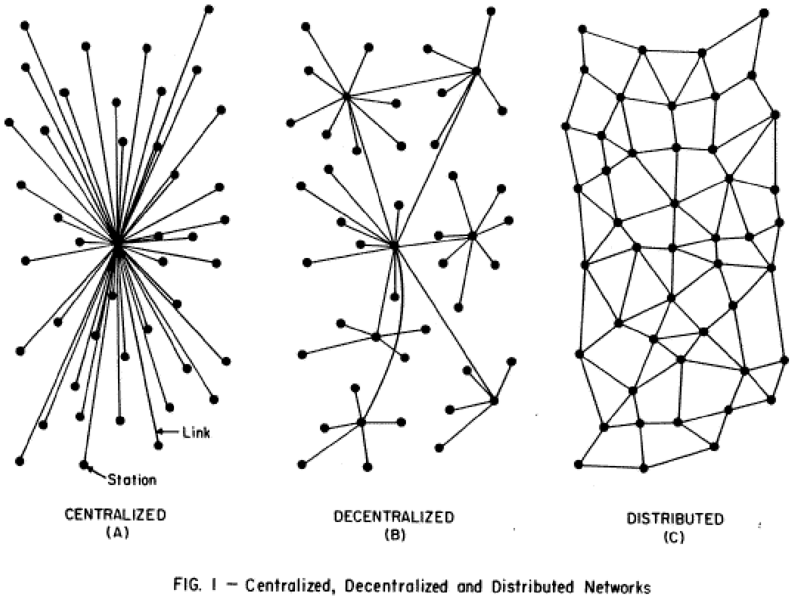

Figure 1: Paul Baran, Distributed Networks, 1964. On Distributed Communications: I. Introduction to Distributed Communications Networks. Santa Monica, CA: RAND Corporation. Available at: http://www.rand.org/pubs/research_ memoranda/RM3420

A centralized network (A) is based on an analogue communications structure such as radio, where one person can broadcast to many people, but the flow of communication is generally in one direction, from the center to the periphery. The decentralized network (B) starts to map our social networks, where community groups are able to communicate through smaller hubs. However note that they all connect to a central hub or node. The distributed network (C) uses the same network of stations or nodes, but provides links between as many of the nodes as possible. The survival strategy relies on information being able to communicated through multiple routes, like the internet packet switching capacity. When thinking about distributed networks we can consider how physical sites such as the art gallery or museum function within a network of groups, archives, records and practices. We might consider a network as a constellation of human and non-human actors that support the development and distribution of ideas across time and space.

If artwork is to be sustainable over generations it needs to operate across different networks, platforms, sites and contexts. It needs to be preserved through online and physical archives, in public and private sites, in industrial and artistic locations and discourses. The role of the curator of contemporary art is to build a context for art within wider socio-political as well as art-historical or museological frameworks. At the same time the preservation of Records, Knowledge and Memory of radioactive waste sites also requires this kind of curatorial knowledge to support its work.

4. Results

4.1 Andy Weir

Two distributed and networked artworks developed through the Nuclear Culture project include Thomson & Craighead's *temporary index*, currently being commissioned by the NDA for the Nucleus Archive at Wick, Scotland; and Andy Weir's *Pazugoo* figures which are being modified for nuclear sites and museum collections around the world.

Andy Weir is an artist investigating knowledge and agency within deep timescales through strategies of complicity and fiction. His artwork *Pazugoo* is a distributed constellation of figures proposed to be buried at specific sites of nuclear waste storage.

The collectively modifiable figures are based on Pazuzu, the Assyrian-Babylonian protective demon of contagion, epidemic and dust. Filtered through the 'gooey' glitched plastic materiality of current digital design and printing technologies, they become Pazu*goo*.

Religious and secular belief systems are a significant part of the debate about nuclear semiotics and how to communicate important knowledge into the deep future.[5] Weir's project creates a thread of digital mutation through replicating the figure of Pazuzu who warns against dangers as intangible as dust and viruses, highlighting the invisibility and mutating force of radiation through a physical modification of the 3D model.


Figures 2 and 3: Andy Weir, Pazugoo, workshop designing and printing figures, Bildmuseet, Umeå University, Sweden, November 2016.

As part of the work, Andy Weir runs workshops to create and distribute *Pazugoo* figures (Figs 2. and 3.). Participants draw on online museum databases of scanned artefacts, and reconfigure them according to the Pazuzu morphology, leading to the production of combinatory designs and printed objects (Figs. 4 and 5).

We are now working on a proposal for both relay and deep time placement of the objects in URL sites. Andy Weir has made a series of small figurines in different materials which are planned to be placed at the entrance to every repository, echoing the placement of St Barbara at the head of Underground Research Laboratories in Meuse/Haute-Marne, Bure, in northern France and HADES, Mol, in Belgium.

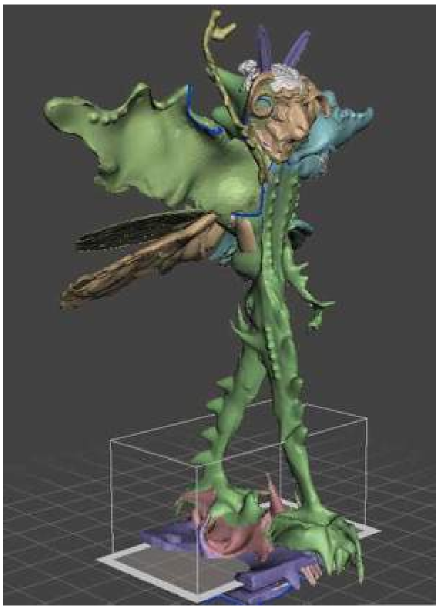

Figure 4: Andy Weir, Pazugoo, design from workshop. Bildmuseet, Umeå University, Sweden, November 2016.

Figure 5: Andy Weir, Pazugoo Prototype S1N1 (2016), polylactic acid, 14cm x 9cm x 4cm.

Through the work, Weir proposes the importance of mythic fiction as a method for navigating between the immense timescales of nuclear storage and human cognition in the present. *Pazugoo* speculates on this through the fabulation of double-flight, a figure with an “excess of wings”,[6] it can be imagined flying billions of years into radiological deep time futures and back to the present.

This use of myth connects two temporal registers of the work: firstly, it draws attention to itself as a material object, slowly decaying over long timescales and becoming a future part of the earth in which it is buried; secondly it enters into discussions around waste now, opening critically engaged debates around responsibility, memory, fiction and materiality.

As a distributed work, it uses the museum exhibition as an ‘index’ to reference objects located and buried, collectively produced and dispersed around the world, connecting local, international and planetary scales of engagement. Following the ‘Perpetual Uncertainty’ exhibition, a *Pazugoo Index* (2018) has been acquired by the Malmö Konstmuseum collection for future preservation and scholarship. Examples of its distributed iterations include a clay burial ritual at a event marking time and toxicity in Amsterdam,[7] and its custodianship with local guides at the Maralinga site in Australia.[8]

4.2 Thomson & Craighead

Artists Jon Thomson & Alison Craighead investigate understanding of geological and planetary time through the relationship between live data and the material world. Their artwork *temporary index* is an array of decorative counters that mark sites of nuclear waste storage across the world. Each counter is a kind of totem marking the time in seconds that remains before these sites of entombed nuclear waste become safe again for humans. These timeframes range from as little as forty years or as much as one million years. A booklet accompanies the collection of counters, which describes each site in more detail, and providing contextual information about the human legacy of nuclear waste and what we as a species have done so far to deal with it.

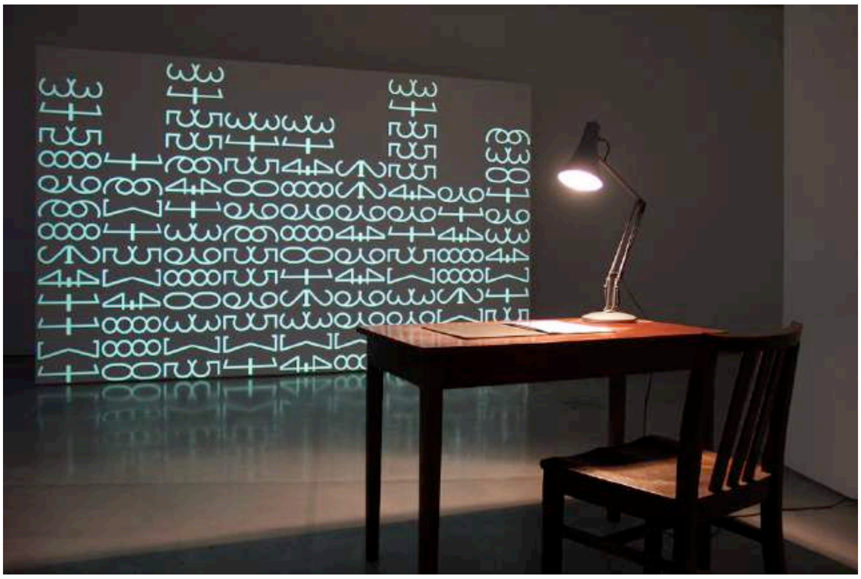

Figure 6: Temporary index, Thomson & Craighead, 2016

At the core of the *temporary index* artwork is a database which drives an array of numeric counters which countdown the probabilistic decay of radioactive materials in seconds. The numbers at the bottom of each column count down in seconds. The counters can be presented as a full array or single totem, embedded in specific sites, syndicated online, presented in an art gallery, included in nuclear archives, and preserved in museum collections. These animated objects of contemplation are representations of time that far outstrip the human life cycle and provide us with a glimpse into the vast time scales that define the universe in which we live in, but which also represent a future limit of humanity's temporal sphere of influence. The design of the counter demonstrates how human measurement of time is a process of linguistic and pictorial language.

Temporary index has been exhibited as a full array of counters at Carroll Fletcher Gallery, London (Fig 6), and the Malmö Konstmuseum in Sweden in 2018. In the Perpetual Uncertainty exhibition at Bildmuseet a single totem operates as a signpost, mapping the distance between the museum and the Chernobyl entombed reactor, tracing the downwind path of radiation that contaminated lichen in northern Sweden, and led to the culling of thousands of reindeer (Fig 7).

Figure 7: Thomson & Craighead, Temporary Index, Chernobyl Reactor #4, Ukraine. Bildmuseet, Umeå University, Sweden, 2016.

At Z33 House of Contemporary Art in Hasselt, 2017, the projected totem counted down the waste waiting to be entombed in the Low Level Waste site at Dessel, just a few miles from the art gallery. In 2019 the artists are creating a totem counter for the Nucleus archive at Wick, Scotland, commissioned by Highland Highlife and the Nuclear Decommissioning Agency (NDA).

We are now developing relationships with radioactive waste storage sites across Europe to build a series of live decay-rate counters, markers of time as well as place. Research for the project has included site visits to the LLW Ltd at Drigg, UK; Horonobe URL, Hokkaido, Japan; Nucleus Archive, Wick, Scotland, and HADES in Mol, Belgium.

5. Discussion

The Nuclear Culture project and the *Pazugoo* and *temporary index* artworks raise many important considerations for future partnerships between the visual arts and RK&M projects as they shift towards the public domain of archives and collections, and informal creative cultural practices.

The visual arts can introduce new conceptual and organisational frameworks for rethinking long-term communication challenges. Artists work between institutional and informal cultural practices that value culture on its own terms, address the limits of institutions. The visual arts can address over-arching and holistic concerns within the nuclear economy, and are not specific to one area of scientific specialism. The tendency for over-reliance on patriarchal closed knowledge management, needs to be addressed to develop distributed more resilient knowledge networks for RK&M. The RWM sector already faces problems with passing on knowledge as people retire, new cultural forms are needed that engage younger generations in nuclear culture.

Visual art addresses the RK&M “dual track” approach to future transmission as each generation of artists builds on the knowledge and practices of their predecessors. Artworks are the focus of gallery and museum education programmes to engage children and young people with complex ideas. The relay of intergenerational culture is also the focus of many socially engaged art practices. Whilst future communications are found in art objects preserved within collections, and public art commissioning processes.

Art can create informal spaces for dialogue that is reflexive, poetic, political and discursive without having to solve problems or comply with specific agendas. Alongside exhibitions, the Nuclear Culture project always organizes an interdisciplinary roundtable discussions to bring citizen stakeholders into discussion with artists, philosophers, architects, sociologists, anthropologists as well as scientists and engineers working in the nuclear field. The roundtable involves presentations from stakeholders, artists and scientists, followed by roundtable discussions in small groups so that everyone has a chance to share their knowledge and experience. In addition to the artists field research, exchange visits enable people to learn about new perspectives on radiation and the nuclear, often moving outside their comfort zone. For example Z33 in Hasselt organised regular tours of the Perpetual Uncertainty exhibition for residents of Mol and Dessel. Whilst in Malmo, museum staff were taken on a tour of their local nuclear power plant.

Museums also function as memory institutions, preserving contemporary objects in perpetuity for scholarship and public display. This includes visual arts objects, research based artworks and documentation of social processes. To achieve this artworks have to be recognised as having a cultural significance within the time in which they are made, so that they continue to reflect their contemporaneity. However, it should be noted that art museum collections tend not to include unrealised public art and architectural proposals. Markers of sites can aim to be permanent or temporary. Temporary public works may have a huge cultural impact which can be recorded and archived, whilst permanent works can be ignored or buried. So the only way to understand visual art as future cultural heritage is to work with its curators.

International mechanisms for contemporary nuclear artworks are both formal and informal. Artists such as Thomson and Craighead are interested in shared server protocols, and distributed artworks which can exist in many different forms as markers of time as well as site. Andy Weir’s *Pazugoo* figure as a spiritual marker of radioactive waste to be located at the entrance to URL’s and waste sites, buried in waste containers and placed in art galleries and museum collections. These 'networked' projects provide an opportunity to include the RK&M Key Information File (KIF) in their archival documentation, connecting museum collections with specific burial sites.

6. Conclusion

The visual arts can only offer methodologies for creative organisation, connecting institutional and public culture through a mix of closed and open source networks, strategic and tactical modes of operation, combining long-term vision with short term relevance.

Working with other disciplines can help to broadened the horizons of the context in which we work, giving people permission to think differently, and speak about concerns that the normative culture of their field doesn't allow space for. It can help to articulate things people already know but don't have the language or support to describe. The arts and humanities can think holistically, they don't need to compartmentalize research-processes and knowledge in the same way as science and engineering. At the same time these disciplines are not homogenous, there are many arts and many sciences. But industry/ research or art/science partnerships often have expectations that art might articulate what is already visible and known, whilst artists might interrogate the interplay of visibility and invisibility both materially and politically in unexpected ways.

Care needs to be given to the methodologies of creative production and distribution. The RWM industry is commissioning artists proposals, but how is that work impacting on the visual arts? How is the work being critiqued, referenced, archived within visual culture?

Several centuries of curatorial work is needed for the nuclear archives to move into the public domain, and to be able to include art and politics. The first step is to establish a curatorial context for the commissioning, production and dissemination of these contemporary artworks within multiple discourses, to find new ways of embedding the complexity of radioactive waste management in our past, present and future cultures.

Acknowledgements

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Jon Thomson is an artist and Professor of Fine Art at the Slade, UCL, London; Alison Craighead is an artist and Reader in Contemporary Art and Visual Culture at the University of Westminster, Lecturer in Art at Goldsmiths University of London.

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[8] Project by Jacob Warren. Maralinga, Australia, is the site of British nuclear tests between 1956 and 1963, and part of land currently proposed as low to intermediate level radioactive waste storage site.

Learning from Socio-Technical Analogues for Monitoring of DGD A Comparative Perspective on Wind Power, Fracking, Carbon Capture and Storage (CCS) and Deep Geological Nuclear Waste Disposal[2]

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1. Summary

Up to date, no country in the world can count on a final repository for high-level radioactive waste. Hence, references about monitoring of radioactive waste in geological disposal facilities are not available. However, the analysis of other social and technological analogues could offer a useful heuristic to identify the challenges related to a long-term monitoring and provide some insight to approach the monitoring challenges related to the disposal of high-level radioactive waste. In this comparative work, we analyze the role of public and civil society actors in the planning, deployment and monitoring of major energy infrastructure projects that are mostly perceived as controversial and potentially noxious. We claim that the development of monitoring systems without civil society´s involvement is not effective and recommendable. On the contrary, a broad inclusion of civil society actors can help to design and improve monitoring systems. Critical questioning of future monitoring concepts and a topical dialogue between natural scientists, engineers, politicians and civil society with addition of lay knowledge can help identifying acceptance problems and mitigating conflicts. This is also necessary because the “wicked problem” of nuclear waste disposal has considerable uncertainties to deal with and it adds to the already given “unknown unknowns” (Themann and Brunnengräber 2019).

Our paper considers major energy infrastructure projects (wind energy, carbon capture and storage, fracking, and nuclear waste disposal) that are faced with differing levels and intensity of social and local acceptability. Similarities between these projects are seen in their impact on health and ecosystems (e.g. groundwater risks), their socio-economic and socio-psychological consequences (spoiling of the landscape and loss in value of the area for tourism, loss of property value, a possible stigma, loss of “sense of place”) and in general diminishing or lacking social or local acceptance. Moreover, all these projects require an involvement of the public during the planning and implementation phase in order to be acceptable in the long term. We argue that in addition to monitoring concepts that mostly screen the surrounding ecosystem and related safety issues as well as technical aspects, sophisticated social monitoring procedures, as an integral part of the general monitoring concept, are needed for the development and the use of contested infrastructure projects. The outcome of our comparison is based on a systematic literature review and an analysis of the

[2] This extended abstract is a contribution by the Environmental Policy Research Centre (Forschungszentrum für Umweltpolitik, FFU) of the Freie Universität Berlin to the project, “Methods and measures to deal with socio-technical challenges in storage and disposal of radioactive waste management – SOTEC-radio”. The project is financed by the Federal Ministry for Economic Affairs and Energy (BMWi, FK 02E11547C).

socio-technical, political and economic implications of these projects and of the forms of public participation used in the planning phase and afterwards.

2. Social analogues between different sociotechnical ensembles?

Regarding the final disposal of highly radioactive waste, one faces the problem that because no deep geological disposal (DGD) facility is in operation yet, there are no possibilities to learn from already existing disposal facilities.

For that reason, we try to explore in what way indirect experiences can be useful. We turn to so called social analogues to gain deeper knowledge about project such as a disposal facility. With social analogues we mean similar infrastructure projects. By analyzing criteria used to assess and implement such different projects, we hope to gain new perspectives and knowledge about certain dynamics that are transferable to the search of a site and finally construction of a DGD.
With this method of identifying and analyzing analogues and the creation of an indirect experience horizon, we try to translate the findings regarding solutions of problems as well as upcoming social problems from one sociotechnical context into another. By doing this, German as well as international contexts are considered.

Overall, we analyze three different infrastructure projects to translate their dynamics and problems into the case of a DGD. Those projects are: Wind turbines or rather wind farms (WF), hydraulic fracturing (fracking) and carbon dioxide capture and storage (CCS). Following Wiebe E. Bijker (1997), we describe such projects as sociotechnical ensembles. In such ensembles, social, political, economic and technical dimensions are embedded. The choice of the projects follows both the idea of similarity on a technological basis (as is the case for fracking and CCS) and political similarities regarding the construction of regulation and law of a technology (as is the case for the development of renewable energies).

3. Conflicts around large infrastructure projects and lack of acceptance

Technical conflicts are not of a temporary nature only. They develop over time, they can intensify within a society and generate or develop incrementally tension over the years. The latter path seems to apply better to our case. Regarding fracking or wind power plants, societal conflicts have intensified. Different reasons and aspects can be named to explain this dynamic: contested land use; nature, or landscape protection; failed distributional justice resulting from uneven distribution of costs and benefits between different stakeholder groups or on the territory; value conflicts, etc. Also, trust in actors who especially represent the predominant system or rather the regime (referring to Geels) has declined, for example actors like power companies (L′Orange Seigo et al. 2014) or the government or the state itself (Gullion 2015).

An unfavorable cost-benefit-analysis (real or perceived) can be at the root of local, but also social conflicts. At the same time, it is hard to increase trust, when facts and knowledge are contested or not even available (Neville and Weinthal 2016, p. 591). When looking at fracking we already deal with a situation in which science and scientists are no longer perceived as neutral or apolitical (ibid., p. 595). Similar developments are observable also in the case of the search for a site for a DGD.

3.1 Security, risk potentials and uncertainties

Projects such as CCS, fracking and DGD, trigger similar fears and negative risk perceptions. These are often related to the contamination of fresh and ground water or of the environment. Also wind turbines can generate fears about oil leakages into the ground. Fears in such cases are mostly diffuse, as no one can observe what happens underground. At the same time, potential risks like CO2 leakages (CCS technology), radiation (DGD), contamination of soil and crops or seismic disturbance (fracking), are feared. But also wind turbines are connected with a threat to species like bats and birds or eventually with spoiling ecosystems like forests in case the siting is not in line with sustainable siting criteria as well as health effects due to noise.

In particular, when we look at socio-political disputes about critical technologies like fracking, we observe dynamics that might be applicable to a DGD project, too. Similar factors are those implying critical security issues and risk perceptions, which connect very different actors across different discourse coalitions. These are based and constructed on different nodal concepts and use different argumentative and rhetoric strategies, because they trigger deep-rooted human fears (Hoeft et al. 2017, p. 98). “Interestingly, the image of possible water contamination mobilizes many different actors. Story lines related to water risks form the basis for vast discourse coalitions involving actors that rarely fight for the same goals with other subjects(…)” (Schirrmeister 2014, p. 5). A similar broad coalition between different actors against the DGD and the process of finding it, is probable as such a divers coalition is already observable in the protests against nuclear energy in Germany. Environmental NGOs, different political groups and mainly the local population (which is a heterogenous actor itself) were strong opponents. In addition, the anti-nuclear movement was able to connect with other movements as the environmental or the peace movement (Roose 2010). As the finding and building of a DGD, like the use of nuclear energy, is connected to value-laden discourses about risks, safety and participation, it is likely that within this process a broad opposing or rather critical coalition will develop, too. Regarding safety and security assessments, current knowledge is not sufficient for designing a long term safety case. There are many open questions that point out the need for further scientific investigations. For example, for the case of “underground” technology such as fracking, CCS and DGD, there is a lack of monitoring strategies or monitoring technologies. For example, currently, in the U.S. there is no detailed monitoring of the ground water quality. The reason for this is not only due to lacking knowledge and know-how, but also of regulation. In the U.S. shale gas production is not regulated under the Safe Drinking Water Act (SDWA), and a ground water monitoring is not mandatory. Nevertheless, suitable monitoring strategies are demonized due to the scientific and practical uncertainty regarding the attitude of several additives that are used for the fracking process (SRU 2013, p. 26; Meyer-Renschhausen and Klippel 2017, p. 122f.; Gullion 2015, p. 55). CCS and fracking pose several uncertainties regarding environmental and health risks. This is also emphasized by the German Advisory Council on the Environment (SRU). In its statement from 2013, the council points to insufficient monitoring opportunities for fracking, a circumstance that is applicable to all underground technologies, as the council states (SRU 2013). There are also methodical problems to estimate possible effects rising from water contamination, because baseline data are missing (Meyer-Renschhausen and Klippel 2017, p. 84f.). Regarding CCS no technology appears to exist to monitor and control the stored CO2 (Krüger 2015, p. 164).

Regarding fracking, Neville and Weinthal (2016) note that “(r)isk assessment and management are difficult when the form and extent of risks are unknown, which shifts decision making from the regulatory into a political arena (Falkner and Jaspers, 2012).” (ibid., p. 590). Overall, fracking and CCS have to deal with a lot of scientific uncertainties and unforeseeable factors (e.g. Gullion 2015, p. 55; Meyer-Renschhausen and Klippel 2017, p. 84; Krüger 2015, p. 177f.; SRU 2013). At the same time, the ability and competence of regulators and operators to deal with those risks and uncertainties is perceived as low (Schulz et al. 2010, p. 289). There is also a lack of trust in the assessment of risks.

In this case we observe similarities to the so called "unknown unknowns" (Eckhardt and Rippe 2016) which we already detected for a final disposal of radioactive waste (cf. Themann and Brunnengräber 2018). The term "unknown unknowns" describes the barely foreseeable consequences of the usage of a certain technology. Because of that, society cannot "work in advance" and is not prepared for consequences and effects. Exactly those uncertainties and unknown unknowns that derive from the use of a certain technology can influence societies over long time spans of decades or even centuries (Brunnengräber and Görg 2017). Those uncertainties show why purely regulatory, technical or planning approaches are not legitimate. There must be a societal debate and decisions about values and what kind of risk the society is able and willing to bear. Long term risks and long term security are issues that cannot be defined by natural sciences alone. These issues arise ethical questions about inter- and intragenerational justice.

3.2 The role of science and scientists

From the comparison of the social analogues it becomes obvious that the beginnings and developments of a technology or large infrastructure projects are dominated by natural sciences and engineering. Yet, for such large infrastructure technologies with massive impacts one does not face just the limit of predictability of risks, but different scientific disciplines show a high diversity in how they value such technologies, too. Disciplinary knowledge claims are highly contested (for fracking e.g. Gullion 2015, p. 152; Goldthau 2016).

The impact of the dissent between scientists extends into those sociotechnical ensembles. For example Gullion (2015) makes us aware of the fact that the role of science in fracking is to provide arguments and facts for each of the discourse coalitions. In this way, pro and contra groups are arguing with scientific facts. In the result, there is a political confrontation on scientific facts and counter facts (ibid. p. 134ff.), which we already observed in the case of Gorleben (Blowers 2017). Gullion also describes for the U.S. context how science became part of the governance of large technical systems and offered the basis for the argumentation of the "powerful". For her "(…) knowledge (is) controlled through use of science. Science is legitimized as the only valid source of knowledge by the people who hold the power to make such designation: the industry and the government regulators" (ibid. p. 136). On the other hand, knowledge and arguments of activists and opponents are marked as emotional and unscientific (ibid. p. 137). Also critical experts and their knowledge seem to be marginalized (for CCS see Krüger 2015). This dynamic also occured in the history of nuclear energy use and finding a final repository in Germany. Critical voices from science and society were marginalized (Brunnengräber 2019; Roose 2010).

This leads to perceptions of critical parts of society that science is part of the "regime" and conducts research for producing legitimacy (Legitimationsforschung) in favor of the decisions of the dominant political and economic groups (e.g. for fracking: Hoeft et al. 2017, p. 113).

The question remains what those conflicts and contests about the power of interpretation mean to the society as a whole as well as for affected groups. For example, mistrust against the validity and objectivity of scientific results could develop further. As a result, science could be perceived as non-neutral and ambiguous.

From this point of view, the social sciences and humanities have a special role to play. In the case of "big" technologies social sciences try to embed these in societal contexts and to assess technologies regarding societal backgrounds and discourses. By doing so, however, they run the risk to be misperceived or misunderstood. As Krüger (2015) observes for CCS projects, social scientists seem only to be involved as researchers for acceptance (Akzeptanzforscher*innen). He describes this development as an "instrumentellen Rückgriff" (instrumental fallback) to social sciences and humanities, in order to enhance the communication about CCS and increase acceptability for the projects (ibid. p. 24f.). A similar observation is made by actors within the anti-nuclear movement in Germany. Also here, social scientist are stigmatized for being "purchaser of acceptance". This leads to a difficult role for social scientists: they are discredited politically and perceived in a partial way.

To overcome those dynamics, parts of science and society already demand a stronger collaboration. The claims coming from society regarding the collaboration with sciences seem far more frequent in the case of finding a DGD than in other technology projects. The implementation of more inter- and transdisciplinarity has been formulated several times from different stakeholders. Regarding the practice of interdisciplinary collaboration, in Germany initial experiences were made within the ENTRIA project[3]. The societal demand for more inter- and transdisciplinarity can be considered the point of arrival after decades of societal polarization and thematic sensitization in the nuclear energy arena in Germany.

Those dynamics show that scientific actors need to be more open for discussion and to take into account affected groups by their science-based political decision-making (Pedersen 2014: p. 548). This demand could be the idealist form of a "context-sensitive science" like Gibbons (2000) terms it on a micro-level or rather in a limited decision-making space of time and subject. In this mode, "society is speaking back to science" (ibid. p. 161). The consideration of the affected actors and stakeholders as well as local knowledge is necessary to achieve socially robust knowledge like Gibbons names it (2000, p. 161). However, to transfer this widely accepted theory of inclusion and transdisciplinarity into practice one needs to deal with several barriers and difficulties. Questions, that need to be asked now, are: "how can society speak back to science and when?" and "how can local knowledge and "amateure expertise" (Finke 2014) complement the specific scientific and technological knowledge of technical experts ?" A first approach towards these questions could be the recently established "National Advisory Board" (« Nationales Begleitgremium ») and the social monitoring concept that we would like to introduce in this chapter.

4. Involve civil society actors into the monitoring system

Values like (procedural as well as distributive) equity and empowerment of all participants and affected stakeholders, the junction of scientific, local and lay knowledge as well as its institutionalization are necessary for processes in which goals are still negotiated and where results and consequences are uncertain or rather unknown (see Reed 2008). Often, participation is enabled too late.

Not only can the inclusion of different types of knowledge help to improve technical monitoring systems, but the inclusion of societal actors and a stronger dialogue between science and society as well as between society and decision-makers could enable what we call social monitoring. In a nutshell, this monitoring concept means to increase the sensitivity for past, present and future societal discourses and dynamics with regard to the societal evaluation of new technologies. Critical questioning of deployment of a technology as well as future monitoring concepts and a topical dialogue between natural scientists, engineers, politicians and civil society with addition of local and lay knowledge can help identifying risk perceptions and value trade-offs, enhance "acceptable" technical systems and mitigating conflicts. To achieve this, independent supervision and social monitoring are key in contexts in which either trust in the regulating institutions declined or rather eroded or where technologies affect basic living conditions. Societal debate and an open dialogue

[3] Project website: https://www.entria.de/entria.html?&L=1

about values is necessary where a technology includes "unknown unknowns" to ascertain what risks society is willing to bear.
Sociotechnical ensembles of the examined technologies can definitely offer a suitable framework from which to derive activities or steps to improve institutionalization and inclusion of different types of knowledge into the planning and monitoring process. Those steps seem quite similar. For tests and experiments regarding CCS technology there is the proposal to establish a "Rat der Weisen" (Council of the Wise) (Schulz et al. 2010, p. 294). For fracking in 2011 an "InfoDialog Fracking" was established. This structure included a Council of "neutral experts". The council had the task to initiate a dialogue with affected societal actors.[4]

Summarizing, the idea of a stronger dialogue between science, politics and society and of the inclusion of citizens in decision-making processes is gaining ground. Yet, the necessary initial steps are not institutionalized enough and there is a lot of criticism regarding the neutrality of experts, the real decision-making power of societal actors and its influence on policy outcome. In Germany, within the DGD ensemble, the establishment of the NBG, a board supervising the process of finding a repository site, represents a first milestone in this process. Especially through this board, the inclusion of other types of knowledge, in particular lay knowledge, seems to develop further in nuclear waste management in Germany. These are maybe the first steps for initiating a social monitoring and buttress socially robust knowledge and decision-making.

[4] For criticism regarding funding of this council and its work, see Saretzki and Bornemann 2014.

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C.c – Session on Summaries of Monitoring Technologies

Current State Of The Art Of Wireless Data Transmission Systems For Repository Monitoring

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1. Summary

This paper summarizes the work performed in Task 3.2, *Wireless data transmission systems for repository monitoring*, of the EU H2020 project Modern2020 and comprises the development, testing and demonstration of wireless data transmission systems for repository monitoring. Wireless systems allow transmitting monitoring data without impairing the safety of barriers, and they hence support the ability to survey the evolution of relevant safety functions of a disposal concept. In Task 3.2, nine international expert organisations developed and tested wireless solutions that address a wide range of applications.

In the project, a major step has been achieved in understanding, designing and demonstrating specific solutions that allow transmitting data through components of the engineered barrier system or the host rock. Different technological solutions covering transmission distances between several meters and more than 275 m have been successfully developed and tested, covering a variety of application situations, disposal concepts, and host rocks. A greater understanding of the underlying technical and physical principles has been achieved, and the provided solutions have been tested under realistic conditions, e.g. in the Tournemire Wireless Testing Bench, from the Tournemire tunnel to the surface plateau, or in the Espoo underground laboratory. The performance of the developed technologies depends on a number of factors which, if carefully implemented, allow transmitting data over distances of 275 m through the underground with less than 5 mWs/bit of transmitted data, or over 4 m or more of a (partially) saturated barrier with less than 1 mWs/bit.

2. Introduction

Relevant part of repository monitoring activities will take place behind safety relevant barriers. Wireless systems allow transmitting monitoring data over these barriers without impairing the safety function by cables. The barriers of interest could be anything from the concrete buffer of a supercontainer design, a borehole plug, sealings of disposal sections or a shaft sealing: wireless solutions are necessary that can bridge distances from less than a meter up to several hundred meters.

Wireless data transmission is used nowadays in numerous applications, bridging efficiently short and long distances in air. However, the presence of solid media as the host rock or components of the engineered barrier system (EBS) can impede the propagation of high frequencies as used by conventional data transmission solutions (hundreds of MHz to GHz). Their applicability in a geologic waste disposal facility is limited to short distances (few meters), raising the need to develop specific solutions for repository monitoring that can bridge larger distances (several meter to several hundreds of meter), based on lower frequencies (kHz to few MHz). Besides, the energy efficiency of the transmission solutions is a relevant design target, requiring custom-tailored solutions for each application case of interest.

This paper summarizes the work performed and lessons learned in Task 3.2, *Wireless data transmission systems for repository monitoring*, of the Modern2020 project [1]. Building on the results of the preceding MoDeRn project, Task 3.2 aimed to address the identified knowledge gaps and to bring wireless technologies further into application. The task consists of a variety of contributions of international expert organisations:

- Implementation of a Wireless Testing Bench (WTB) at the Tournemire URL (IRSN)
- Increase of the range of short range data transmission system through hydrating sealing material (Arquimea)
- Development of a 125-kHz-based short range data transmission system (VTT)
- Understanding and improvements of a long range data transmission system (Andra)
- Implementation of signal hopping strategies to provide robust data transmission over longer transmission distances (RMWC)
- Evaluation of an adapted wireless Through-the-Earth commercial technology (Amberg)
- Test of a miniaturized transmitter for vibrating wire sensor in the WTB (Andra)
- Link of the mINT interrogator behind a supercontainer buffer with a wireless transmitter (EURIDICE)
- Evaluation of a combination of wireless data transmission systems that allow transmitting sensor readings from the inside of a disposal cell to the surface on top of the Tournemire URL (Amberg, Arquimea, IRSN, and NRG)

3. Methodology

Since high frequencies lead to high signal attenuation when transmitting through a (partially) saturated barrier, all current wireless techniques, except for very short distances (<1 m) make use of the very low frequency (VLF) to – medium frequency (MF) range (3 kHz to 3 MHz). Table 1 summarizes data transmission experiments performed as part of Modern2020 in URLs under conditions relevant for underground disposal of radioactive waste. Additional to the data transmission experiments, Andra demonstrated signal transmission through 275 m of limestone and shales at the Tournemire URL, and over 300 m in a surface-surface configuration at the Tournemire URL and the Andra URL.

Table 1: Wireless data transmission experiments performed in URLs as part of Modern2020

Distance	Transmission mode	Frequency	Host rock/barrier (location)	Organization
4 - 6 m	λ/4 loop antenna	2.2 MHz	(Partially) saturated bentonite (Tournemire URL)	Arquimea
5 - 10 m	Magnetic loop antenna	8.5 kHz	(Partially) saturated bentonite (Tournemire URL)	Andra
23 m	Magnetic loop antenna	125 kHz	Granite + Air (Espoo research hall)	VTT
30 m	Magnetic loop antenna	4.0 kHz	(Partially) saturated bentonite (Tournemire URL)	Amberg
275 m	Magnetic loop antenna	8.7 kHz	Limestone & Shale (Tournemire URL)	NRG

An important performance figure for wireless solutions is their energy need, certainly for the long distance. The research initiatives in WP3.2 were therefore directed in understanding energy efficiency, and extending and improving the energy efficiency and the range of existing solutions. Experiments were performed in relevant environments, in order to account for interactions with the host rock or EBS of interest.

4. Results

In summary, within WP3.2 successful data transmission has been demonstrated on all ranges. For long range data transmission, frequencies below 10 kHz are applied, although under unsaturated conditions as present in e.g. the Tournemire URL, higher transmission frequencies may be used as well. On the medium range, a variety of frequencies are used, ranging from 4 kHz to 2.2 MHz.

Next to the above mentioned transmission systems, a Wireless Testing Bench (WTB) was set-up at the Tournemire URL. The WTB was used to perform tests with short range transmitter systems of three partners under realistic conditions and shall serve as reference facility for future testing of wireless systems. In addition to the direct transmission experiments performed, a system was developed and successfully demonstrated featuring data transmission from the disposal facility to the surface in several stages, by means of several sequential relays. Furthermore, in an integrated approach, an overall transmission chain allowing data transmission from the inside of a disposal cell to the surface on top of the Tournemire URL was assessed: by combining different short and long range expertise and solutions, a wireless transmission chain in two stages was projected and will be demonstrated in 2019 as part of Modern2020's WP4.3.

The overall performances in terms of data rate and energy need achieved by the different data transmission systems in Modern2020 and other projects are summarized in Table 2.

Table 2 Performance of current wireless data transmission systems in URLs (bold: Modern2020)

Distance	Transmission mode	Energy efficiency [mWs/bit]	Data rate [bit/s]	Frequency	Host rock/barrier (location)
4 m	**λ/4 loop antenna**	**0.75**	**38'400**	**2.2 MHz**	**(Partially) saturated bentonite (Tournemire URL)**
20 m	**Magnetic loop antenna**	**~0. 5**	**75**	**8.5 kHz**	**(Partially) saturated bentonite (Tournemire URL)**
23 m	**Magnetic loop antenna**	**1000**	**1**	**125 kHz**	**Granite + Air (Espoo research hall)**
25 m	Magnetic loop antenna	7	75	8.5 kHz	Sedimentary rock (Meuse / Haute-Marne URL)
30 m	**Magnetic loop antenna**	**1**	**1600**	**4.0 kHz**	**Limestone & Shale (Tournemire URL)**
30 m	Magnetic loop antenna	500	20	575 Hz	Bentonite/shotcrete (Grimsel URL)
225 m	Magnetic loop antenna	1100	25 - 100	1.8 kHz	Boom Clay & saturated sandy aquifer (Hades URL)
250 m	Magnetic loop antenna/ relay system	3710	75	8.5 kHz	Sedimentary rock (Horonobe URL)
275 m	**Magnetic loop antenna**	**2880***	**75**	**8.5 kHz**	**Limestone & Shale (Tournemire URL)**
275 m	**Magnetic loop antenna**	**<5**	**>30**	**8.7 kHz**	**Limestone & Shale (Tournemire URL)**

*signal transmission experiment

5. Discussions

The experience gained at the Tournemire URL, and the Hades URL raises confidence that long range transmission over distances larger than 300 m can be achieved as well. Methods have been developed and successfully applied to quantify transmission behaviour from in situ measurements, allowing the estimation of data transmission power needs for each location of interest with relatively small effort.

With regard to short range data transmission over several meters, several options are available, operating at frequencies between 4 kHz and 2.8 MHz. Each one of those technologies has its own advantages, and successful data transmission through solid media has been demonstrated for all of them. Versatile, “all-in-one” solutions, integrating different analog and digital sensors, have been developed and tested under realistic conditions at the WTB facility in Tournemire. A variety of options and transmission frequencies for various application cases of interest are available on the short range. Which of these frequencies is the most suitable will depend on the transmission distance to be achieved, the electrical conductivity of the EBS and host rock and the presence of magnetic permeable materials. Another consideration for the selection of the transmission frequency over short and medium ranges could be to decrease the overall complexity by using the same technology on all distances.

In order to bring wireless technologies to a readiness level that allows its application in disposal facilities, a number of topics are identified that need further attention:

- A general topic in repository monitoring is the long-term reliability. As for all other components of monitoring systems placed behind safety relevant barriers, the life time of the components used for wireless solutions is essential, because maintenance of the components will be difficult or even impossible.
- Potential interactions of transmitter antennas with magnetic permeable materials in a repository (e.g. steel used for gallery support) and the effect of heterogeneities on field propagation through the overburden leave some questions with respect to the transferability of the current results to other locations of interest. These should be resolved by field experiments and demonstrations.
- Wireless data transmission was successfully demonstrated over a distance up to 275 m, and the relevant parameters that define the overall performance and energy need were determined. While current understanding allows to extrapolate these results to larger distances as well, some need to demonstrate data transmission over larger distances is noted, since the typical repository depth is 500 m or deeper.
- The large (man-made and natural) interferences in the 1 - 10 kHz range are a challenging feature of low frequency data transmission and may strongly limit the overall performance. More sophisticated data processing methods may significantly improve the energy efficency and overall performance of a system, and more data on the variability of noise and interferences on day to-day level may allow improving the reliability of the data link under unfavourable conditions (e.g. thunderstorm).
- The demonstration of the combination of wireless data transmission systems with alternative power supply sources as developed in Modern2020’s Task 3.2 is seen as an important topic for future research.
- To develop the 125 kHz data transmission technology to a more mature state, automatic tuning of the antennas is necessary.

6. Conclusion

Within Task 3.2, a major step has been achieved in understanding, designing and demonstrating specific solutions that allow transmitting data through components of the EBS or the host rock. Different technological solutions covering transmission distances between 0.5 and more than 275 m have been developed and tested, comprising a variety of application situations, disposal concepts, and host rocks. A greater understanding of the underlying technical and physical principles has been achieved, and the provided solutions have been tested under realistic conditions, e.g. in the Tournemire Wireless Testing Bench (WTB), from the Tournemire tunnel to the surface plateau, or in the VTT underground laboratory. The performance of the developed technologies depends on a number of factors, allowing data transmission over distances of 275 m through the underground with a power consumption per transmitted bit below 5 mWs, or over 4 m or more of a (partially) saturated barrier with a power consumption below 1 mWs/bit.

In conclusion, wireless data transmission is a promising technology for repository monitoring allowing the use of a variety of sensors placed behind safety-relevant barriers, and major progresses were achieved in Modern2020. A variety of solution exists that covers all transmission distances of interest. General principles are well understood, and further research should aim at testing, demonstrating and optimizing wireless technologies under repository conditions.

Acknowledgements

This paper summarized work performed in Modern2020's Task 3.2 by J.L. García-Siñeriz (AMBERG), G. Hermand (ANDRA), H.L. Abós Gracia (ARQUIMEA), J.C. Mayor Zurdo (ENRESA), J. Verstricht (EURIDICE), P. Dick (IRSN), J. Eto (RWMC), M. Sipilä and J.-M. Saari (VTT). The Modern2020 project is co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme.

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Electric Power Sourcing of Wireless Repository Monitoring Sensors

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1. Summary

This presentation gives an overview of the research activities carried out in Modern2020 Task 3.3 (Alternative power supply sources). The research has addressed three alternative cable-free power sourcing technologies for nuclear repository environment: thermal energy harvesting, wireless energy transfer and nuclear batteries. The applicability of these power sourcing technologies can be improved by an interim energy storage, the technology alternatives of which have also been investigated. Applied research methods have been technology reviews based on available material, theoretical performance analyses and simulations, laboratory pilots and field pilots in an environment that partly represents the final nuclear repository. The results indicate that all the three alternative power sourcing technologies are relevant for powering wireless repository monitoring sensors. Their comparison also indicated clear differences in their applicapility in various repository environments. In the design of the interim energy storage, some features of the existing energy storage technologies such as the self-discharge and the lifetime should be assessed case by case. Forthcoming energy storage technologies are expected to enable better interim energy storage solutions than the existing technologies. The follow-on steps of the research should be targeted to the further development, demonstration and verification of the powering subsystem as a part of more complete wireless sensor units (WSUs) and repository monitoring sensor systems. A detailed description of the methods, results and conclusions of the research can be found in the Modern2020 deliverable D3.3.

2. Introduction

Electric power is necessary for sensor units in nuclear repositories as well as for running electrical devices in general. Since cables through nuclear repository barriers entail risks of radionuclide transport out from the repository, sensor units embedded in nuclear repositories should be preferably linked by a cable-free interconnection between the repository and its outer environment, which concerns both wireless communication and supplying electric power for the sensor operations. Moreover, supplying the power by chemical batteries is not a reasonable solution, since the chemical batteries feature relatively short lifetime due to their limited energy storage capacity and self-discharge, as well as materials not permitted inside some nuclear repositories.

This presentation gives an overview of the research carried out in Modern2020 Task 3.3 (Alternative power supply sources). This research has focused on the following alternative power sourcing technologies of wireless sensor units (WSUs) in nuclear repositories that are proposed in preceding research projects to overcome the above-mentioned problems:

- thermoelectric energy harvesting based on thermal gradients around the high-level waste (HLW) containers,
- wireless energy transfer through repository barriers by applying low-frequency (LF) magnetic fields,

- radioisotope thermoelectric generator (RTG) type nuclear batteries.

In addition, the research has addressed potential technologies for the interim energy storage that is usually necessary with limited power sources such as thermoelectric energy harvesting and wireless energy transfer.

3. Thermoelectric energy harvesting

3.1 Methodology

Thermoelectric energy harvesters (TEHs) generate electric power from temperature gradients by a thermoelectric generator (TEG), the operation of which is based on the Seebeck effect [1]. In addition, a TEH usually involves an interim energy storage and energy management (EM) electronics for voltage boosting, power storing and power conditioning for the use of the sensor payload and wireless communication. The basic operation principle of a TEG consisting of one or several couples of n- and p-type semiconductor materials is presented in Figure 1.

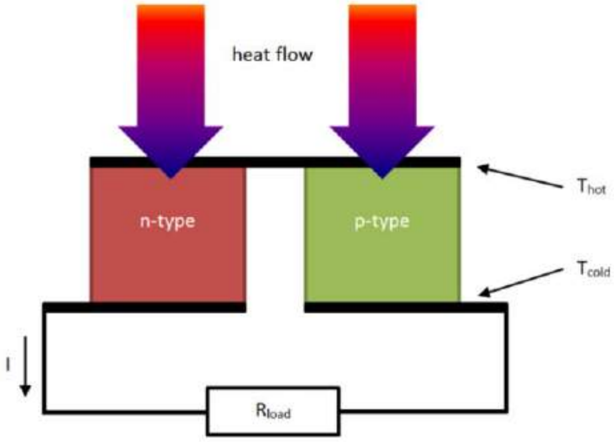

Figure 6: Basic principle of a TEG [1].

The goal of the study in Modern2020 performed by NRG has been to quantify the performance and efficiency with relatively small temperature differences (<2°C) as expected around an HLW canister in a disposal situation. The target operation environment has been the generic Dutch OPERA disposal concept in Boom Clay [2]. The study has applied an experimental test bench setup (Figure 2) for quantifying the TEH.

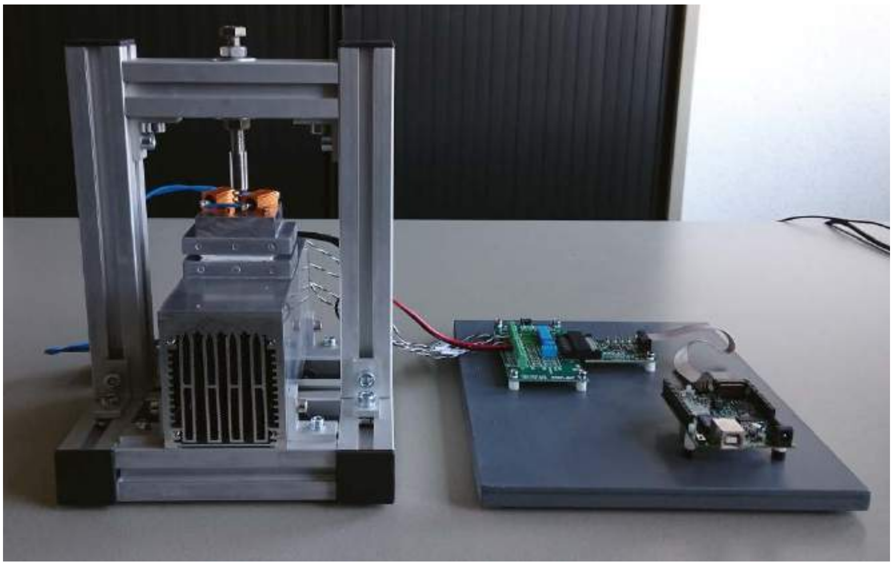

Figure 7: Thermoelectric test bench.

3.2 Results

Figure 3 shows the expected evolution of the temperature differences between different positions in a HLW disposal gallery after 100 years of surface interim storage. Hence, in order to provide energy over a relevant period, the TEH must be able to operate at temperature gradients of 2 °C or less.

Several measurements in the test bench were performed to quantify two different 40 x 40 mm TEGs, TEG-1 (287 *p-n* legs) and TEG-2 (199 *p-n* legs), with the EM electronics and the energy storage. Based on the result, Table 1 gives an overview of four alternative TEH designs and their estimated power sourcing performance at 0, 50 and 100 years after the disposal.

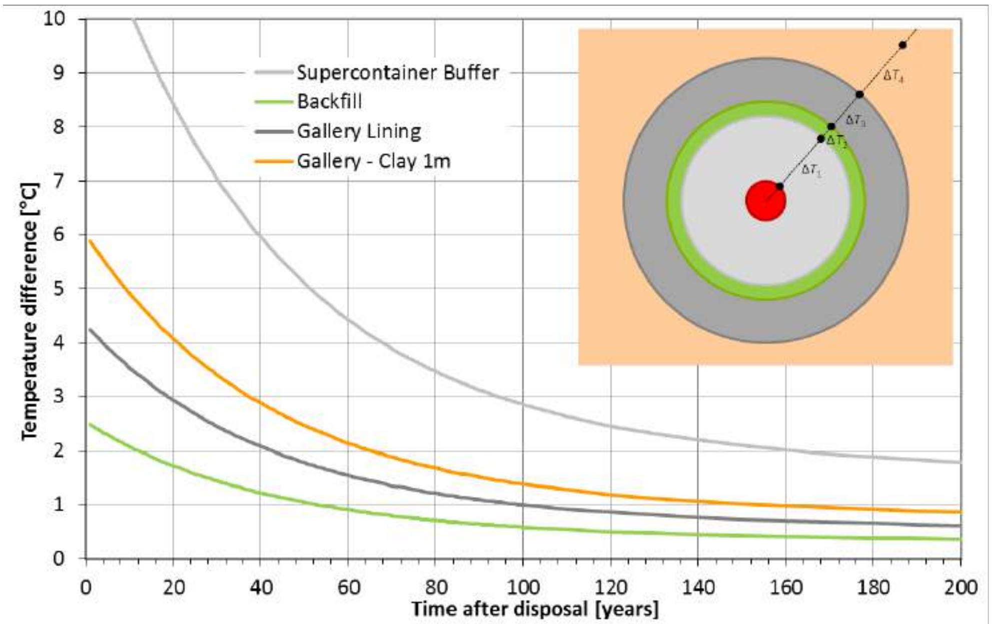

Figure 8: Estimated temperature gradient between several positions in the OPERA disposal concept for a Cogema CSD-V container.

Table 1: Four alternative TEH designs and their estimated output power.

Design	TEH position	Length	Diameter	T_{min} [°C]	P_{out} [µW] 0 years	50 years	100 years
TEH-1S	Gallery lining	50 cm	5 cm	0.64	500	78	20
TEH-1L	Gallery lining	50 cm	10 cm	0.46	1020	170	54
TEH-2S	Backfill	15 cm	5 cm	0.46	370	52	8
TEH-2L	Backfill	15 cm	10 cm	0.40	490	72	14

4. Wireless energy transfer

4.1 Methodology

Based on the results of earlier studies on electromagnetic field propagation, a low frequency (LF) inductive radio e.g. at 125 kHz frequency could be a potential solution for powering repository monitoring sensors through the repository barriers. Two different concepts of this have been investigated and demonstrated in Modern2020. The first one is a combined solution for wireless energy and data transfer through crystalline host rocks with low electrical conductivity developed by VTT. The second one is a wireless energy transfer solution through high electrical conductivity host rock and saturated components of the engineered barrier system (EBS) developed by NRG.

The goals of the study have been a closer performance analysis of the wireless energy transfer through repository barriers, and improving the understanding about the relations between the power transfer performance, design parameters (e.g. antenna dimensions) and the operation conditions such as the medium conductivity. The study has been carried out by applying the existing theory of inductive coupling and inductive power transfer without the effects of the medium conductivity ([3], [4], [5]) and analysis of the field damping by the conductive medium by the existing theory of electromagnetism ([6], [7], [8], [9], [10], [11]). In addition, experimental measurements through medium representing repository barriers and through the air for reference have been carried out by pilot systems in Figure 4 and Figure 5.

Figure 9: The pilot system in co-axial antenna configuration through host rocks with low electrical conductivity (Espoo, Finland). The left photo shows the power receiver and the right photo the power transmitter.

Figure 10: Field measurement of antenna impedance with a conductive medium (wet grassland in Ursem, NL).

4.2 Results

Table 2 summarises the estimated power transfer performance of the pilot system in Figure 4 by two different theoretical methods without medium interaction and by measurements. The results indicate that the crystalline host rock between the power transmitter and the power receiver does not feature any significant degradation of the power transfer performance. In general, the following relations concern the diameter of the antennas and the wireless operation performance through air or host rock with low electrical conductivity:

- the received power level is inversely proportional almost to the sixth power of the wireless distance,
- doubling the diameter of both antennas will almost double the maximum wireless distance,
- doubling the diameter of the receiver antenna will increase the received power by 6 - 9 dB.

Table 2: Measured vs. estimated power transfer performance of the pilot system in Figure 4.

Medium	Estimated by coupling coefficient approximation		Estimated by mutual inductance calculation		Measured by the pilot system	
	10 m air	7 m rock + 1 m air	10 m air	7 m rock + 1 m air	10 m air	7 m rock + 1 m air
Transmitted DC power	100.3 W	25 W	100.3 W	25 W	100.3 W	25 W
Receiced DC power	132 µW	123 µW	56 µW	52 µW	50.5 µW	79.4 µW
DC-to-DC efficiency	1.32 ppm	4.93 ppm	0.56 ppm	2.08 ppm	0.504 ppm	3.18 ppm

The pilot system in Figure 4 also involved the modulation and demodulation parts of a bi-directional data transfer add-on. The tests of these parts indicate that the wireless data transfer add-on can be implemented with a power leakage that is clearly below 5 µW and thus without compromising the power transfer performance in Table 2 significantly.

Table 3 shows theoretically estimated link efficiencies with conductive medium for two coplanar loops according to Figure 5. Table 4 shows measured link efficiencies in two different pilot sites.

Table 3: Estimated link efficiencies for two coplanar loops (Figure 5) through electric conductive medium.

Wireless distance	**Electric conductivity σ [S/m]**					
	0	0.01	0.02	0.05	0.10	0.20
5 m	46495 ppm	14189 ppm	8405 ppm	3755 ppm	1972 ppm	916 ppm
7.5 m	5801 ppm	1814 ppm	1131 ppm	543 ppm	277 ppm	106 ppm
10 m	1163 ppm	394 ppm	257 ppm	122 ppm	55 ppm	15 ppm
15 m	111 ppm	45 ppm	30 ppm	11 ppm	3 ppm	0.4 ppm

Table 4: Measured link efficiencies for two coplanat loops (Figure 5).

Wireless distance	**Measured link efficiency in Petten, NL (unsaturated sandy soil)**	**Measured link efficiency in Ursem, NL (wet grassland)**
5 m	3835 ppm	5386 ppm
7.5 m	423 ppm	503 ppm
10 m	90 ppm	72 ppm
15 m	16 ppm	4 ppm

Table 3 and Table 4 show a strong decrease of the link efficiency for higher conductivity of the medium and longer wireless distance. Looking to the largest wireless distances, where the effect of the conductivity is the strongest and the relative contribution of the measurement errors the smallest, electrical conductivities of about 0.02 S/m and 0.05 S/m could be reasoned for the Petten and Ursem environments respectively. Although both experimental and calculated values feature some uncertainties, the results give some evidence that the applied theoretical model can provide reasonable estimates when designing a wireless energy transfer system for disposal repository applications that involve saturated host rocks or engineered barriers.

5. Radioisotope thermoelectric generator

5.1 Methodology

Radioisotope thermoelectric generators (RTGs) convert the decay heat from a specific radioisotope source into electricity by a thermoelectric generator (TEG). Thus, the physical operation principle of the RTG is similar to the thermal energy harvester presented above, but the technical implementation is much different.

The research in Modern2020 carried out by ORANO has involved a generic state-of-the-art study of radioisotope based power generators [12]. The research has also involved a feasibility study of a 5 W RTG in a disposal vault, which has addressed especially the selection of the radioisotope, numerical thermal modelling of different vault designs with variable number, size and position of cooling plates, and a plan for the follow-on activities for prototyping.

5.2 Results

The radioisotopic material for an RTG has to be selected by considering the type of the radiation, the half-life of the isotope, the decay energy of the radiation, costs of the material, and possible harmful radiation forms [13]. For the case study, ^{241}Am (half-life 433 years) was selected for the preferred radioisotope.

Figure 6 presents the temperature field provided by a thermal model for the reference design (RTG with two 3 m long and 5 cm thick cooling plates). The model gave a temperature difference of 6.9 °C between the hot and cold side of the cooling plates with a hot side temperature of 57.2 °C near the radioisotope source. The thermal model also indicated that the temperature difference between the hot and cold side of the cooling plates is about the same with vertical and horisontal cooling plates and the highest with two cooling plates. The thermal model also showed that it is possible to evacuate the heat released by an RTG delivering 5 W electric power inside a geological underground disposal facility without violating the thermal criterion on the concrete.

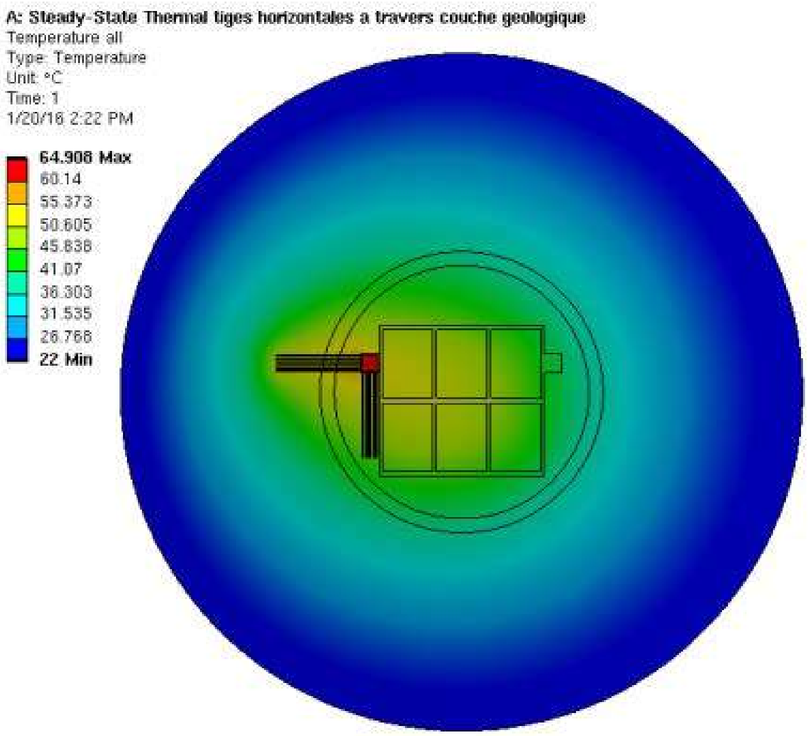

Figure 11: Simulated temperature field of a reference RTG.

6. Interim energy storage

6.1 Methodology

With limited power sources such as thermoelectric energy harvesting and wireless energy transfer, the wireless sensor untis (WSUs) have typically to operate in a low duty cycle mode, which means that their operation is comprised of alternating long energy accumulation periods without any activity of the WSU and short activity cycles with sensor measurements and wireless communication. This arrangement is relevant in nuclear repository monitoring applications, since they typically are sufficed by very low measurement rates, i.e. the interval between successive measurements can be hours, days or even weeks. It also enables the exploitation of very low (even down to around 10 μW) power sources. On the other hand, it entails a need of an interim energy storage with appropriate energy and output power capacity, long lifetime and low self-discharge rate.

The research in Modern2020 by Arquimea has addressed potential technologies for the interim energy storage as a part of the powering subsystem. This has invovled an analysis of available material of potential energy storage technologies and a study of their application to a specific reference WSU, the methods of which can be applied to repository monitoring WSUs in general.

6.2 Results

The most potential energy storage technologies for WSUs are rechargeable batteries, supercapacitors, electrochemical pseudocapacitors, and hybrid capacitors combining several energy storage technologies.

In general, conventional batteries would be an appropriate solution during the initial years of the WSU, but the aging of the batteries will reduce their performance and limit their lifetime. There are some commercial batteries, for which the manufacturer declares calendar life close to 20 years, but the exact calendar life depends much on the environmental and operational conditions, which have to be considered case by case. Another limitation of batteries is their relatively low output power capacity.

Supercapacitors provide much lower energy storage capacity per unit volume but remarkably higher output power capacity than batteries. Current supercapacitors suffer from relatively high self-discharge, which makes long energy accumulation periods (e.g. several days) impossible. Current supercapacitors also suffer from relatively short lifetime, which depends much on the operation conditions (Figure 7).

Electrochemical pseudocapacitors and hybrid capacitors such as lithium-ion capacitors and battery-supercapacitor storage devices have recently been commercialised with the objective to solve the previous drawbacks and to combine the best features of the batteries and supercapacitors. As they represent novel technologies, these energy storage devices lack currently reliable data about the effects of aging to the performance parameters in different environmental and operation conditions. In the long run, these technologies are potential to enable better energy storage solutions for repository monitoring WSUs than the current batteries and supercapacitors.

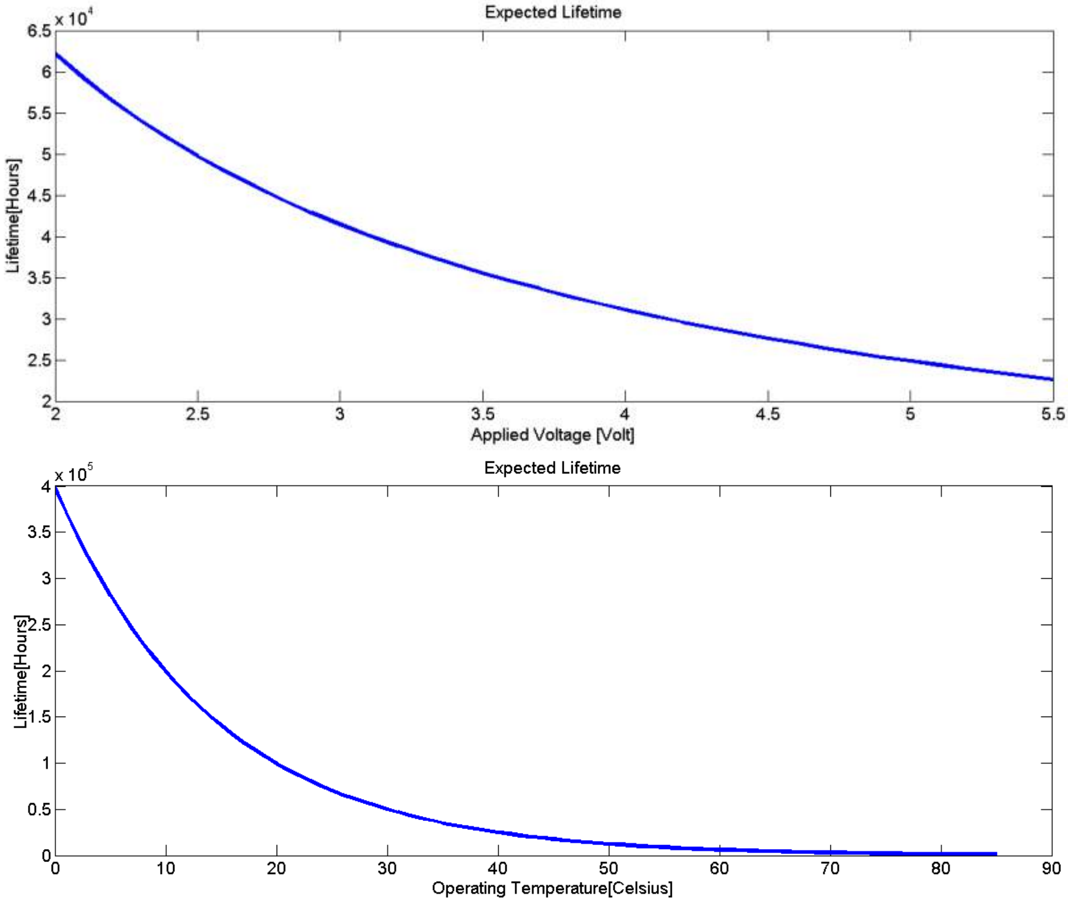

Figure 12: Dependency of the expected supercapacitor lifetime on the applied voltage and operating temperature [14].

7. Discussion

The results of the research in Modern2020 indicate that the proposed three alternative power-sourcing technologies are relevant and feasible for powering wireless repository monitoring sensors in general. Each technology has its own advantages and preferred application area, concerning features such as power output capacity and its temporal variations, potential placement of the powering subsystem in the repository, and possible impacts to the entire disposal concept (Table 5).

Table 5: A generic comparison of the power sourcing options.

Feature \ Power sourcing option	Thermoelectric energy harvesting from the HLW containers	Wireless energy transfer through the repository barriers	RTG nuclear battery
Typical output power capacity	tens of µW to a few mW per unit	tens of µW to several mW (depends much on the wireless distance and the antenna size)	several W
Operation mode	continuous power output	continuous or discontinuous power output	continuous power output
Temporal variations in power output	slowly decreasing power output, depending on the decay of the HLW heat production	constant power output, can be adapted on demand by adjusting the power level of the power transmitter	slowly decreasing power output, depending on selected radionuclide(s)
Placement	one or more units can be placed in a disposal cell; application limited to heat-generating waste	placement preferably close to the sealing plug; application in all waste sections possible	flexible unit placement possible; consideration of heat transport necessary; application in all waste sections possible
Expected impact on disposal concept	low impact, placement in single barrier is possible with minor alteration of the overall heat flow	low, due to placement close to the plug	safety assessment of introduced radionuclides necessary, interactions between heat pipes and the EBS need to be considered
Specific future research needs	energy storage options, long-term reliability	energy storage options, long-term reliability, interactions with electrically conductive and magnetic permeable materials in the EBS, adaptive antenna tuning	safety and long-term reliability, heat transport in specific placements, energy storage options in applications with high peak power consumption

The results of the research also indicate that the interim energy storage for the accumulation of the sourced energy improves the applicability of the power sourcing solution, especially those with limited power output capacity. In the design of the interim energy storage, some features of the existing energy storage technologies such as the self-discharge and the lifetime should be assessed case by case. Finding a proper overall solution for a WSU may require balancing between the capacity of the power source, the powering demand of the WSU and the capacity of the interim energy storage. This balancing may require adjusting the design parameters of the power source, adjusting the operation scenario of the WSU such as the measurement rate and communication scheme, and proper selection of the interim energy storage. This can be managed by energy-budged analysis of the WSU. Forthcoming interim energy storage technologies such as lithium-ion capacitors are expected to give more freedom for this.

8. Conclusions

The research carried out by now has made the basic features of the investigated power sourcing technologies well understood. An overall implication of the results is improved readiness for the design of complete repository monitoring systems for long-term operation of even several decades, in which the powering of the geological repository monitoring WSUs is a key enabling technology. The research has resulted in relevant input by investigating the adaptation of the proposed powering technologies to the nuclear repositories under development and construction, as well as their fundamental limitations that may require balancing of the WSU operation to be inside its powering constraints. Moreover, the pilot designs can serve as reference material in the development of the powering subsystem of the final repository monitoring WSUs.

The follow-on steps of the research should be targeted to the further development, demonstration and verification of the powering subsystem as a part of more complete WSUs and repository monitoring sensor systems according to comprehensive repository monitoring strategies. In addition to the powering subsystem, these pilot systems should also involve the sensing and communication payload, encapsulation that can tolerate the target repository environment, and the repository external parts for covering the interactions with the repository barriers. The verification of these comprehensive pilot systems should take place in a testing environment that emulates as much as possible the final repository environment, including e.g. the ambient bentonite with moisture saturation, pressure and temperature drift. In addition, measures for improving the long-term reliability such as applying redundancy, allowing for component parameter drift margins, component derating, qualification and screening are necessary. All these activities will also facilitate forthcoming cost estimations and provide additional indications how competitive these solutions are in comparison with each other and with traditional batteries.

Acknowledgements

We thank our Modern2020 Task 3.3 partners Héctor Luis Abós Gracia (Arquimea), Pierre Forbes (Orano), Ecaterina Rosca-Bocancea (NRG) and Thomas Schröder (NRG) for making this presentation possible by their contribution in the related research.

This project has received funding from the Euratom research and training programme 2014-2018 under the grant agreement no. 662177.

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Overview of Optical Fiber Technologies for Radioactive Waste Disposal Site Monitoring

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1. Summary

This paper surveys the possibilities of optical fiber sensing in radioactive waste disposal sites and it summarizes the results obtained by the partners UMONS, ANDRA, EURIDICE, XLIM, NAGRA and EDF-DTG under the subtask 'Task 3.4: New sensors' of the work-package WP3 'Research and development of relevant monitoring technologies' of the European project Modern2020 number 622177.

2. Introduction

Many nuclear power plants should be dismantled in the following decades leading to a huge amount of long-lived radioactive waste that must be safely isolated and contained for long periods. In many countries, research on disposal in geological repositories is carried out as these geological sites are believed to be the most appropriate strategy for ensuring the long-term safety of people and the environment.

Radioactive waste disposal in geological sites complies with safety analysis and monitoring of the underground facilities is not always required by the regulators. Nevertheless, long-term monitoring of the underground galleries is an added value to check the repository is performing as expected. To this end many parameters could be recorded, i.e., temperature, strain, humidity, pH, hydrogen concentration, irradiation dose, concrete cracks, dry density of bentonite, ... as shown in table 1 adapted from [1].

On the other hand, optical fiber technology is more and more studied for its use as transmitting element or as sensors in nuclear industry. The reason for this extensive research work comes from the optical fiber insensitivity to electromagnetic pulses and interferences as the key material is amorphous silica glass (SiO_2). Moreover, the low weight and small dimensions of the fibers make them also very attractive for space applications and reduce the quantity of waste after nuclear power plant dismantlement. Finally, this technology enables remote sensing; measuring devices can be placed hundreds of meters away from the sensing area, in safe enclosure where maintenance is ensured, which provides longevity for the whole sensing system [1,2].

Table 1: Typical parameters to be monitored.

Parameters	Typical range	Target sensitivity	Target spatial resolution
Temperature	20 to 90 °C	0.1 °C	20 cm
Displacement	0.5 to 2.5 mm/m	1 µm/m	10 cm
Strain in concrete	10 µm/m	3 µm/m	10 cm
Concrete cracks	200 µm		10 cm
Gap evolution inside cell	10 mm (in 100 years)	0.5 mm	1 m
Hydrogen	0 to 4 % with a sensitivity of 500 ppm 4 to 10 % with a sensitivity of 1 %	100 ppm <1 %	1.5 to 3 m
Gamma radiation	0.1 to 1 Gy/h TID of 10 MGy on 100 years	50 mGy	1.5 m
Dry density of bentonite	1000 to 2000 kg/m^3	10 kg/m^3	1 m
pH	7 to 13	0.5	1 m

3. Methodology

Optical fiber sensors can be used to measure many of the parameters of table 1 and several optical technologies are possible such as:

- Fiber itself for distributed measurement of temperature, strain, hydrogen, pore pressure, bentonite density evolution, radiation, ...
- Fiber Bragg grating for localized measurement of temperature, strain, radiation, hydrogen, pH, ...

3.1 Fiber sensitivity to radiation

When fibers are exposed to gamma radiation, the attenuation increases through the interaction of the gamma flux with the color centers or point defects present in SiO_2. This creates the so-called radiation-induced attenuation (RIA) that will limit the performance of the optical system. The RIA is complicated to study because it depends on the fiber chemical composition, the fiber history, and the nature and parameters (gamma, neutrons, continuous, pulsed, dose rate, total dose, ...) of the radiation. It has been shown that the most impacting factor is the nature of the fiber dopants (Ge, P, Al or N are used to increase the refractive index whereas F or B are used to decrease it) used to realize the refractive index profile. Many data exist in the literature leading to the conclusion that pure silica core fibers with F dopants in the cladding are the most radiation resistant fibers whereas P-doped core fibers are the most sensitive [3].

3.2 Rayleigh scattering

Optical Time Domain Reflectrometry (OTDR) is a technique schematically described in figure 1 that consists of launching an optical pulse from an optical source (LD) into the fiber under test (FUT) and analyzing the Rayleigh backscattered signal with a photodetector (PD). If the light velocity is known, the time delay between the injected pulse and the backscattered pulse can be converted in a distance along the fiber length, allowing to locally sense the fiber. This is indeed a distributed sensing system used for temperature, strain, ... monitoring [1,2]. Total distance range can reach kilometers; standard spatial resolution is 1m, improved down to the centimeter scale in the most recent developments.

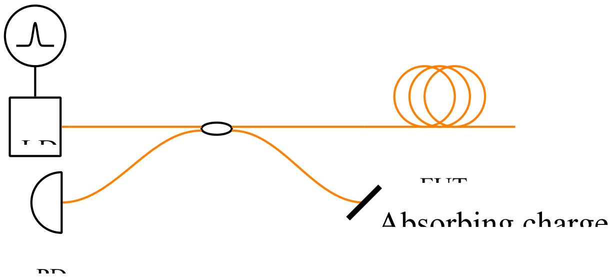

Figure 1: Basic principle of optical reflectometry, LD laser diode, PD photodetector and FUT fiber under test.

Rayleigh scattering is quite simple to use, but it is sensitive at least to strain and temperature simultaneously. So, special optical fiber cables design should be used to discriminate strain and temperature.

OTDR works in the time domain with optical pulses as short as some nanoseconds. An alternative way is to work in the frequency domain with a technique referred to as Optical Frequency Domain Reflectometry (OFDR).
Classical OTDRs/OFRDs use the Rayleigh backscattered power to get the attenuation picture of optical links and detect anomalous events along the light path. To get the temperature or strain, two measurements are done: one is a reference trace and the other one is the perturbed trace by temperature change ΔT or strain change $\Delta\varepsilon$. By doing cross-correlation analysis between these two traces, the Rayleigh spectral shift $\Delta\nu_R$ given

$$\Delta\nu_R = C_T^R \Delta T + C_\epsilon^R \Delta\epsilon \quad (1)$$

is computed from which temperature or strain profiles can be recovered. C_T^R and C_ϵ^R depend on the fiber composition and typical values are −1.5G Hz/°C and −0.15 GHz/με respectively [1].

3.3 Raman and Brillouin scatterings

The response of silica material to light becomes nonlinear for intense electromagnetic fields propagating into the fiber core. Among all nonlinear effects, Raman and Brillouin scatterings can be used for distributed sensing purposes.

Raman scattering is an inelastic interaction between the light and the molecular structure of the fiber that transfers a small fraction of the incoming power into two other fields whose frequencies are downshifted and upshifted by an amount that is linked to the vibrational modes of the fiber. As shown in figure 2, incident light at wavelength λ_0 acts as a pump to generate a Stokes wave at λ_S and an anti-Stokes wave at λ_A.

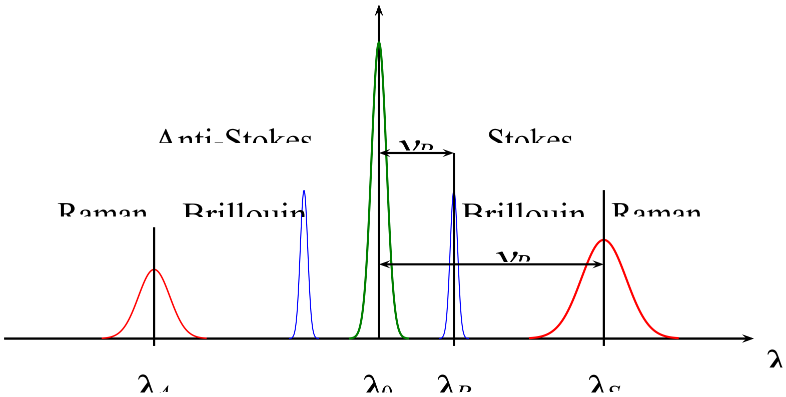

Figure 2: Typical spectra of Raman and Brillouin waves generated by a pump wave at λ0 (not to scale).

In Raman scattering, the ratio *R* of the anti-Stokes to the Stokes wave intensities is function of the temperature T according to [1,2]:

$$R(T) = \left(\frac{\lambda_S}{\lambda_A}\right)^4 \exp\left(-\frac{h\nu_R}{k_B T}\right) \quad (2)$$

where *h* is the Planck's constant, *c* is the velocity of light, ν_R is the Raman frequency shift, k_B is the Boltzmann's constant and *T* is the absolute temperature. If Raman scattering and OTDR are combined, it is possible to measure this ratio *R*(*T*) at every location along the fiber length. This then gives the temperature profile that can be used for monitoring purposes and this technique is called Raman Distributed Temperature Sensor (RDTS) [1,2]. It is worth to note that strain does not affect the temperature measurement.

Brillouin scattering is similar to Raman scattering, except that the nonlinear interaction is taking place through the acoustic modes of the fiber to generate a Stokes wave at λ_B and an anti-Stokes wave. Being linked to the acoustic velocity in the fiber, Brillouin scattering is mainly used for structural health monitoring, because it is possible to retrieve temperature and/or strain. Indeed, sensing information is encoded in the Brillouin frequency shift (BFS) noted ν_B and the variation $\Delta\nu_B$ of this shift is proportional to the temperature variation ΔT and the strain variation $\Delta\varepsilon$:

$$\Delta\nu_B = \nu_B - \nu_{B0} = C_T^B \Delta T + C_\epsilon^B \Delta\epsilon \quad (3)$$

where ν_{B0}, C_T^B and C_ϵ^B depend on the fiber composition and typical values of C_T^B and C_ϵ^B are respectively 1MHz/°C and 0.05MHz/με [2, 4]. If Brillouin scattering and OTDR are combined, the system is referred to as Brillouin Optical Time Domain Analysis (BOTDA) and can be used to measure the profile of the temperature or the strain [1,2].

3.4 Summary

Raman distributed measurements is a good technology for temperature profile measurement, whereas Rayleigh and Brillouin distributed measurements are good candidates to monitor temperature and strain distribution in the underground galleries, provided that the fiber properties are not affected by the environmental conditions inside the tunnels (radiation level, humidity, oxygen and hydrogen concentrations, ...). Table 2, adapted from [1] summarizes main properties of the techniques used for distributed measurements.

Table 2: Main characteristics of distributed optical sensors.

	Rayleigh	Brillouin	Raman
Diffusion type	elastic	inelastic	inelastic
Fiber type	singlemode	singlemode	multimode singlemode
Measuring distance	20 km (OTDR) 70 m (OFDR)	30 km	30 km
Spatial resolution	20 cm (OTDR) 10 mm (OFDR)	10 cm	1 m
Temperature sensitivity	$C_T^R = -1.5$ GHz/°C	$C_T^B = 1$ MHz/°C	0.1 °C
Strain sensitivity	$C_\varepsilon^R = -0.15$ GHz/με	$C_\varepsilon^B = 0.05$ MHz/με	insensitive
Measuring time	10 min (OTDR) 10 s (OFDR)	10 min	1 min
Power budget	10 dB (OTDR) 70 dB (OFDR)	10 dB	10 dB

3.5 Fiber Bragg gratings

A fiber Bragg grating (FBG) is achieved by creating a *z*-periodic modulation of the refractive index of the fiber core, which generates a distributed reflector characterized by its period Λ and modulation depth δ*n* (see figure 3).

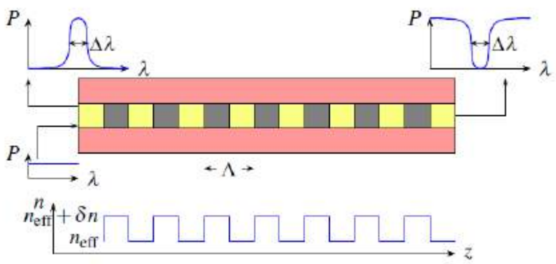

Figure 2: Basic principle of fiber Bragg grating.

When a white light is injected into the FBG, the wavelength satisfying the Bragg condition:

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (4)$$

is reflected whereas the other wavelengths are transmitted. The FBG acts thus as a pass-band filter in reflection and a notch filter in transmission. FBGs are excellent sensors because λ_B changes linearly with strain variations $\Delta\varepsilon$ and temperature variations ΔT according to:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left\{\frac{1}{n_{\mathrm{eff}}}\frac{\partial n_{\mathrm{eff}}}{\partial\epsilon} + \frac{1}{\Lambda}\frac{\partial\Lambda}{\partial\epsilon}\right\}\Delta\epsilon = (1 - p_e)\Delta\epsilon \quad (5)$$

$$\frac{\Delta\lambda_B}{\lambda_B} = \left\{\frac{1}{n_{\mathrm{eff}}}\frac{\partial n_{\mathrm{eff}}}{\partial T} + \frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T}\right\}\Delta T = (\xi + \alpha)\Delta T \quad (6)$$

where $p_e \approx 0.22\times10^{-6}\,\mu\varepsilon^{-1}$, $\xi \approx 8.6\times10^{-6}\,{}^{\circ}C^{-1}$ and $\alpha \approx 0.55\times10^{-6}\,{}^{\circ}C^{-1}$ are respectively the strain-optic coefficient, the thermo-optic coefficient and thermal expansion coefficient and the values are those for silica-based optical fibers. FBG are thus used for point temperature and point strain monitoring [2]. Again, a large amount of data exists in the literature leading to the conclusion that FBG can sustain radiation under proper conditions, making them very useful for measuring in nuclear applications.

4. Results

4.1 Temperature and strain measurements

Distributed optical measurement technologies from different manufacturers as Omnisens (Brillouin device), Luna (OFDR Rayleigh device), Silixa (Raman device) and Neubrex (Rayleigh and Brillouin device) have been tested with and without gamma radiation to measure strain, temperature, dry density, ... in geological galleries where radioactive waste will be stored [1,5].

From theses campaigns, it is clear that coupled effects of temperature and radiation are always present and should be evaluated to correctly interpret the measurements. Coupled effects of temperature and radiation improve the sensing performances of strain distributed sensors exploiting the stimulated Brillouin scattering in Ge-doped and F-doped singlemode fibers. At 80°C, 100°C and 120°C, compared to room temperature, the radiation induced attenuation is significantly reduced. However, the Brillouin frequency shift is not modified by coupled temperature influence, as it remains in the order of 4 MHz at 1MGy (air) for the Ge-doped fiber and only 2 MHz with the developed F-doped fiber, which approximately corresponds to 80 µm/m and 40 µm/m maximal errors in strain measurement.

Rayleigh scattering has proved to be a very promising solution for strain sensing. It is even less affected by radiation than Brillouin scattering. With custom fibers based on F-dopants instead of Ge-dopants, the influence of radiation on Rayleigh frequency shifts is as small as −3.75 GHz at 1 MGy (air), or 25 µm/m error, whatever the working temperature (80 °C, 100 °C and 120 °C).

Special fibers with carbon coating designed to resist to radiation and to hydrogen-rich environment have been tested as candidate for distributed temperature monitoring based on Raman scattering. Results show that measurements done in a single-ended scheme are strongly affected by radiations. F-doped optical fibers are quite insensitive to radiation and are thus mandatory. But it is not efficient enough to reduce temperature measuring errors as the main problem arises from Stokes and anti-Stokes differential attenuation. One of the easiest ways to solve that issue is to make double-ended measurements, i.e., measurement of the Raman scattering from both side of the fiber and averaging of the results. Indeed, double-ended measurement configuration allows obtaining a good evaluation of the temperature even for measurements done with irradiated multimode fibers. However, temperature measurement quality is significantly degraded with a measured temperature error reaching 5 °C.

4.2 Radiation measurements

Total integrated radiation dose can be measured through RIA computed at 1550 nm. Different fiber samples (Al-doped, GeP-doped and Ge-doped fibers) have been gamma irradiated up to 1 MGy (air) and the results show that:

- Al-doped sample is clearly the most radiation-sensitive, it could provide distributed measurement until a dose of 470 Gy, then attenuation is too high to continue measurement.
- GeP-doped fiber worked until 4 kGy before being unusable.
- Ge-doped fiber could measure RIA till MGy dose despite its lower sensitivity.

So, combination of fibers should be used to measure the full range up to MGy. Moreover, optical fiber lengths and working wavelength are nevertheless two other parameters to adjust to the application. Further work is still necessary as a strong dependence of curing effect and coupled temperature and radiation influences was demonstrated.

4.3 Bentonite density measurement

Distributed Raman scattering has been adapted to determine the distribution of the thermal conditions (density and water content) around an optical sensing cable placed inside an engineered barrier made of bentonite (swelling clay). A heated fiber-optic cable was placed inside bentonite blocks. By heating the bentonite samples with the heating part of the cable and recording the distributed temperature profiles by the Raman effect in the fiber part of the cable, distributed thermal conductivity can be estimated. Analyses of heating and cooling behavior along the cable enabled to recover the distributed thermal conductivity, from which the dry density and the water content of the bentonite are recovered [5].

4.4 Hydrogen measurement

Hydrogen leakage in the gallery is a potential problem that should be detected as earlier as possible. Three fiber-based techniques have been tested: a specialty fiber incorporating hydrogen sensitive material [6], the use of Brillouin shift versus hydrogen concentration [4], and a fiber Bragg grating (FBG) surrounded by a hydrogen sensitive layer that modifies FBG Bragg wavelength [7],

If palladium is added in the fiber core, the core properties are sensitive to hydrogen and measuring the Brillouin frequency shift or the induced birefringence allow to estimate hydrogen concentration. Proof of concept has been demonstrated but still many tests should be done to fully qualify this sensor.

Point hydrogen concentration can be detected with coated fiber Bragg gratings. Uniform FBGs were inscribed into standard singlemode fibers and recovered by a hydrogen sensitive layer made of WO_3 nano-lamellae. In the presence of hydrogen in air, the oxidation of H_2 molecules by O_2 molecules is an exothermic reaction that elevates the temperature around the FBG. H_2 sensing is therefore based on the monitoring of the Bragg wavelength shift induced by a temperature change. By optimizing the fabrication, H_2 concentration detection well below the explosion limit of 4 % was obtained, whatever the relative humidity level and for temperatures down to −50 °C. Nevertheless, tests under radiation reveal poor adherence of the sensitive active layer and more progress should be done.

4.5 pH sensor

Measuring pH is possible by using a sensor based on relative refractive index changes monitored by a tilted FBG covered with a mineral coating, a porous silica sol-gel encapsulating an indicator. Silica sol-gel is chosen here because its refractive index is close to that of the silica fiber, enhancing in turn the response. Moreover, its chemical resistance and its good adhesion on silica fibers is an advantage. In this first test, classical Bromophenol blue was used due to its convenient pK_a.

While the transition of free indicator Bromophenol blue in the pH range 3.0 to 4.6, tests show that it works correctly around a pH of 7. This difference can be explained by the interaction between the indicator and porous silica sol-gel. As the target value of the pH to be monitored in the repository is around 11-13, a dedicated porous sol-gel silica layer comprising a specific indicator should be developed and tested in harsh conditions.

5. Conclusions

A lot of experimental data obtained during the project has shown the viability of these optical technologies in radioactive waste geological disposal sites. The project enabled to qualify not only the optical fiber but the whole sensing cables; ageing tests were performed under gamma and temperature constraints to quantify the durability of these technologies.

The main conclusions drawn during the project are:

1) Temperature is retrieved from Raman scattering in a multimode fiber. To fulfill the nuclear waste disposal conditions, carbon-primary coating is mandatory to prevent hydrogen diffusion and F-doped fiber is mandatory to reduce the RIA but is not sufficient to suppress dramatic radiation impact on temperature sensing. Double-ended configuration proved to be efficient, at the expense of temperature uncertainty, which reaches 5 °C at 1 MGy.

2) Strain is retrieved from Brillouin scattering in a singlemode fiber. Again, carbon-primary coating is mandatory to prevent hydrogen diffusion and F-doped fiber is mandatory to reduce the RIA and Brillouin frequency shift. Coupled effects of temperature and radiation have been quantified. Temperature reduces the negative impact of radiation on distributed sensors exploiting the Stimulated Brillouin scattering. At 80 °C, 100 °C and 120 °C, compared to room temperature, the radiation induced attenuation is significantly reduced and maximal distance range will thus be improved. The Brillouin frequency shift is in the order of 4 MHz at 1 MGy for the Ge-doped fiber and only 2 MHz with the F-doped fiber, which approximately corresponds to 80 µm/m and 40 µm/m maximal errors in strain measurement.

3) Rayleigh scattering has proved to be a very promising solution for strain sensing. It is even less affected by radiation than Brillouin scattering. With fibers based on F-dopants instead of Ge-dopants, the influence of radiation on Rayleigh frequency shifts is as small as −3.75 GHz, or 25 µm/m error, whatever the working temperature (80 to 120 °C).

4) Regarding distributed radiation sensing, Al-doped sample is clearly the most radiation-sensitiveand Ge-doped sample the less sensitive. A combination of different fibers should be deployed to measure the radiation spatial distribution on the MGy range.

5) Special cable to measure bentonite properties through distributed Raman temperature has beendesigned and proved to be a viable solution.

6) Hydrogen sensing has been obtained by palladed silica optical fibers paired with Brillouin scattering and by functionalized fiber Bragg gratings. Proof of concept has been obtained but there is still a lot of research to do to assess the lifetime of the sensitive element.

7) pH sensing is feasible but should be tuned to the range 11-13.

Although TRL is 9 for distributed temperature and/or strain measurement with an optical fiber in classical environments, its value is 6 in radioactive waste disposals as cross-sensitivities with radiation and hydrogen diffusion have been analyzed in laboratory conditions, and specialty fibers show promising performances although not yet sufficient for real conditions. For the distributed radiation sensors and hydrogen detection, the TRL is 3 whereas for pH sensing it is 3 for pH around 7 and only 1-2 for pH in the basic range 11 to 13.

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Geophysical Monitoring Of High-Level Radioactive Waste Repositories

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1. Summary

Non-invasive monitoring of radioactive waste repositories is one of the key objectives addressed in the MODERN2020 project. For this task, geophysical techniques offer excellent means. Previous studies have identified seismic full waveform inversion (FWI) to be the most promising option for delineating subtle changes within a repository using data acquired outside of the repository. Significant anisotropy of the host rock, particularly in clay environments, precluded so far application of FWI technology for repository monitoring. With the development of a novel model parameterization, this problem could be resolved. Moreover, incorporation of structural constraints further improved the quality and reliability of our FWI algorithms. This was demonstrated with a field data set acquired in the Mont Terri rock laboratory. For a better characterization of small differential changes between two consecutive experiments, a novel differential tomography methodology was developed. It was tested with field data sets, with which differential traveltime inversions were performed. It is expected that this new method can be transferred in a straightforward manner to FWI problems. FWI technologies require extensive data analyses and substantial computer resources. Therefore, it was checked, if it is possible to employ quick and inexpensive tools, with which temporal changes in a repository can be detected, but not necessarily imaged. For that purpose, an anomaly detection algorithm was developed, and it will be tested with field data. In addition to seismic methods, geoelectrical techniques can provide valuable information for repository monitoring. For that purpose, tomographic algorithms for geoelectrical and induced polarization data were established and tested with laboratory data. For transferring the electrical parameters, obtained from these tomographic inversions, into relevant physical parameters, such as temperature and moisture content, calibration measurements were performed, and constitutive relationships between these parameters were established.

2. Introduction

Geophysical techniques offer powerful means for the implementation of non-invasive monitoring of radioactive waste repositories. The indirect nature of geophysical measurements (i.e., material properties are not measured directly, but through the geophysical data that are affected by the material properties relevant to repository system) allows obtaining information on the repository and it engineered barrier system (EBS) without placing sensors within the regions of interest. However, this can result in considerable uncertainties and ambiguities and more research is required for obtaining meaningful diagnostic information. Extensive reviews of previous work indicated that seismic full waveform inversion (FWI) currently offers the most promising opportunities, but also geoelectrical methods can provide very useful information. Results, obtained so far with these techniques, show that there is a great margin for improvements.

Here, we present results from several studies, in which a variety of geophysical techniques, suitable for high-level radioactive waste repository monitoring, have been employed. In particular, novel FWI and differential tomography techniques, suitable for waveform data, are presented, an anomaly detection algorithm is discussed, and geoelectrical and induced polarization techniques are proposed. Finally, an innovative calibration technique is presented that allows conversions from geophysical quantities to engineering parameters, such as moisture content and temperature.

3. Seismic full waveform inversions (FWI)

In FWI experiments, elastic waves are generated at some distances from the repository. These waves propagate through the repository and are recorded by a seismic acquisition system. Due to interactions between the seismic waves and the repository, the recorded seismograms are influenced by the physical state of the repository. Hence, the seismograms contain information about elastic properties of the repository. This information is used by the FWI algorithm to construct subwavelength resolution images of the elastic properties of the repository.

The unknown physical parameters, influencing the seismic waves, include the elasiticity tensor, and density. Since typical host rocks may exhibit significant anisotropy, several elements of the fourth-order elasticity tensor need to be considered. Recent work has shown (e.g. [1–3]) that an appropriate model parameterization is essential for the success of anisotropic FWI.

Here, a model parameterization was sought that is suitable for crosshole experiments. Extensive testing with synthetic data revealed that a parameterization including four velocity parameters and density is most suitable. More details can be found in [4]. To further improve the reliability of the FWI results, cross-gradient constraints were applied, which enforced structural similarity between the five model parameter types [4].

The novel FWI algorithm was applied to a data set acquired at the Mont Terri URL in the Opalinus Clay in north-west Switzerland. The experiment was focused on the imaging of a 1-m-diameter tunnel and its excavation damage zone (EDZ) (Fig. 1). Seismic signals were generated with a high frequency P wave sparker source at every 0.25 m in the lower borehole and recorded with 48 three-component geophones. The geophones were cemented in the upper borehole with 0.5 m spacing between the sensors.

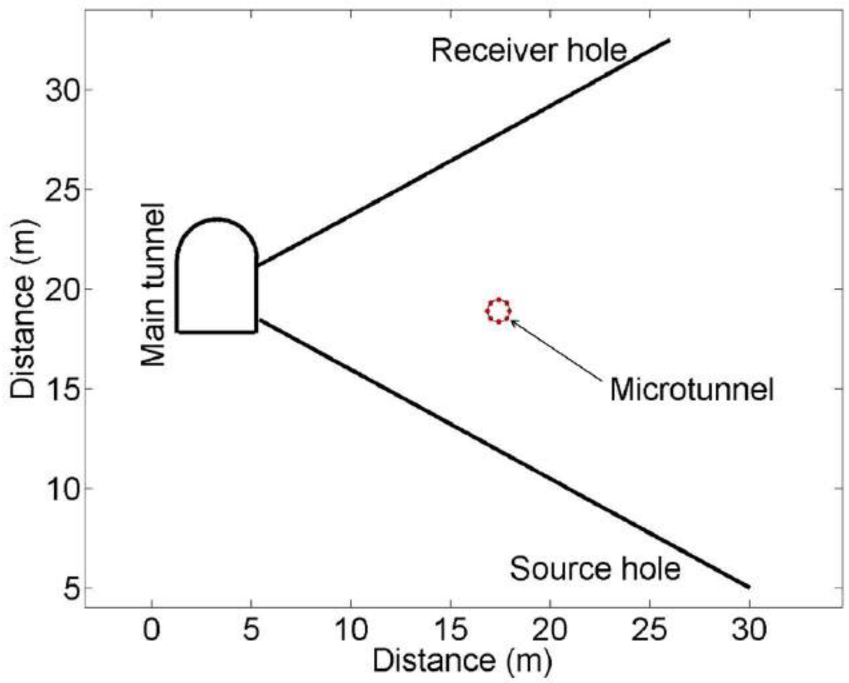

Figure 13. Schematic drawing of the layout of the non-intrusive seismic tomography experiment in the HG-A micro-tunnel at Mont Terri URL.

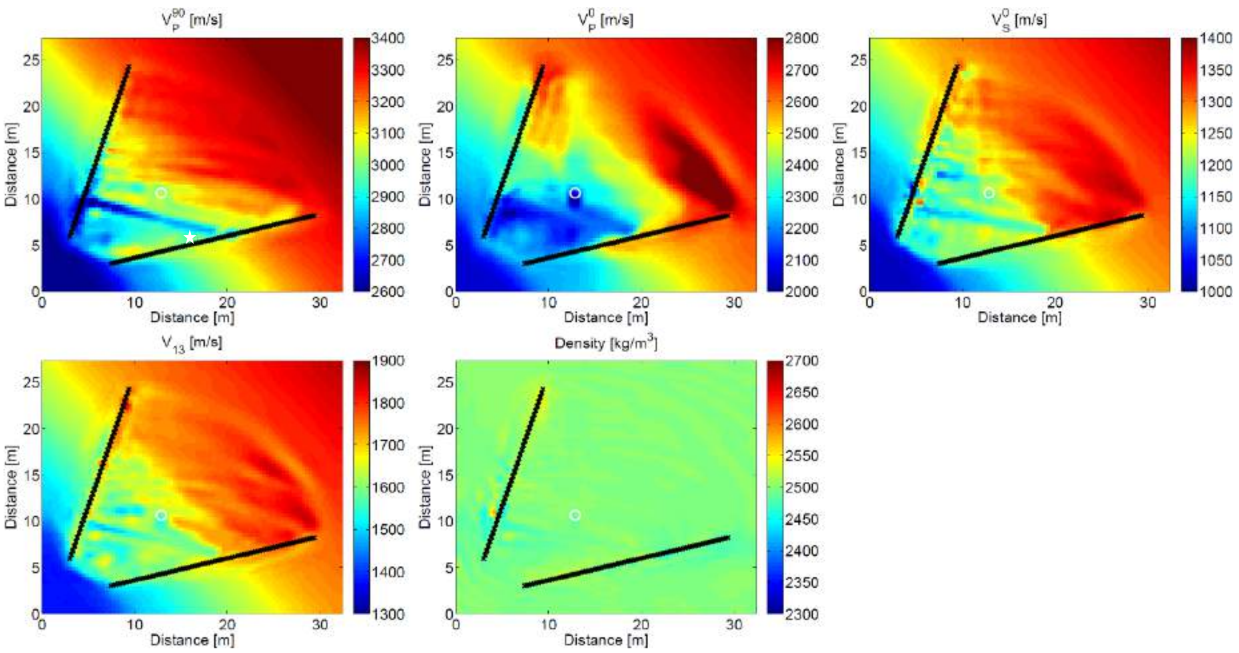

Figure 14. FWI results of data recorded in Mont Terri. The coordinate system is rotated in order to make the direction of symmetry axis vertical. Black crosses indicate locations of sources and receivers. White circles indicate location of the microtunnel.

Figure 2 shows FWI results. Images of the three velocity parameters V_P^{90}, V_S^0 and V_{13} show a clear, 1-2 m wide layer with lower velocities. This layer can be interpreted as a fracture zone also detected by borehole logging [5]. Additionally, reconstruction of V_P^0 shows hints of the microtunnel and its EDZ.

4. Differential tomography with boerehole radar data

Monitoring temporal changes within a volume of interest is one of the primary missions of geophysical surveying, and it finds many applications related with near surface targets, such as groundwater fluctuations (e.g., [6]), freezing and thawing of permafrost (e.g.,[7]), and radioactive waste repository monitoring (e.g., [8]).

The simplest monitoring option is to perform repeated surveys in a consistent manner and to analyze the data sets individually. Temporal changes can then be inferred by qualitative or quantitative comparisons of the results (parallel difference strategy, e.g. [9]). If a tomographic inversion algorithm is involved in the data analysis, the results obtained from a first data set can be used as the initial model for the inversion of the follow-up data set (sequential difference strategy). It is also possible to invert directly for the differences of two data sets. This is referred as the double-difference strategy [9]. This approach is particularly useful (i) in the presence of systematic data errors, and (ii), when the data differences can be determined more accurately and/or more consistently than the actual data.

Double-difference traveltime tomography was applied to a borehole radar data set acquired in the framework of the FE full scale experiment at Mont Terri [10]. Its main objective is to demonstrate that high-level radioactive waste can be stored safely in a deep geological repository. For that purpose, a 3 m diameter tunnel was drilled that should mimic a full-scale repository. High-level radioactive waste canisters are simulated by placing three heaters within the tunnel. After their installation, the tunnel was backfilled with a granulated bentonite mixture (GBM) and finally sealed with a shotcrete plug. The heaters were then switched on, and temperatures reached approx. 130° Celsius on the heater surfaces, and, depending on the position, 45 to 60° at the tunnel walls.

For monitoring temporal changes of the GBM, two fiberglass pipes were inserted prior to the installation of the shotcrete plug. As shown in Fig. 3, these pipes extended beyond the first heater in the tunnel. They were employed for a variety of borehole logging surveys and crosshole measurements.

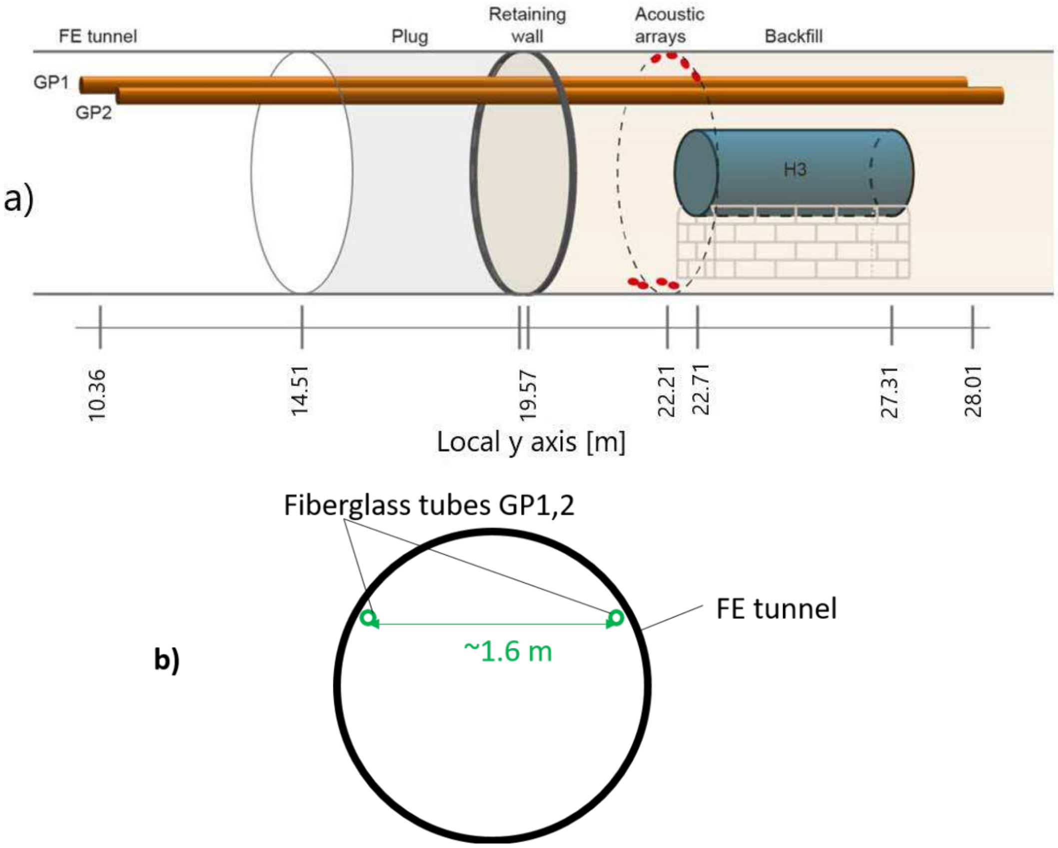

Figure 15. Setup of the FE experiment. a) Side view – GP1 and GP2 are the fiberglass tubes within which the crosshole experiments were performed. H3 represents the heating unit. b) View along the tunnel axis.

Here, we consider crosshole radar measurements performed between GP1 and GP2. Travel-time tomography results are shown in Fig. 4. The left panels show absolute tomograms of the six experiments carried out so far. The first experiment was performed prior to switching on the heater. After switching on the heater, there is a considerable drop of radar propagation velocity in the region of the heater. This is due to the temperature dependency of the dielectric permittivity that governs the radar velocities. At later experiments, we observe the appearance of low- and high-velocity heterogeneities. They can be attributed to the penetration of moisture into the GBM and the formation of air-filled voids.

The right panels in Fig. 4 show the results obtained from double-differnce tomography. These images are particularly useful for studying the evolution of the small-scale heterogeneities that appeared in the course of the experiments.

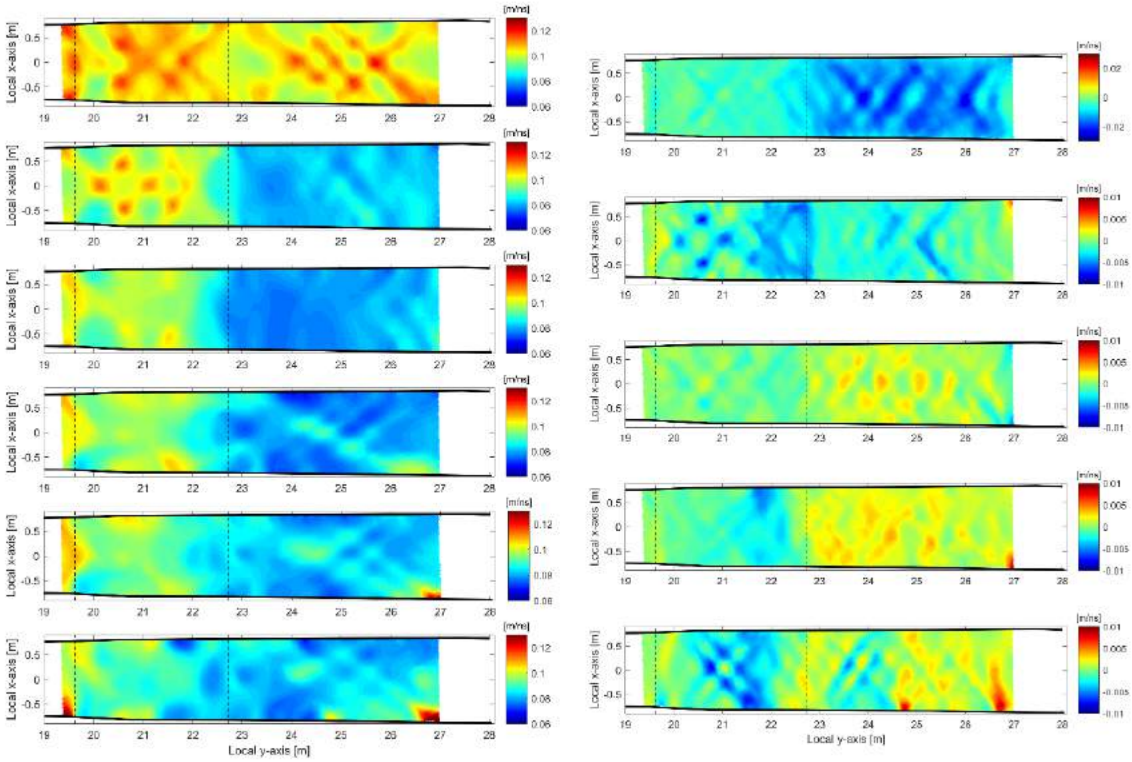

Figure 16. Results from crosshole radar tomography. Left panels show absolute tomograms, and right panels show double-difference tomography results (differences of consecutive experiments).

5. Anomaly detection algorithms

Geophysical tomography often requires extensive data analyses and substantial computer resources. Therefore, it was checked, if it is possible to employ quick and inexpensive tools, with which temporal changes in a repository can be detected, but not necessarily imaged. For that purpose, an anomaly detection algorithm has been developed.

The methodology is based on the idea to use computer vision techniques to describe the structures in the geophysical data and detect anomalies using feature vectors and direct inversion [11]. The original algorithm was implemented for the gravity field data, and it was tested on a predefined set of simple anomaly bodies with density contrasts.

The application to seismic data sets required the algorithm to be modified. As the underlying physical model in seismic phenomena is more complex compared with gravity, it was decided to focus on the supervised learning based on decision trees and support vector machines.

The heart of the modified algorithm is a pre-trained classifier with ability to distinguish predefined normal and abnormal repository configurations. The algorithm itself was updated using synthetic seismic data. The model was simulating an experimental analogue of the repository tunnel with different levels of water saturation. The configuration with low water saturation was selected as an abnormal situation and corresponding data sets were labeled as abnormal, the rest of the data were labeled as normal.

The input data model included 113 sources and 108 receivers. The waveforms of each shot gather was represented as a matrix. The matrices were normalized to a value range from the interval <0,1> and thresholded at 9 levels from 0.1 to 0.9 yielding 9 images.

The seismic velocity and elasticity parameters in the saturated tunnel are so close to those of the host rock, such that the tunnel is nearly invisible. The dry tunnel exhibits more contrast - the reflection of the waves in the tunnel are visible in the thresholded images. The images were converted into feature vectors of the form [N_{01}, …, N_{09}, S_{01}, S_{02}, …,S_{09}] (N_{0n} is the number of objects detected at the threshold level n and S_{0n} is the total area of the objects detected at the corresponding threshold level).

To select the most suitable architecture of the classifier, the Matlab Classification Learner was used to identify the best fitting classifier structure. The best results were obtained with the fine decision tree using the Gini diversity index and maximum number of splits was set to 100. Table 1 summarizes the accuracy of the classification for different classifier types.

Table 1: The different classifier structures and accuracy of the classification

Classifier type	Fine tree	Medium tree	Coarse tree	SVN linear	SVN quadratic	SVN cubic	SVN Gaussian
Detailed Description	Max 100 splits	Max 20 splits	Max 5 splits	Linear kernel	Quadratic kernel	Cubic kernel	Gaussian kernel, scale 0.75
General accuracy of classification	87,3 %	85,5 %	82,9 %	77,8 %	81,1 %	86,9 %	87,7 %

The best results were obtained with the fine decision tree and the SVN based on a fine Gaussian kernel. The abnormal situation in the repository (“dry tunnel”) was correctly detected in 91 % of all the simulations using the fine decision tree and in 92 % of all the cases using the SVN structure. In a next step, we implemented the algorithms with the support of Tensor Flow and its libraries. We have trained the decision tree classifier with the same training data as in the Matlab environment. The average classifier accuracy of our implementation was 88 %. The full algorithm is now available in Python.

6. Geoelectric and induced polarization tomography

Electrical resistivity tomography (ERT) is a widely proven and robust method for characterizing subsurface structures and monitoring subsurface processes for geological, geotechnical, hydrological and environmental applications. Recent advancements in data collection hardware and imaging software enabled ERT to become practical for variable scale 3D characterization and high-resolution 4D time-lapse monitoring applications. The sensitivity of subsurface electrical conductivity to a number of important hydrological and geotechnical parameters enables ERT efficiently to provide non-destructive and often non-intrusive information.

Induced polarization (IP) measurements and induced polarization tomography (IPT) can be carried out in parallel to geoelectrical measurements. They are sensitive to additional electrical parameters, such as chargeability. Low-frequency (below 1 kHz) induced polarization is caused by the transport and accumulation of charge carriers (ions and electrons) in micro-heterogeneous materials (e.g., rock or soil) due to an external electric field. Induced polarization phenomena can be observed both in time and in the frequency domain.

ERT and IPT data are particularly interesting for monitoring bentonite, in which high-level radioactive waste is typically embedded. The electrical conductivity of compacted bentonite blocks and bentonite pellets is influenced by the porosity, dry unit weight, pore water (gravimetric water content, degree of saturation and volumetric water content), as well as pore water salinity. It is found that for high water salinities, the electrical conductivity is most significantly related to the volumetric water content. The high electrical conductivity of injected salt solution has only little effect on changes of the bulk resistivity of the bentonite blocks or pellets on the water contents between 30 and 80 % [12].

We have developed time-lapse (4D) inversion and conceptualization processes with and without petrophysical and thermo-hydro-chemical constraints. Furthermore, measuring and signal processing protocols for simultaneous ERT and IPT imaging of the canister-buffer-bedrock systems were established. Simultaneous inversions of ERT and IPT data allow application of the same geological (structural) constraints to both data sets, thereby enhancing the reliability of the results. The inversion algorithms were tested with a laboratory experiment. First results are encouraging, and it is envisaged to apply the methodology to data sets acquired with a realistic repository monitoring geometry.

7. Calibration and validation of constitutive relationships between electrical parameters and temperature and volumetric water content

For the operational monitoring phase of buffer materials in deep geological repository, saturation and temperature are two key parameters that have been mentioned in every international collaborative work on monitoring strategies and parameters selection. Geoelectrical and induced polarisation data are sensitive to changes in saturation and temperature [13–15]. If a constitutive relationship between the geoelectrical/induced polarisation data and saturation and temperature can be established, this will offer powerful means for non-invasive monitoring of engineered barriers.

For establishing a relationship between geeolectrical/induced polarisation data and saturation and temperature, comprehensive laboratory measurements on bentonite samples were carried out. They were prepared by mechanically mixing bentonite clay with synthetic water up to the target gravimetric water content at 1000 rpm for 5 minutes. All samples were left in a sealed bag for 24 h for homogenization before any test was performed.

The volumetric water content and temperature of the samples was varied systematically, while measuring the electrical resistance and induced polarisation effects. The data were acquired by injecting the current into copper electrodes located at both extremes of the sampler in contact with the cross section of the sample and the difference in potential generated are read by two electrodes located on the top of the sample.

Figure 5 shows the electrical resistivity as a function of volumetric water content and temperature. Resistivity values of the bentonite samples are relatively low, even in samples with low volumetric water content. This was expected, given the good conductivity property of the bentonite material. As expected, resistivity values decrease with increase of volumetric water content, and there is a decrease of resistivity values with increase of temperature of exposure. Those differences are becoming less pronounced with increasing volumetric water content.

The relationship between volumetric water content, temperature and chargeability is harder to assess (Fig. 6). It can be observed that for all temperature series the peak chargeability values are reached between 30 and 50% of volumetric water content. This behaviour may be explained by the presence of fixed sites on the clay surface that are responsible for active IP. When only a few of these sites are occupied by water, there are only a few mobile ions, as they are closely attached to the clay surface, as a result the IP response is small. However, as the volumetric water content increases, the sites become available for ion exchange, which gives a marked increase in the IP response.

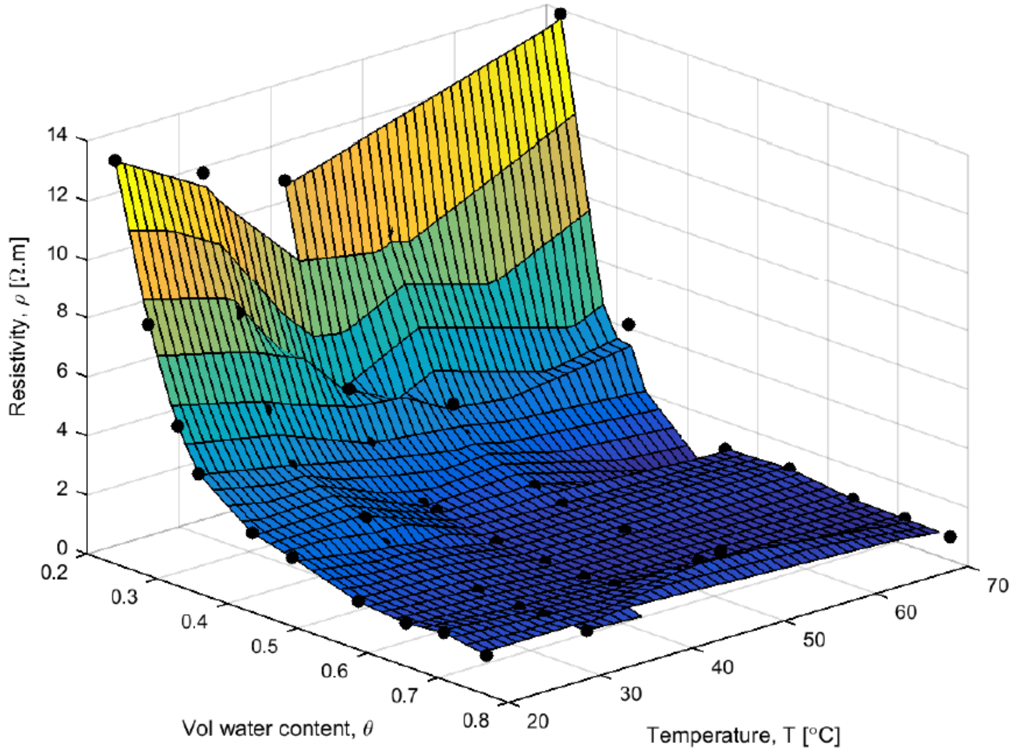

Figure 17. Resistivity results of bentonite samples. Black dots indicate measurements.

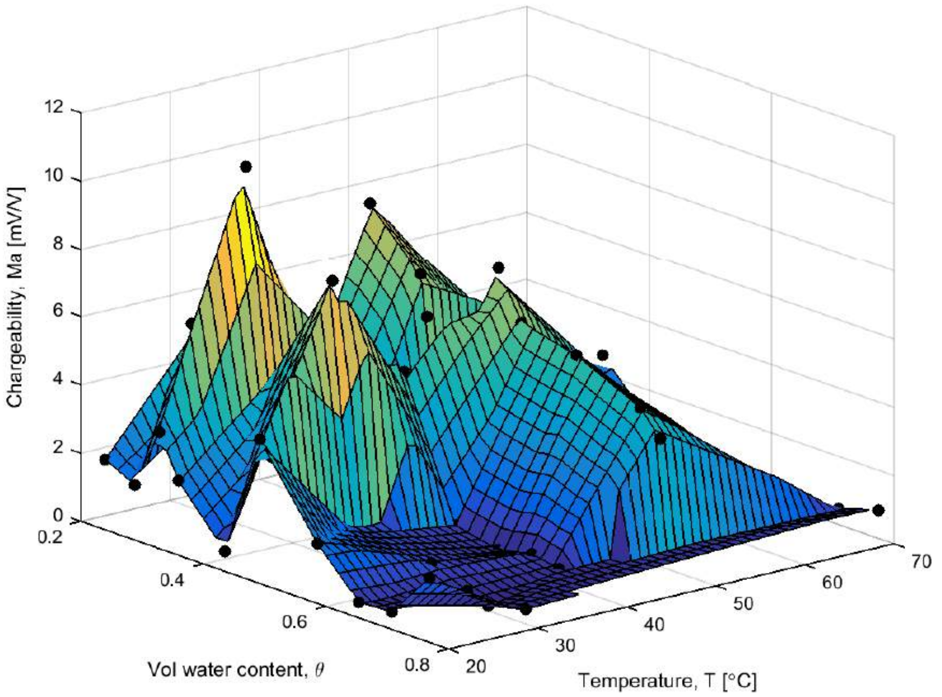

Figure 18. Chargeability results of bentonite samples. Black dots indicate measurements.

8. Conclusions and outlook

In the framework of these studies, several significant advances in geophysical monitoring of high-level radioactive waste repositories could be achieved. Key developments can be summarized as follows.

- *Seismic full waveform inversion (FWI)*
  - The long-standing problem of FWI in the presence of anisotropy could be solved using a novel parameterization scheme and structural constraints.
  - The method was validated with an application to a realistic field data set.
- *Differential tomography*
  - Novel procedures for performing differential inversions have been developped.
  - The methods were validated with an application to a crosshole radar data set, but it is important to note that this technology can be transferred easily to other inversion problems, such as FWI and ERT/IPT.
- *Anomaly detection*
  - An anomaly detection algorithm, suitable for seismic data, has been proposed. Initial tests with synthetic data are promising.
- *Geoelectrical and induced polarization tomography (ERT/IPT)*
  - Suitable algorithms for inverting geoelctrical and induced polarization data have been implemented.
  - They were validated with laboratory-scale experiments.
- *Calibration of geoelectrical and induced polarization data*
  - Constitutive relationships between geoelectrical/induced polarization data and volumetric water content and temperarture have been established using comprehensive laboratory tests.

Despite the various successes, further research is required for making these technologies applicable for actual repository monitoring. Important tasks that are already scheduled include

- application of the newly developed differential tomography algorithm to FWI problems,
- validation of the anomaly detection algorithm with field data, and
- larger-scale geoelectrical investigations at the Tournemire test site.

Finally, it is important to note that the costs and processing efforts are quite different for seismic and geoelectrical techniques. Seismic data acquisition requires expensive equipment, and it is difficult to perform the measurements in an automated fashion. Moreover, seismic FWI techniques require substantial computational resources. In contrast, geoelectrical equipment is cheaper and can be operated in an automated fashion. However, seismic FWI offers a much better spatial resolution. Therefore, an appropriate choice of geophysical monitoring depends strongly on its objectives.

Acknowledgements

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement no 662177.

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Methodology for qualifying monitoring components

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1. Summary

This paper summarizes the work performed in Task 3.6, *Reliability and Qualification of components*, of the EU H2020 project Modern2020. It synthezises progress made by eight expert organisations on a common multi-stage methodology for qualifying monitoring components (MC) of the measurement chain (sensor, connecting cable and/or wireless system/controller) at a Deep Geological Repository (DGR). This study was reported as document D3.6 [1] in the Modern2020 project and results from a multi-stage analysis including: i) the study of transferable experience gained from the energy and space fields, ii) the feed back of long-term and demonstration experiments operating in conditions close to those expected in repositories at Underground Research Laboratories (URLs) or at large mock-up, iii) the initiatives for the development of a qualification process for selecting and testing the monitoring components and at last, iv) the proposal for a global protocol appropriate to all monitoring contexts.

2. Introduction

This analysis converges towards a global protocol that may be subdivided in four steps. The first step concerns the selection of components (sensors, cables, housing, DAS etc.) based on detailed specifications of the application. It can be described as a theoretical exercise with lots of input from the manufacturers and from earlier tests for identifying possible influence parameters. The second step is that of laboratory tests for testing components under controlled conditions to quantify metrological performances. The third step concerns the on-site testing. It means testing of the whole system under realistic conditions, where some events (dust, variability of concrete, patience of worker…) may play an important role. It can also be part of the safety demonstration. At last, previous to on-site tests, an optional step based on mock-up tests may be considered if there is a need for a more realistic use of components.

The best way to articulate this methodology could be that the organization in charge of the surveillance shall document an Approval DOCument such as the one proposed in this paper with the goal of approving each component intended for use in the repository.

3. State of the art and gathering of transferable experiences from other fields

The ability to ensure reliable and durable monitoring system with repeatable quality through the time life is critical for DGR implementation. However, as there is still no implemented DGR existing analogies can also be a way for qualifying the monitoring components (MCs) and obtain reliable equipment over the long term. The analysis of transferable experience from other fields aims at summarizing the different protocols used by other industries with respect to the monitoring components to deliberately accelerate their ageing and qualify their use. This was done by taking into account the feedback from industries working in harsh environments through a bibliographic research made around two major companies EDF and ESA, involved in the energy and the space field, respectively and by comparing it to the approach proposed by Andra, the French agency for radioactive waste management, for the Cigeo project.

3.1. Experience from the energy industry field

Innovations (eg. new design of the hydraulics at Marèges, France), accidentology (eg. Malpasset, Rance) and pathologies of works at dams (alkali-reaction concrete at Chambon, France) fueled a need for remote long-term quality monitoring. This especially concerned reliability of data transmission as dams are not easily accessible in winter. Nuclear power plant monitoring was inspired by these practices by using similar sensors as dam monitoring, for instance telemetry systems. However, in order to take into account different characteristics between these structures, as well as the large number of sensors involved in hydraulic and nuclear power plants (around 20,000 sensors in 600 civil engineering works), EDF has defined and implemented an industrial policy for the choice, the qualification and the maintenance in operational conditions of auscultation equipment. It is based on the following three main principles:

- Use of a limited number of types of equipment,
- Development of a selection and qualification process for materials,
- Sustainability of qualified materials.

This has conducted EDF to develop an original approach for selecting and qualifying the components for the monitoring of Dams and of Nuclear power plants implemented through five main tasks summarized in Figure 1 after [2] and including:

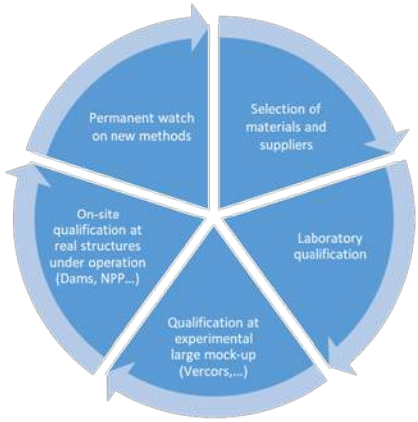

Figure 1: Selection and qualification process implemented at EDF for monitoring components

The selection of material and suppliers further to a permanent watch on technologies is based on the following features: accuracy (absence of drift over time), insensitivity to environmental conditions (temperature, humidity, surges), reliability (inaccessible device, continuity of measurements), robustness (hostile environment: humidity, cold, lightning...), and maintainability.

The materials are selected according to their manufacturer characteristics. EDF is preferably looking for "close" (European) suppliers who are well represented in the area to benefit from a better after sales service and easier dialogue as part of a partnership. The cost aspect of the material is obviously considered. However, this criterion is weighted against the others (in particular the reliability and the robustness) because the recurrent failures of a hardware installed on an isolated site become very quickly expensive.

The laboratory qualification includes the verification of metrological characteristics, tests for sensitivity to influence quantities, verification of functional and ergonomic features, and verification of compliance with the standards in force, robustness and ageing tests.

At last, on-site qualification is performed either on large scale mock-up or on real structures. The former is generally operated in parallel with devices already in place and qualification pronounced after a satisfactory exploitation time lasting at least one year. The use of large-scale mock-up aims at verifying the behaviour of components at a larger time scale and at conditions similar to real ones or even better controlled. One example is that of the Vercors (Monitoring System for Reduced Scale Containment Model.) experiment developed for verifying the behaviour of components associated to a reactor structure [3].

3.2 Experience from the space field

Concerning the space field, Europe via The European Space Agency (ESA) has created its own European “organism” for space qualification, namely the European Space Components Coordination (ESCC). It is shown that despite different influencing parameters, due to the rocket take-off (vibrations) or the space conditions (vacuum, temperature, radiations), the qualification process is rather similar to that developed in the energy field. The selection of components is a complex process that alone accredited companies (SAFT, TRAD, IAS) are able to perform. It includes the analysis of performances, design, operational, environment, manufacturing and testing.

The testing of components requires qualification campaigns in space simulators, controlled clean environments, thermal vacuum space cycling, vibration pot and irradiation facilities and is considered achieved when the Part Approval Document (PAD) is fully filled up and signed [4].

3.3 Andra's approach for the repository field

An overview of typical environmental conditions, expected operating performances such as durability and precision, and other specific constraints imposed by the repository safety requirements were presented in the MoDeRn Technical Requirements Report [5]. It is recommended that available state-of-the-art monitoring technology is adapted and qualified to meet these requirements, and where necessary innovative technology is developed and qualified as well. To illustrate this recommended approach, a succinct description of the qualification process that Andra has set up is provided. It entails testing and qualifying the complete measurement chain, by progressive steps, knowing, to be able to anticipate them, the failure rates and mastering the possible long term drifts. The overall process is inspired from the qualification guide for non-destructive methods. Global test sequence includes four stages such as in Figure 2:

- Stage one consists in acquiring in-depth knowledge of the sensing technology, engineering solutions, practical implementation constraints. It aims at selecting the technologies best suited to the specific requirements of monitoring the geological repositories for long-lived nuclear wastes. When commercially-available sensing chain performances do not fulfil requirements, research programs will be initiated.
- Stage two consists in carrying out laboratory tests, under fully supervised and/or controlled environmental conditions, to qualify the sensitive component and assess the complete measurement chain performances. Sensors are tested in air, and embedded in host material of interest.
- Stage three consists in outdoor tests, to evaluated field implementation influence. At this stage, the sensing chain is preserved from hazardous conditions, extreme temperature or gamma rays. Unexpected influence parameters might thus be revealed.
- Fourth stage involves hardening in view of the application environmental conditions. In the envisioned French geological repository, temperature (25°C to 90°C), gamma radiation (dose rate of 10Gy/h at HLW contact), and hydrogen (up to 100%) are amongst the main stresses to be analyzed.

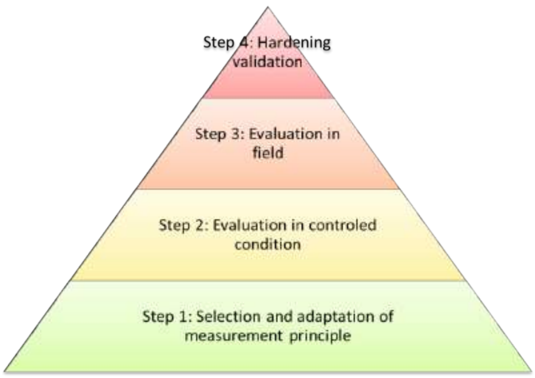

Figure 2: Qualification process for technology implementation in the Cigeo projet

3.4. Main feedback from other fields

Results indicate that there is a strong synergy between DGR and other fields (Energy, Space,…) concerning the needs, such as robustness, long-life power supply, and optimization of communications. All fields consider at least three common stages: i) Selection of components, ii) Laboratory qualification and iii) On-site qualification.

4. Lessons learned from existing long-term experiments

The second part of this study concerned the analysis of case studies of monitoring components operating in conditions close to those expected in repositories. The main idea was to obtain information about ageing, accuracy, possible drift over time and robustness of sensors installed. This was done through a selection of large in situ experiments performed at URLs or in large mock-ups (GCR, FEBEX, SEALEX, POPLU, PROTOTYPE). The selected experiments can be shared into two categories: demonstrator and long-term. In demonstrators the general rule was to use high Technology Readiness Level (TRL) monitoring components essentially wired connected sensors such as in GCR and FEBEX. However, for the sake of redundancy and also for qualifying new or low TRL instruments, more innovative components including wireless sensors were applied in long-term experiments such as in POPLU, MPT or in SEALEX. Each selected experiment was summarized through an experiment form detailing the type (long-term or demonstrator), present status (dismantled or on-going), goals, means and main results with respect to survival rate of sensors, the failure origin, if any, and the possible improvements [1]. Table 1 summarizes main conclusions with respect to the survival rate of wired/wireless sensors for the given experiment duration.

Table 1: Behaviour of sensors for a selection of long-term or demonstration experiments at URLs

Partner	ANDRA	NAGRA AMBERG	IRSN	SKB	VTT	SKB
URL/LAB (country)	LMHM (F)	GTS (CH)	Tournemire (F)	Äspö (S)	Onkalo (FIN)	Äspö (S)
Dismantled long-term and demonstrator experiments	GCR	FEBEX in situ				
Long-term experiments			SEALEX	MPT	POPLU	PROTOTYPE
Duration (y)	6	18	6	5	5	8
Total number of sensors						
Wired/Wireless	-	176/0	149/105	194/33	132/0	328/0
Total/Survival	134/9	176/108	149/113	227/99	132/20	328/125
% survival rate	93%	39%	24%	56%	85%	61%

The first lesson is that experiments only lasted a few years which is far below the 100 year operational phase expected for DGRs. The second finding is that despite a strict selection of the best technical solution of the moment, the analysis of the different long-term and demonstrator experiments suggest improvements on monitoring components:

- For wired sensors, preference was given to passive measuring methods such as the vibrating wire technique and the optical fiber distributed sensing for which an extension of recording time is required to demonstrate the absence of water short circuits along the cables. In case of potential leakage, wireless technologies should be used and the size and number of cables

should be limited; cables should also be more armored and resistant to corrosion to prolong their service life.
- For wireless sensors many problems occurred during swelling of the bentonite-based seal under waterflow. Improvements mostly concern a better isolation between transmitters and sensors for avoiding electrical short circuit with free water and the extension of batteries' lifetime.

5. Development of a qualification process

The process must first consider the list of influence parameters requiring a monitoring component. But this part is not included in the qualification process.

5.1. Methodology for selecting monitoring compounds

As for monitoring contexts in other fields the selection requires upstream to verify:
- Metrological characteristics and performances (compliance with environment requirements including lifetime, radiations levels, mechanical stress, thermal stress, humidity exposure, and storage duration…).
- Sensitivity to influence parameters (Temperature, Humidity, Stress, Strain, Corrosion under in situ conditions, Hydrogen...).
- Functional and ergonomic characteristics and design.
- Compliance with current standards (safety, CE marking, PAD, approved at accredited labs...).
- Operation: input/output power, operating temperatures, wavelength, modulation, consumption, end of life, etc.
- Testing: list the physical quantities, functionalities and number of tests to be carried out, establish the measurement ranges and the number of measurements to be made, select the off-site laboratories, screening definition, prioritize the realization of tests (laboratory or on-site).
- Quality and Product Assurance: focus on reliability and traceability, define the customers' reviews as early as possible, the list of documents to be delivered, how the hardware is accepted for delivery, and criteria for batch rejection.
- TRL: Propose the minimum required Technology Readiness Level.

5.2. Methodology for testing and evaluating monitoring compound

The second step of the qualification process consists in testing components under laboratory or real conditions of use. It is recommended that laboratory tests be conducted prior to field testing. A test form was sent to partners with the goal of having their feedback from laboratory testing methodologies. Two categories of laboratory tests were identified: Tests of robustness and ageing tests [1]. In both cases tests seek to estimate the degree to which a system or component can function correctly in the presence or stressful environmental conditions but ageing tests alone look at the normal degradation with actual time of use by accelerating artificially the process through a time-dependent stress.

Irradiation test is a good example of ageing test such as those performed on new sensors developed in the framework of Modern2020. Tests were performed at the IRSN (IRMA) and CEN-SCK (RITA) facilities with Total Ionizing Dose (TID) of about 1MGy and of 0.1 MGy, respectively. Most of the tests concerned Optical fibers and provided very promising results in view of their integration in a DGR. However, a lot of work remains to do to quantify precisely the Radiation Induced Attenuation on the fiber itself with the necessity to use a dopant or to evaluate the coupled impact of influence parameters (temperature, radiation, hydrogen…) on the sensing cable.

An example of robustness test is proposed by VTT for the Nordic repository case with the aim of developing a procedure to simulate long-term conditions in EBS environment. Robustness tests are planned to be done in cycles so that it will give provisional results already during the test program. Test plan will consist of selected sensors and dummy sensors made to mimic the shape and having the same piping and tightness as the real ones and manufactured from different materials. Idea is to test sensor enclosure and sensor cable armouring/sheltering pipe with the dummy sensors. A test would consist of 20 iterative steps as illustrated in Figure 3.

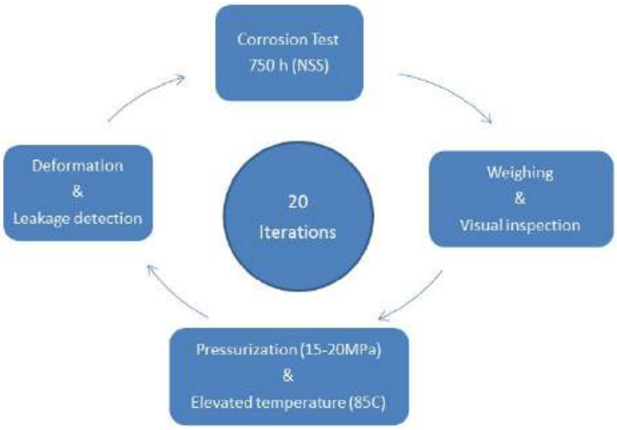

Figure 3: Example of cyclic robustness test applied to monitoring compounds to simulate their long-term conditions in the EBS environment

Contrary to laboratory tests, on-field tests may allow testing the complete measurement chain metrologically and functionally under real conditions of use. But for the moment, only demonstrators in underground, long-term experiments at on-site/off-site laboratories or at large mock-up can serve as dummy on-site tests. Monitoring strategies like that proposed by Andra also suggests using some “sacrificial”, “surveillance” or “witness” structure [1] exhaustively equipped to fulfil the monitoring goals at the future repository.

6. Discussion and conclusion

The study resulted from a multi-stage analysis including: i) the study of transferable experience gained from other industry fields, ii) the analysis of case studies operating in conditions close to those expected in repositories, iii) the initiatives for the development of a qualification process for selecting and testing the monitoring components and at last iv) the proposal for a global protocol appropriate to all monitoring contexts.

Main conclusions are that:

- A strong synergy with respect to the monitoring components exists between energy and space fields with needs for a DGR facility such as robustness, long-life power supply, and optimization of communications. The qualification process of those different fields always consider at least three stages including i) Selection of components, ii) The laboratory qualification and iii) On-site qualification. The cost aspect of the components is obviously considered. However, this criterion is weighed against the others (in particular the reliability and the robustness) because the recurrent failures of a material installed on an isolated site quickly become expensive [2]. It is noteworthy that there is no public information about the cost of the qualification process in percentage with respect to that of the monitoring system under review.
- Despite a strict selection of the best technical solution of the moment, in situ and long-term experiments performed at URLs or at large mock-ups suggest improvements that can only be checked in situ where conditions will be as close as possible of the real one at DGRs.
- The Initiatives for the development of a generalized qualification procedure must combine robustness, ageing and on-field tests. This can be summarized by the global sketch given in the Figure 4.

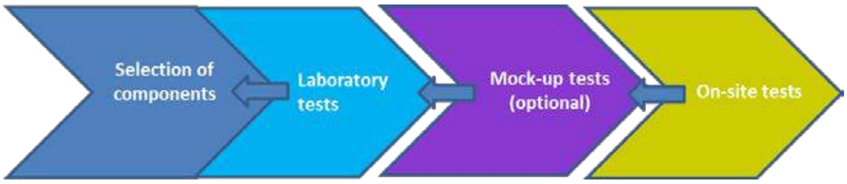

Figure 4: Global sketch for the qualification of monitoring components in DGRs

The proposed global qualification protocol combines the same three successive steps proposed by other fields with an optional large-scale mock-up stage and a retrofit process in case of dissatisfaction of one of the three/four major steps. The first step concerns the strict selection of component candidates with the aim of measuring influence parameters and to define the list of tests to be carried out. The goal of the second step is to proceed on the laboratory testing of components/combined components under adverse conditions. The last step is linked to testing under real conditions of use. To package this methodology, an Approval DOCcument (ADOC) is proposed as a mean to control the approval status of a monitoring component whatever the repository context (Appendix 1).

The objective of the ADOC document is to provide information about a monitoring component and its acceptability with respect to its selection, laboratory test and on-site test. The entity in charge of the surveillance of the repository shall document the ADOC sheet for approval of each component type intended for use in the repository.

Acknowledgements

This study has been carried out as a part of Modern2020, Work package 3, Task 3.6. The Modern2020 project is co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme - contract 622177.

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Appendix 1: Sample of an ADOC sheet for a monitoring component qualification

Project: **Prepared by:**	**Doc n°:** **Date:**
Approval requested by: **Family:** **Technology Detail specification:**	 **Component:**

Approval status:

Evaluation programme required:	☐ Yes	☐ Not

Selection of components

TRL: Fit the D31requirements :	☐ Ok	☐ Not Ok
Influence parameters with measurement range and sensitivity:		
Sensitivity to influence parameters	☐ Ok	☐ Not Ok
Verification functional and ergonomic characteristics	☐ Ok	☐ Not Ok
Verification of metrological characteristics	☐ Ok	☐ Not Ok
Verification of compliance with current standards	☐ Ok	☐ Not Ok
Requirement for additional tests (in case not ok)	☐ Yes	☐ No
If yes, test required Lab – Robustness	☐ Yes	☐ No
Lab – Robustness tests	☐ Yes	☐ No
Lab – Ageing tests	☐ Yes	☐ No
Mock-up tests	☐ Yes	☐ No
In situ – Long-term	☐ Yes	☐ No
In situ – demonstration	☐ Yes	☐ No

Laboratory test (testing of components/combined components under adverse conditions)

1. Robustness tests:	☐ Yes	☐ No
Laboratory name:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	
2. Ageing tests	☐ Yes	☐ No
Laboratory name:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	
3. Communication tests	☐ Yes	☐ No
Laboratory name:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	

On-site test (testing of the whole components under real conditions) or off-site at large mock-up (optional)

1. Tests at URLS / offsite at large mock-up	☐ Yes	☐ No
URL/mock-up:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number Date		
Results: ☐ Ok ☐ Not Ok		
2. Test at DGR witness structure/cells	☐ Yes	☐ No
DGR:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number Date		
Results: ☐ Ok ☐ Not Ok		

C.d – Parallel Session on New Developments in Repository Monitoring Technologies

Application of ultrasonic techniques for quality assurance of salt concrete engineered barriers: Shape, cracks and delamination

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1. Summary

The closure of underground nuclear waste disposal facilities requires reliable gas- and water-tight engineered barriers. In Germany, barriers made from salt concrete have been evaluated in full scale. While the barriers seem to fulfill the requirements regarding permeability, some unexpected cracks have been detected at the surface and at depth. In cooperation between the Federal Company for Radioactive Waste Disposal (BGE) and the Federal Institute for Materials Research and Testing (BAM), several experiments have been carried out to evaluate the applicability for ultrasonic measurements in crack detection and general quality assurance. Both commercial instruments and specially developed devices have been tested on site.
Using commercial ultrasonic echo devices designed for concrete inspection it was possible to detect cracks and object in salt concrete up to a depth of 2 m. The check for delamination in shotcrete is another field of application. A unique device available at BAM, the wide aperture, deep penetration instrument LAUS, was able to locate cracks and objects up to a depth of 8 m so far, which is thought to be a record for ultrasonic echo measurements in concrete. Adapted imaging procedures, partly adopted from geophysics, helped to reveal 3D structure at depth.
In addition, we have developed ultrasonic probes to be deployed in boreholes, currently at up to 20 m depth. They can collect information on cracks and other features in a radius of about 1.5 m around the borehole in the current version and might be used in echo or transmission mode. Evaluation experiments have been performed at an experimental barrier at the ERAM site in Morsleben, Germany. The results showed several empty and injected cracks as well as built in instrumentation. The results have been verified using borehole endoscopy as well as core examination and will be used to set up a reliable quality assurance system for engineered barriers. All instruments are based on ultrasonic shear wave transducers with a frequency range between 25 kHz and 100 kHz. Current research focuses on the improvement of the hardware (e. g. optimization of array characteristics) and imaging techniques as Reverse Time Migration, both aiming at the improvement of depth of penetration, resolution and probability of detection.

2. Introduction

Engineered barriers are crucial elements for underground nuclear waste disposal facilities. Galleries, adits and shafts must be sealed watertight permanently for extremely long periods of time. The barriers must be adapted to the host rock type and geomechanical requirements. Research in Germany has so far been focused on depositories in rock salt. Meanwhile a new search for a disposal site has been re-opened independent of host rock type. However, the existing depositories, e. g. the ERAM rock salt site in Morsleben, central Germany, must be sealed properly.

In recent years, a test barrier made from salt concrete has been evaluated in full scale at ERAM. While the barrier seems to fulfill the requirements regarding to permeability, some unexpected cracks have been detected at the surface and at depth. Since 2013, in cooperation between the Federal Company for Radioactive Waste Disposal (BGE) and the Federal Institute for Materials Research and Testing (BAM), several experiments have been carried out to evaluate the applicability for ultrasonic measurements in crack detection and general quality assurance [3]. Both commercial instruments and specially developed devices have been tested on site. This study reports some examples from ongoing tests, research and development.

3. Methodology

3.1. Instrumentation

Ultrasonic echo methods for concrete inspection have made a tremendous development during recent years [4]. The principle of operation is based on sending an ultrasonic impulse into the strcture, which is scattered or reflected at inhomogeneities (e. g. boundaries, objects or cracks). The energy appearing back at the surface is recorded by a set of receivers. Data from many transmitter -receiver combinations are combined in sophisticated processing algorithms to provinde an image of the interior of a strcture. Almost non-existing 25 years ago, commercial instruments are meanwhile used e. g. for bridge inspection on a regular basis. However, penetration depth is limited to around 1 m in most cases.

Engineered barriers typically have diameters of several meters and lengths of tens of meters. To be able to inspect these kind of structures as well as other massive constructions, BAM has developed a unique large aperture ultrasonic system (LAUS, [5]). It consists of several independent wireless transducer arrays including individual transmitter electronics, digitizers, data transmission modules and batteries (Fig. 1, left). A coupled set of 32 ultrasonic shear wave transducers with a frequency range between 25 kHz and 100 kHz are used in each unit (Fig. 1, right). The units can act as transmitters or receivers (resulting in 132 combinations for a set of 12 units) and is controlled by a standard notebook computer. Preliminary results can be displayed on site. Several sets of measurements can be combined and processed to give 3D images of the subsurface. Meant to be a research tool, the LAUS has been used in a couple of commercial projects meanwhile as well [6]. Depth of penetration is 5 m in reinforced concrete and 9 m in salt concrete so far.Other than commercial ultrasonic echo devices, the transmitter/receiver units can be placed individually to avoid obstacles on the surface or to improve the imaging by using adapted distances (“aperture”) in between the units. The full potential of this feature is not exploited yet.

Still, the LAUS is currently not able to image the full length of an engineered barrier. To get more information at least from the experimental barrier at ERAM, a borehole probe has been designed and built to be deployed in existing boreholes (Fig. 2). The same type of transducers is used as in the LAUS system, but so far limited to a fixed offset between transmitter and receiver arrays, consisting of six individual transducers each. The transducers are lifted at put to borehole wall by a pneumatic system. The array can be rotated manually by an aluminium rod, which is as well used to push the probe into the borehole. The array arrangement and the rotation results in a certain degree of directionality, but the aperture angle is at least 90° sideward.

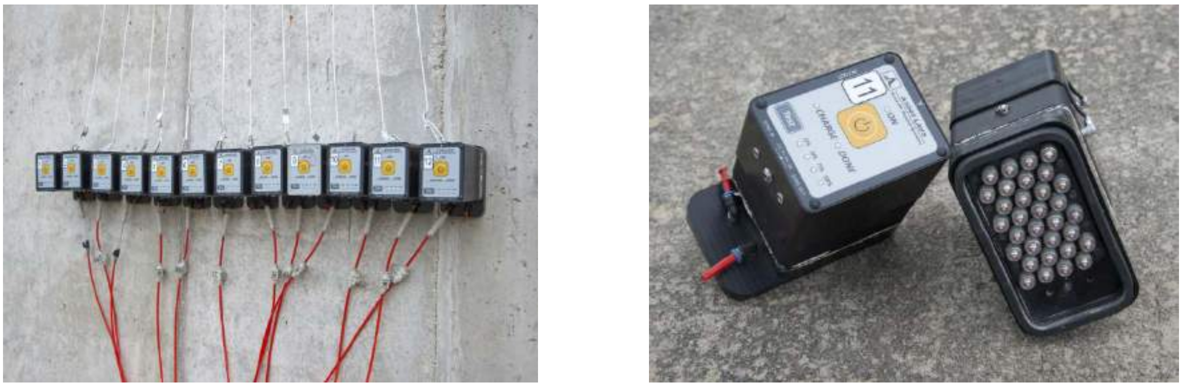

Figure 1: Left: The LAUS deep penetration ultrasonic echo device with 12 independent wireless transducer arrays. Red lines are pressure hoses to supply the suction pods. Right: LAUS transducer array with 32 coupled shear wave transducers. From [6]

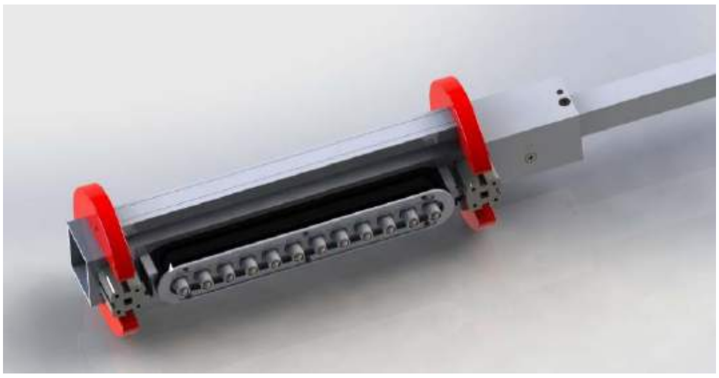

Figure 2: Ultrasonic borehole probe, with 6 transducers each used as transmitter and receiver (BAM).

3.2. Imaging

As most ultrasonic arrays have a large aperture angle (angle under which energy is transmitted into the structure and received from there), the data acquired must be processed to provide images, which are sufficiently sharp and approximately geometrically correct. The quality of the results depends on many parameters, including instrumentation, variation of transmitter-receiver distance, number and density of data and the imaging method used.

The synthetic aperture focusing technique (SAFT) is the standard tool (or in fact family of tools) for ultrasonic echo data imaging. The software collection InterSAFT developed and maintained by University of Kassel [7] is in our opinion the most versatile tool for ultrasonic data evaluation in civil engineering. For the LAUS system, a special version of InterSAFT was developed [8]. However, SAFT, which is very close to the seismic imaging method "Kirchhoff migration" has certain limitations, including a lack of imaging capability for steep reflectors. This means that refectors (including cracks) which are perpendicular to the surface would not appear in the ultrasonic images.

Recently several groups have started to explore and adapt more sophisticated (but computationally more expensive and not applicable on-site) methods from geophysics as "Reverse Time Migration" (RTM)[9][10]. RTM uses simulations of the full wavefield in the structure forward from the transmitter and backwards from the receivers to provide a more detailed and sometimes more accurate images. In many cases, ir is possible to get images even from vertical reflectors.

4. Results

4.1. Measurements on the front face using the LAUS

In early 2018, the front face of the test barrier at ERAM (Fig. 3 right) was scanned using the LAUS system (Fig. 3 left). Due to open boreholes and other obstacles, not the entire area has been covered. Main target was a steel sheet inside the barrier in about 8.5 m depth.

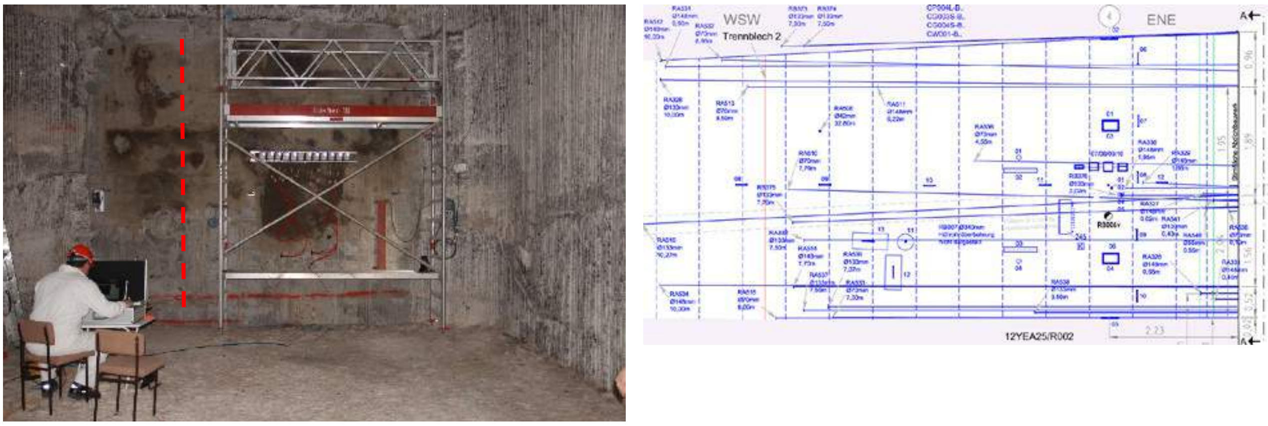

Figure 3: Left: LAUS applied to the center of the barrier at ERAM. Red dashed line: Profile discussed in Fig. 4 and Fig. 5. Right: Cross-section of the barrier. Front face is at the right. Vertical red lien is the steel plate.

Fig. 4 (left) shows the 2D SAFT results of a vertical line at the left of the barrier. Several smaller reflectors (instrumentation inside the barrier and smaller cracks) are visible in the depth section (annotations 2,3,4). At 6.5 to 7 m depth strong reflections are visible, which have been between interpreted as two individual cracks (1,6). A weaker reflection follows at 8 to 8.5 m depth (5). As this reflection covers only a part of the image, it wasn't quite clear whether this is related to the steel plate. Fig. 4 (right) shows the RTM results for the same data set. While the image seems to be more blurred due to inherent artefacts and some additional data processing performed by the InterSAFT software, some features are imaged clearer. The deep cracks (1,6) seem to be connected. The existence of this crack has been proven by borehole endoscopy at least for a part of the cross-section. The suspected steel sheet covers a larger part of the cross section (which supports the interpretation). The side walls (blue dashed line in Fig. 4) of the barriers are imaged neither by SAFT nor by RTM in their full extent.

4.2. Measurements using the borehole probe

The borehole probe has been deployed at several places at the ERAM site. Figure 5 shows the combined results of three measurements: to the left and right from borehole 1 and to the right of borehole 2, which was blocked at 8.5 m. The boreholes had been drilled into a large salt concrete block which supports the ceiling at a former salt mining gallery. This was chosen to be shown here, as this is the only combined image available so far and deepest boreholes investigated yet. Measurements in the boreholes were carried out in reflection mode (using one probe) and transmission mode (using two separate ("bistatic") probes).

The image shows several large cracks, consistent over the connected images. One of two main features are a crack visible at the front face of the block between the boreholes and proceeding to borehole 2 and beyond to the right. The other prominent crack connects the two boreholes in the deeper part and continue to greater depth to the left. The connection between the two boreholes was verified by a pressure test.All imaged cracks along the borehole axis could be verified by core examination and borehole endoscopy.

It must be considered that the cracks are indeed 3D structures. The limited directionality of the probes might lead to geometrical inaccuracies.

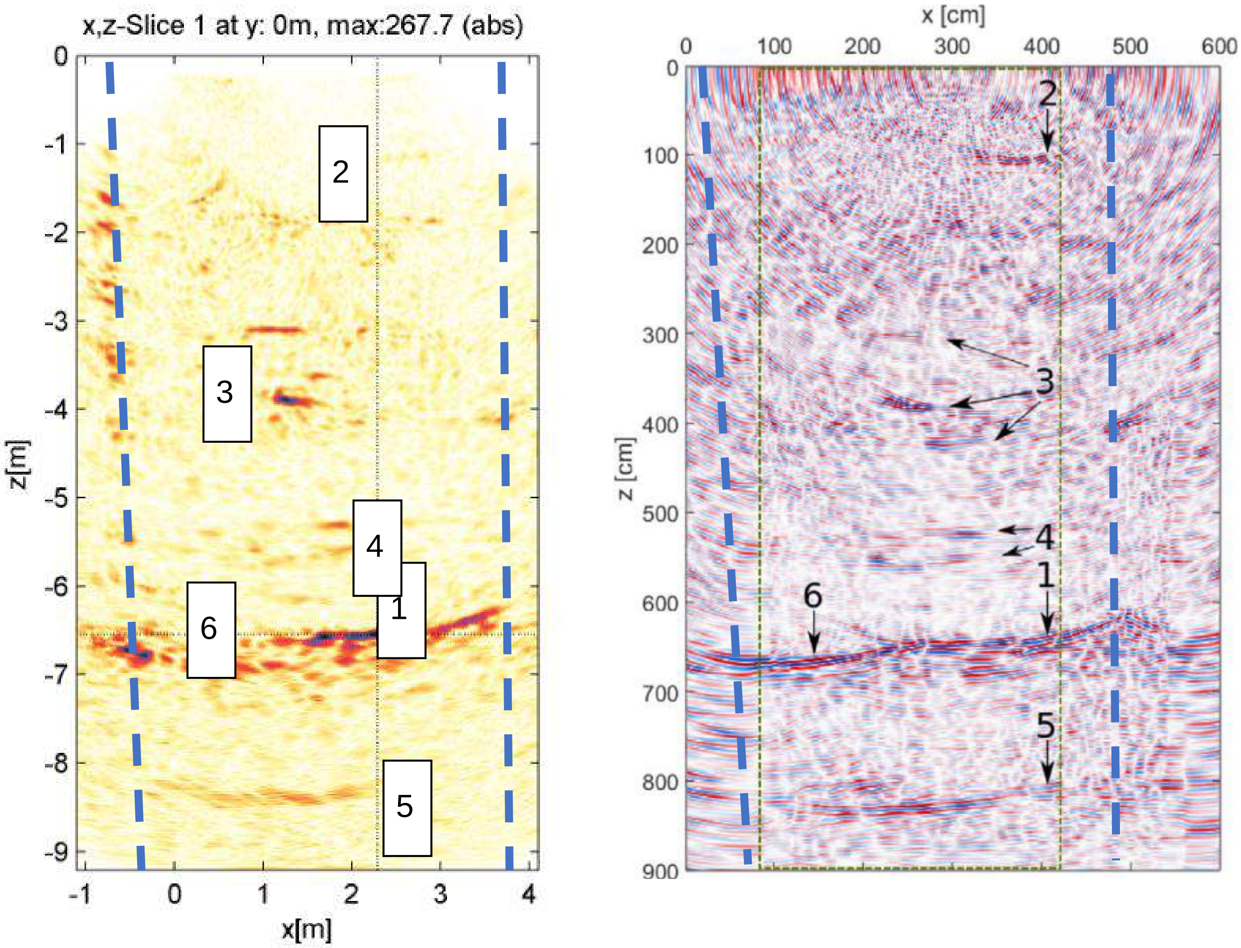

Figure 4: Result of SAFT (left) and RTM (right, from [10]) imaging (full waveform data) for vertical line on the barrier. Horizontal axis x has 1 m offset (-1 m on the left graph corresponds to 0 m on the right graph).

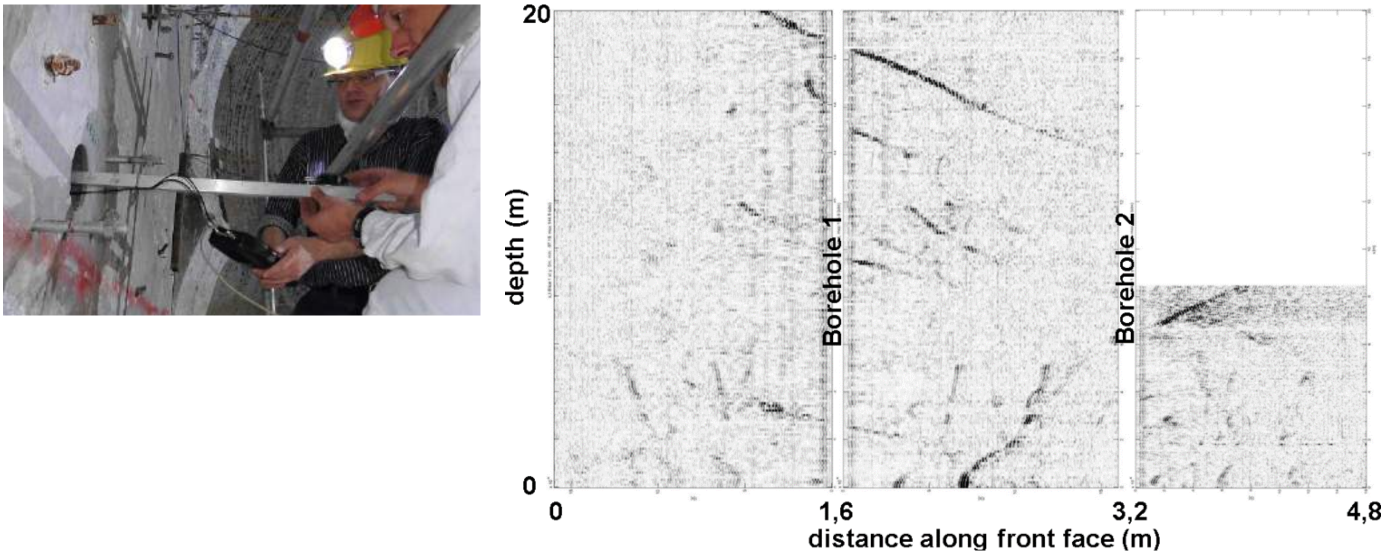

Figure 5: Left: Application of the borehole probe at a salt concrete plug. Right: Combined result of borehole measurements in two horizontal boreholes. Several reflectors are due to validated cracks.

5. Conclusion and Outlook

The ultrasonic measurements at the ERAM site have shown that cracks and other features can be imaged in high resolution using the LAUS and a borehole probe in more detail and at greater depth as ever before. However, there are still limitations in imaging accuracy and artefacts, reaching even greater depths or properly combining the results of different methods. Employing new imaging methods as an improved RTM technology might be a part of the solution.

Meanwhile more investigations have been performed also at barriers at another underground disposal site. It showed that ultrasonic technologies could be applied to check shotcrete structures as well.

While both BGE and BAM intend to continue and extend their fruitful cooperation focusing on the practical and large-scale application aspects, the basic gaps in the non-destructive (and other) methodologies must be filled otherwise. BAM is currently setting up the internally funded, interdisciplinary, cross departmental project “SealWasteSafe”[11]. This project will include work on a new material for engineered barriers in rock salt avoiding shrinkage, short and long-term monitoring methods as RFID and fiber-optic sensors as well as improved ultrasonic instrumentation and imaging.

Acknowledgements

The work presented in this study is based on contract work performed by BAM for BGE. The assistance of several colleagues from BGE and BAM as well as at the ERAM site is greatly appreciated.

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The Long Term Rock Buffer Monitoring (LTRBM) in situ test, assessing under realistic conditions the performances of monitoring devices developed in Modern2020

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1. Summary

The demonstration of monitoring technologies in repository like conditions is essential to asses the quality of engineering design and determine safety strategies. This study offers a summary of the design and field operations that have led to the construction of a dedicated in situ test called the Long Term Rock Buffer Monitoring (LTRBM) experiment aimed at testing new monitoring technologies developed in and outside the Moder2020 project. A preliminary evaluation of the new and innovative technologies, including new sensors and wireless transmitting devices is also detailed. The proposed design setup consists of a large diameter horizontal borehole backfilled with a 4 meter long bentonite buffer artificially saturated through 5 independent hydration mats and confined by a 2 meter long cement plug. The new sensors and wireless devices were placed in and around the engineered barrier system to monitor chemical, pressure and saturation variations during the hydration of the buffer. The first performance assessment of these sensors was carried out 6 months after the installation of the test and reveals that a large majority of the sensors are working and present similar trends to the standard commercial ones located nearby. Though, some of the new prototypes have failed to measure or transmit data, the LTRBM experiment offers a reliable, cost effective and reproducible setup to assess the performance of a wide range of monitoring technologies.

2. Introduction

The demonstration of technologies in the Modern2020 project is considered as an essential step to validate the work performed in WP2 (implementation of the monitoring strategy into a practical plan) and WP3 (development and field assessment of innovative sensing systems) as well as to establish confidence amongst both technical and non-technical stakeholders. This prerequisite has led different partners of the Modern2020 project to build a joint generic in situ test called the Long Term Rock Buffer Monitoring (LTRBM) test which sole aim is to assess the performance of new monitoring devices developed in WP3 (mainly wireless devices and new sensors) in conditions as close as possible to those expected in a real repository. The tested prototypes were designed to be placed in or around a multiple barrier system (shale, bentonite buffer and cement plug) to monitor key safety and performance assessment parameters (saturation, humidity, temperature, pressure, deformation and chemical composition). When possible the new sensors were installed next to standard commercial ones to validate their performance.

2.1. Experiment layout

The LTRBM design was based on a series of performance assessment sealing experiments called SEALEX (Barnichon et al., 2012), implemented at IRSN'S Tournemire Underground Research Laboratory (URL), and uses the existing infrastructure of these experiments in order to minimise the development costs. The general setup consists of a main horizontal borehole (MB) measuring 60 cm in diameter and 10 m in length. The MB was drilled from the Niche_08 (Figure 1) with an excavation direction towards 197°, the axis of the main LTRBM borehole is oriented obliquely (55°) to the strike of the bedding. The MB was backfilled with a 4 meter long bentonite-sand buffer (highly compacted bentonite-sand blocks and a granular bentonite-sand mixture) and confined by means of a 2 meter long bentonite-cement plug (Figure 2). The buffer was equipped with 5 independent artificial saturation systems, composed by hydration mats inside the MB and connected to a water injection system, to accelerate the saturation of the buffer (Figure 2).

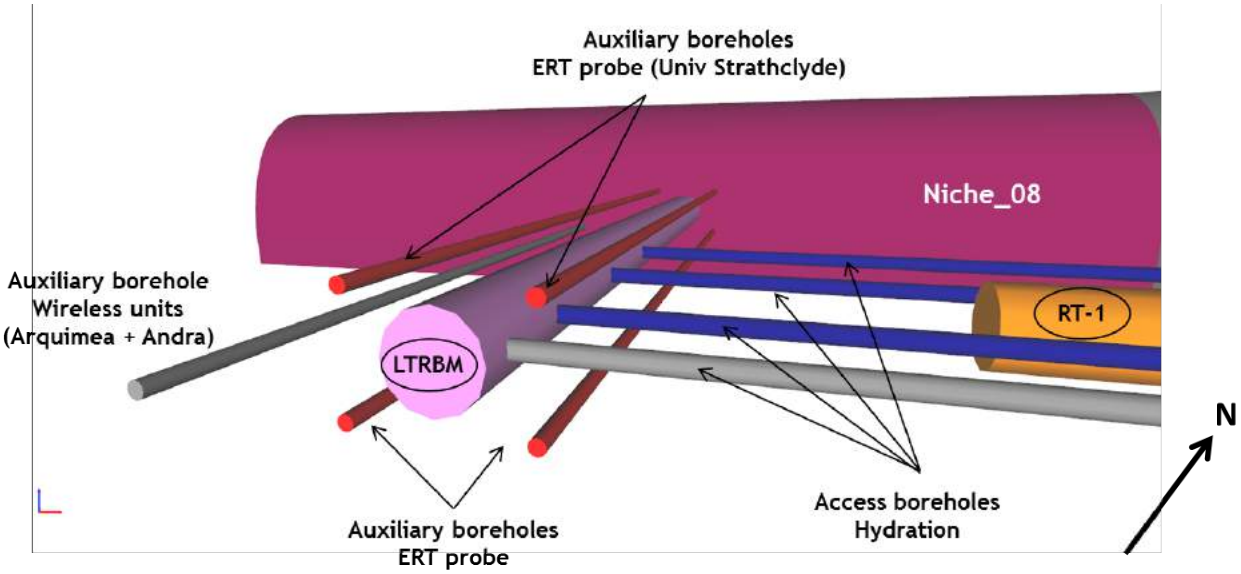

Figure 1: LTRBM borehole layout

In addition, 9 auxiliary boreholes were drilled perpendicularly and parallel to the MB:

- 4 were drilled perpendicularly to the MB and used to pass the hydration lines and wired cables from the buffer to the data acquisition system, thus avoiding cables to run through the buffer and create preferential pathways. The boreholes were PVC cased and cemented with a high performance resin to avoid any water flow inside the boreholes;
- 4 were drilled around (50 cm) and parallel to the MB, and were used to house 4 geophysical streamers for electrical resistivity tomography (ERT);
- 1 was drilled parallel to the MB at a distance of 1.5 m to house wireless receivers.

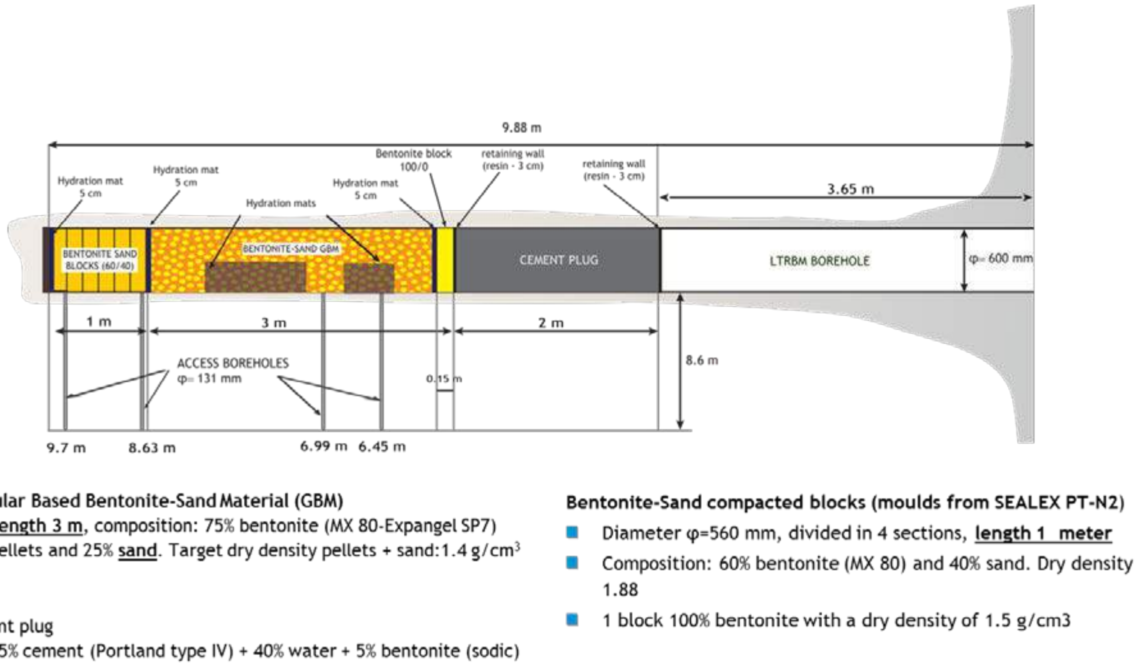

Figure 2: Conceptual view of the engineered barrier layout distribution inside LTRBM main borehole (sensors are not shown)

2.2. Geological overview

The LTRBM boreholes were drilled in the Upper Toarcian shale formation of the Mesozoic sedimentary Causse basin (SW France). The shale features typical anisotropic textures induced by compaction and presents an average dip of the bedding of 10° with a dip-direction in the N330° direction. The mineral composition of the host rock around the test is relatively homogenous a part from 5-10 cm thick layer formed by an ammonite-rich layer and a diagenetic carbonate rich nodule layer. The mineral composition of the rock contains 50% of clay minerals (illite and illite/smectite), mixed layers rich in illite (with 50 to 90% of illite (Tremosa 2010), 10% kaolinite, 5% chlorite and non-negligible amounts of quartz and carbonates (~15% each) mainly calcite but also dolomite and siderite as well as 5% of accessory minerals (pyrite, K-feldspar and organic matter). The host rock exhibits very low permeability to saturated water flow (~10^{-22} – 10^{-21} m^2), significant porosity values ~11% (Dick et al. 2015) and post-excavation self-sealing characteristics (Thatcher et al., 2016).
The stress field in the vicinity of the test was defined with a series of leak off tests performed in a vertical borehole at 125 m from the current experiment. The stress regime is characterized with a σ_1=4 ±2 MPa, horizontal and oriented N162° ±15°, σ_2=3.8 ±0.4 MPa 7-8° inclined from the vertical in the N72° direction and σ_3=2.1 ±1 MPa 7-8° inclined from the horizontal in the N72° direction. The pore water pressure in the vicinity of the newly excavated gallery varies between 840 and 860 kpa, the fluctuations coincide with seasonal variations (higher pressure in the summer and lower at winter).

2.3. Excavation damage zone

Several excavation damage zone (EDZ) features can clearly been seen all around and along the MB. These features are associated with the construction of the borehole and more particularly to the natural ventilation of the galleries causing the development of desaturation fractures. These structures are oriented parallel to the bedding and have a radial extension of ~7 cm. A water injection experiment (located next to LTRBM) combined with numerical modelling has shown that these cracks when artificially saturated tend to seal after a few years thus enabling the permeability of the EDZ zone to decrease and eventually reach the low permeability values of the undeformed host rock (Thatcher et al., 2016).

3. Test construction

3.1. LTRBM drilling operations

The LTRBM boreholes were drilled between December 2017 and June 2018. The boreholes were drilled with a Hilti DD-780 and 600, 100 and 130 mm diamond core bits. The drilling sequence is as follows:

- Drilling of auxiliary boreholes (ERT) December 4th to December 15th 2017
- Drilling of main borehole (MB) from March 27th to April 27th 2018
- Drilling of access boreholes from May 14th to June 6th 2018

The drilling procedures for the MB consisted in (i) the drilling of a horizontal, 10m long and 101 mm diameter pilot borehole, (ii) the overcoring of the pilot borehole with a 600 mm core bit, (iii) after 40-45 cm of overcoring, a hydraulic splinter was inserted in the pilot borehole and inflated to break the rock, (iv) the rock could then be removed from the borehole. These successive operations enabled the drilling of a 10 m long 600 mm diameter borehole in 2 weeks. Once the drilling operations finished, the borehole was sealed from the gallery to prevent the development of hydric fracturing along the borehole.

3.2. Bentonite buffer production

Bentonite is widely considered as a potential buffer material in most concepts for geological disposal of radioactive waste (Finland, France, Sweden and Switzerland). For industrial purposes two main bentonites exist: (i) the sodium bentonite which has the property to expand by absorbing as much as several times its dry mass in weight and (ii) the calcium bentonite which has the property to absorb ions in solution and has been widely used in industry as a cleaning agent. In this study, the widely used 'LAVIOSA BENTOSUND A100' natural sodium-rich bentonite was chosen as raw material for the LTBRM experiment.

3.2.1. Bentonite blocks

28 bentonite blocks were produced by Laviosa MPC using moulds from the PT-N2 SEALEX test (Barnichon et al., 2012). These moulds were ¼ disks designed with a groove and tongue (Figure 3A) to facilitate the emplacement and stability of the blocks inside the horizontal borehole. The discs dimensions are: 560 mm in diameter and 150 mm in width. The blocks were compacted at Saint Etienne using a LAEIS HPF 1600 presse and were produced on June 6th, 2018. In order to ensure a fast hydration and a swelling pressure of at least 1 MPa, 24 highly compacted blocks were made from a bentonite/sand mixture in a ratio of 60/40 (in dry mass). In addition to these blocks, 4 blocks were made from pure bentonite (ratio of 100/0).
The chosen production parameters were a water content (wc) of 11% and a compaction pressure of 28 MPa for the 60/40 mixture, and a wc of 15.7% and a compaction pressure of 13.3 MPa for the 100/0 mixture. The selected compaction pressure and wc for the 60/40 mixture resulted in an average dry density (dd) of 1.875 g/cm^3, whereas for the 100/0 mixture the average dd was 1.517 g/cm^3.
After production, the blocks were stocked and wrapped tightly with plastic foil to prevent water absorption from the environment, which could have caused damaged. The blocks were then stored on June 25th 2018 in the Tournemire URL.

3.2.2. Granulated bentonite mixture

The granular bentonite mixture (GBM) was made from granular bentonite (75%) and sand (25%). The granular bentonite produced by Laviosa MPC under the commercial name Expangel SP7 consists of pellets of pure bentonite (each pellet has a 7 mm diameter). The pellets (Figure 3B) were industrially produced by instantaneously compacting a powder of the BENTOSUND A100 bentonite in a mould of 7 mm of diameter and 7 mm of height. The fabrication was done with a wc = 5% - 7% and at dd =1.998 g/m^3 - 2.12 Mg/m^3. The pellets were received in packages of 25 kg and wrapped with plastic foil to prevent any hydric absorption.

Figure 3: Photos of the bentonite buffer used in LTRBM. A: Highly compacted ¼ disks of bentonite and sand. B: Pure bentonite pellets.

3.3. Backfilling concept

The backfilling machine used to fill the MB with the GBM was designed to emplace the GBM as tightly and homogenously as possible inside the MB. The location of the section to be filled (between 5.6 and 8.6 m from the borehole mouth), the width of the gallery (3.7 m) and the diameter of the main borehole (0.6 m) implied the construction of a double auger machine. The first part of the auger was installed in the gallery (Figure 4A), the pellets and sand were put inside the auger and conveyed through a tube with a rigid coil (Figure 4B) in to a second auger located inside the MB (Figure 4C). The second auger transported the GBM through and identical system and deposited the GBM inside the borehole.

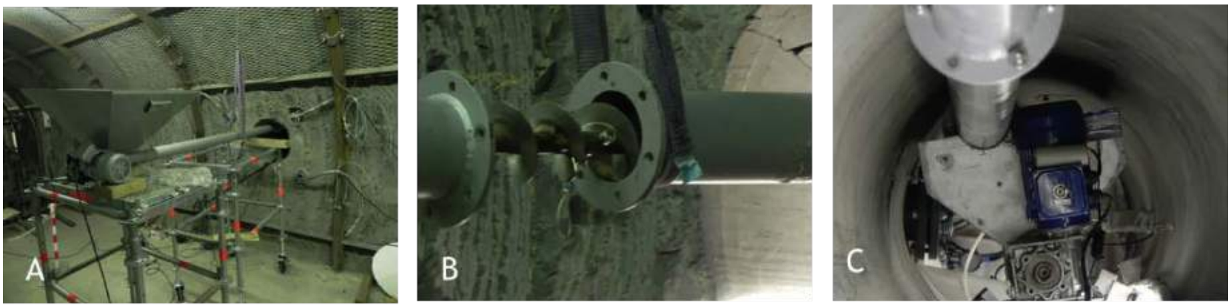

Figure 4:. Photos of the double auger machine at the Tournemire URL. A- 1st auger situated outside the borehole. B- Auger screw conveyor. C- 2nd auger located inside the borehole

3.4. Hydration system

Two types of hydration systems were designed inside the test. The first consists of three 5-cm thick hydration mats, two located on either side of the precompacted bentonite blocks and one between the GBM and the pure bentonite precompacted block (Figure 2). This hydration system contains a circular rigid plastic reinforcement mesh that is covered by a geotextile mat. The rigid mesh allows each mat to contain around 10 l of water, thus enabling a substantial amount of water to be available within the buffer and therefore facilitating a quicker hydration of the buffer. The second hydration system consists of two independent hydration mats each one 1-m long, lining ½ of the bottom borehole within the GBM section (Figure 2). Each hydration mat is connected to a hydration panel located on the gallery wall next to the main borehole mouth. Each mat can be actioned separately from the others.

Figure 5: Photo of hydration mats used to hydrate the precompacted blocks. A- Hydration Mat 1 with 4 tube inlets (2 on top, 2 at the bottom). B- Rigid plastic mesh placed inside the geotextile mat.

3.5. Cement plug

The bentonite buffer section was confined on its downstream side with a 2 m long cement frictional plug. The cement plug (55% cement, 40% water and 5% bentonite) was poured through a retaining wall installed at 3.65 meters from the borehole mouth. In order to avoid the pouring of cement inside the buffer another retaining wall was placed between the GBM and the cement plug. The bottom plate (nearest to the borehole mouth) was cut in half to allow a two-step installation of the cement plug. The first step enabled the filling of the lower half of the retaining plug, once completed an optical fibre was placed on the top of the fresh cement. The second part of the retaining wall was then installed and cement was poured into the borehole. This operation was done to permit the fibre optical cable to be situated in the middle of the cement plug without being attached to any other device.

4. Instrumentation

The instrumentation installed in the bentonite buffer can be divided in to four main categories (Table 1):

- New measuring instruments to be tested and developed in WP3 of Modern2020;
- New measuring instruments to be tested, developed outside Modern2020 but never been used inside a bentonite buffer;
- Standard measuring instruments to verify the performance of new sensors;
- Instrumentation required to control and follow the test evolution.

4.1. Data transmission

In addition to the wired sensors that were directly cabled to a single data acquisition unit, three wireless data acquisition systems were used to transfer data measured inside LTRBM tests to receivers placed outside the buffer. Two different types of wireless units were installed inside the bentonite buffer and were designed to extract data recorded from within the buffer to wireless receivers located in the adjacent gallery. One (provided by ARQUIMEA) was based on a high frequency transmission (2.2 MHz), while the other (provided by Andra/ Sakata Denki) used a low frequency transmission (below 10 kHz). A third wireless transmission system, developed by NRG, was installed (temporarily) in the main Tunnel (transmitter) of the Tournemire URL and on top of the plateau (receiver). The objective of this third wireless transmission device was to demonstrate in a combined effort a full data transmission solution that allows transmitting wirelessly sensor readings out of the LTRBM borehole to the earth's surface (e.g. across 275 m of clay and limestone rock).

Table 1: Specifications of the different sensors installed in LTRBM.

	Sensors	Buffer	Measurement	Manufacturer/ Provider	Data transmission
New measuring instruments from WP3 to be tested:	**Chemical sensors** based on potential difference between an ion-selective electrode and a reference electrode	Precompacted blocks (60/40)	**pH, Eh & Cl^-**	**VTT**	**Wired**
	Thermocouple Psychrometers	Precompacted blocks (60/40) and GBM	**Relative Humidity (RH)** - 95% RH to 99.9% RH	**ARQUIMEA**	**Wireless**
	A **THMC smart sensor**	Precompacted blocks (100/0))	**Total pressure, temperature, pore pressure and humidity**	**CTU**	**Wired**
Other new measuring instruments to be tested:	**Pore water sensors** (vibrating wire based) attached to a wireless transmitter	Precompacted blocks (60/40) and GBM	**Pressure in kpa**	**Andra**	**Wireless**
	Total pressure (fibre-optics based)	Precompacted blocks (60/40)	**Pressure in MPa** (up to 7 MPa)	**Andra**	**Wired**
	ERT probes	Host rock	**Volts**	**IRSN**	**Wired**
Standard measuring instruments to cross check the performance of the new ones:	**Fibre optic cable**	Cement plug	**Strain** (up to 1% strain) and **temperature** (-30°C – 70°C)	**IRSN**	**Wired**
	Miniature piezoresistive pore pressure sensors	Precompacted blocks (60/40) and GBM	**Pressure** (0 to 0.5 MPa)	**AMBERG**	**Wireless**

	Sensors	Buffer	Measurement	Manufacturer/ Provider	Data transmission
	Piezoresistive total pressure cells	Precompacted blocks (60/40)	**Pressure** (0 to 4 MPa)	**AMBERG**	**Wired**
	Capacitive type hygrometers	Precompacted blocks (60/40) and GBM	**Relative Humidity** (0 – 100%)	**AMBERG**	**Wireless**
	Automatic tensiometers	Precompacted blocks (60/40) and GBM	**Pressure** (0 to – 1000 kPa)	**AMBERG**	**Wired**
	FDR type water content sensors	Precompacted blocks (60/40) and GBM	**Volumetric water content VWC)** – > 0.05 VWC	**AMBERG**	**Wired**
	Wescor psychrometers	Precompacted blocks (60/40) and GBM	**Relative Humidity (RH)** - 95% RH to 99.9% RH	**ARQUIMEA**	**Wireless**
	TDR	GBM	**Moisture content**	**University of Strathclyde**	**Wired**
Instrumentation required to control and follow the test evolution:	**Displacement sensors**	Cement plug	**Displacement** (mm)	**AMBERG**	**Wired**
	Hydraulic pressure sensors	Precompacted blocks (60/40) and GBM	**Pressure** (0 to 5 bars)	**AMBERG**	**Wired**
	Weight sensor	Tunnel	Water volume in tank (0-50 kg)	**AMBERG**	**Wired**
	PT100	Precompacted blocks (60/40) and GBM	Temperature (0 – 100°C)	**AMBERG**	**Wired**

5. Instrumentation and installation of the precompacted blocks

5.1. Instrumentation of the bentonite blocks

The instrumentation of the blocks took place between June 25th and July 6th 2018. The 28 different blocks were marked, weighed, mechanized to house corresponding sensors and weighed again. The sensors were installed and the blocks were assembled together and placed on to an insertion cradle. The blocks were kept assembled with some tape to avoid them from moving during the installation. The instrumentation and assemblage of the bentonite blocks (Figure 6) did not present any major problems. However, the construction of the bentonite package was very laborious and time consuming in order to obtain the best fit possible for the sensors and cable recess.

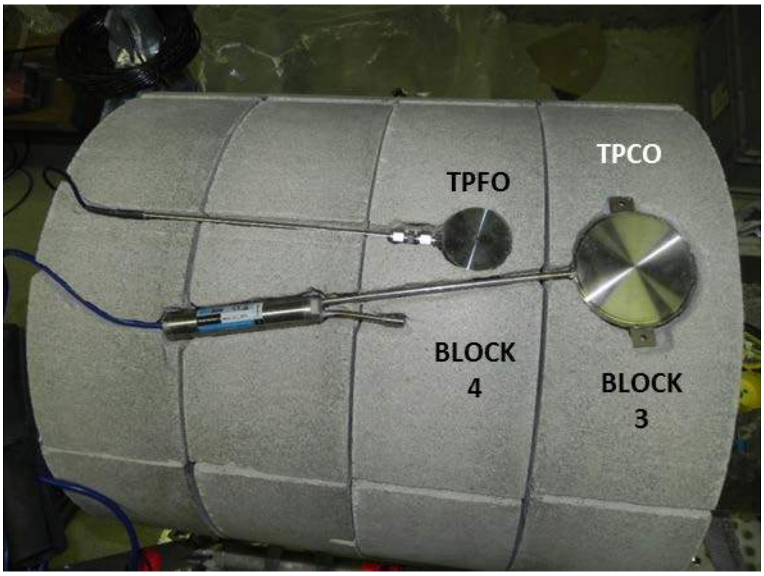

Figure 6: Photo of the total pressure sensor is based on fibre optic technology (TPFO) and the crosschecking total pressure commercial sensor (TPCO) manufactured by Opsens. The TPFO sensors were provided by Andra and were never tested in a bentonite buffer under realistic in situ conditions.

5.2. Instrumentation inside the GBM

The number of sensors installed in the section containing the GBM is proportionally much less than in the precompacted blocks. The reason for this is to enable a long enough section of buffer with very little metallic parts for geophysical surveys. Thus, only 7 Time-Domain Reflectometers (TDR) were attached on the wall of borehole, two wireless transmitters with their sensors were also installed one next to the precompacted blocks the other near the cement plug.

5.3. Geophysical instrumentation

A geophysical method based on Electrical Resistivity tomography (ERT) was also carried out around on LTRBM to image the saturation changes in the bentonite buffer from electrical resistivity measurements. The monitoring components consist of 4 electrode probes each one containing 32 electrodes (spaced every 27 cm). The probes were placed in the four auxiliary boreholes (Figure 1) at a distance of 50 cm from the edge of the MB.

6. Installation and hydration operations

The installation operations covered four full weeks. The first part of the installation took place from June 25 to July 13, 2018 and consisted in (i) the construction of the bentonite blocks (+sensors), (ii) preparing the MB and access boreholes, (ii) Installation of hydration panels and (iv) the installation of data acquisition system (DAS). The second step lasted one week from July 16 to July 20, 2019 and involved (v) the insertion of the granular based material (GBM) and (vi) the sealing the LTRBM borehole with a cement plug.

The hydration of the bentonite buffer started on September 21st, 2018. The synthetic water used for hydration has the same chemical composition as the pore water of the Callovo-Oxfordian claystone from Andra's URL in Meuse Haute la Marne (France) (Wang et al., 2013). The objective of this first phase was to fill all the macro voids within the buffer in order to accelerate the saturation of the bentonite. The hydration procedure consisted in allowing the water from the tank (located one meter above the test, i.e. 1m water head) flow freely in to the buffer. Each mat was tested independently in order to observe that each hydration system worked properly. The first hydration step consisted in injecting water in to Mat 1 located at the upstream side of the buffer (Figure 2). After the injection of 33 kg of water inside the buffer an important leak was observed inside the bottom access borehole. The hydration had to be stopped through this mat. Another hydration was carried out on the downstream side of the buffer by injecting water through Mat 5 located between the GBM and pure bentonite block (located behind the cement plug). Once again, after the injection of only a few liters of water, a leak was observed coming from behind the cement plug. A decision was taken to stop the hydration and wait for a month for the bentonite to swell and eventually seal the leaks. Hydration resumed one month later on October 18, 2019, following the same procedure than before. The hydration through Mat 1 had to be stopped immediately as water started to flow through the bottom access borehole. The hydration through Mat 5 enabled 6 kg of water to flow in the buffer before another leak was observed coming from the cement plug. The hydration was then stopped. A third hydration test was carried out on November 7, 2019, by injecting water through Mat 2, located between the two bentonite buffers. Once again, an important leak was observed from the bottom access borehole.

On January 29, 2019, a fourth attempt to hydrate the buffer was done. This time it was decided not to use the hydration mats between the bentonite buffers but to hydrate the buffer from one of the mats located in the GBM. This option was successful as no leaks were observed after the injection of nearly 85 l of water between January and March 2019.

7. Preliminary results from new sensors

All the new sensors were thoroughly checked before there installation, either onsite or before their shipping to the Tournemire URL, to ensure that they were fully functional. Once installed in the buffer and connected to the data acquisition system, all the wired sensors, except the THMC-smart sensor (Table 1), sent signals that could be converted in to data. Despite the efforts put in to capture a signal from the THMC Smart-sensor, no data was ever recorded from this sensor.
The two different wireless units imbedded in the buffer have experienced mixed fortunes. Whilst the wireless units provided by Andra/ Sakata Denki always managed to record and send data to the receiver in the adjacent gallery, the units provided by ARQUIMEA were never able to send any readable signal to their receiver. Thus, not only was it impossible to assess the performance of these units it was also impossible to assess the performance of all the sensors connected to these units (particularly the new Thermocouple Psychrometers).

The other new wired sensors (chemical electrodes and total pressure sensors) are all working and are recording realistic values 4 months after their installation in the buffer (Figure 7). However, since the end of December the pH and Cl electrodes are no longer recording any data variation. For the moment it is not clear if the problem comes from the sensor itself or the data acquisition system. Data obtained from the new total pressure sensors were analysed between July 2018 and January 2019 (Figure 8). The new total pressure sensors present striking differences. Two have identical trends to those measured by the standard commercial ones. However, the values recorded by these sensors are much lower than the predicted values and are surprisingly similar to those measured by the pore pressure data. The low pressures measured by the new and standard sensors may indicate that the sensors are no longer attached to the buffer and that they are not measuring the swelling of the buffer. On the other hand, one of the new total pressure sensors (S101) seems to still be attached to the buffer as the measured pressures continue to increase significantly since the first hydration phase (Figure 8). The reaming new pressure sensor has measured a decrease in total pressure since the beginning of the first phase of hydration phase. This anomaly could either be due to stress relaxation within the buffer or a problem with the sensor.

The pore pressure sensor data recorded from the two wireless units installed in the precompacted blocks and GBM material were analysed during a period spanning from July to November 2018 (Figure 9). The results show that the data from both sensors had identical trends as the standard pore pressure sensor installed in the GBM.

A summary of the performance of these sensors is given in Table 2.

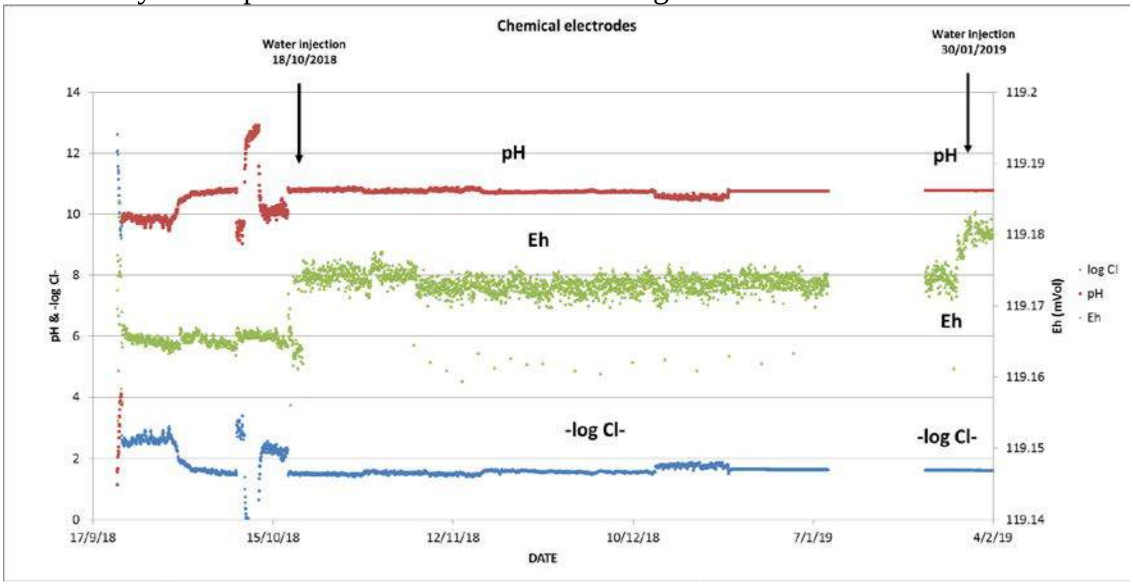

Figure 7: Time series plot showing the evolution of chemical parameters, pH, conductivity (Eh) and chloride concentration (-log Cl-) during the injection of the synthetic water inside the buffer.

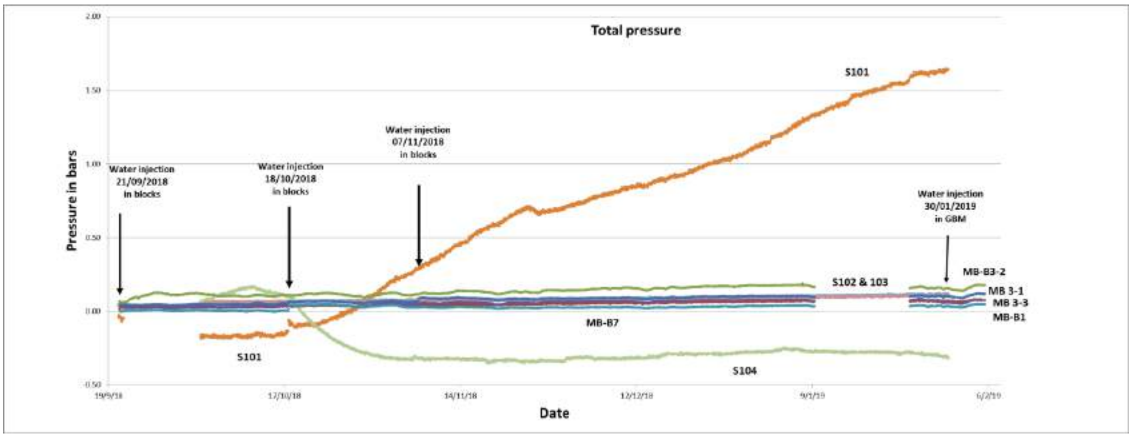

Figure 8: Time series plot showing the evolution of the standard wired sensors (MB-B1, MB 3-1, MB-B3-2, MB-B7) and wireless transmitted total pressure sensors (S101, S102, S103, S104).

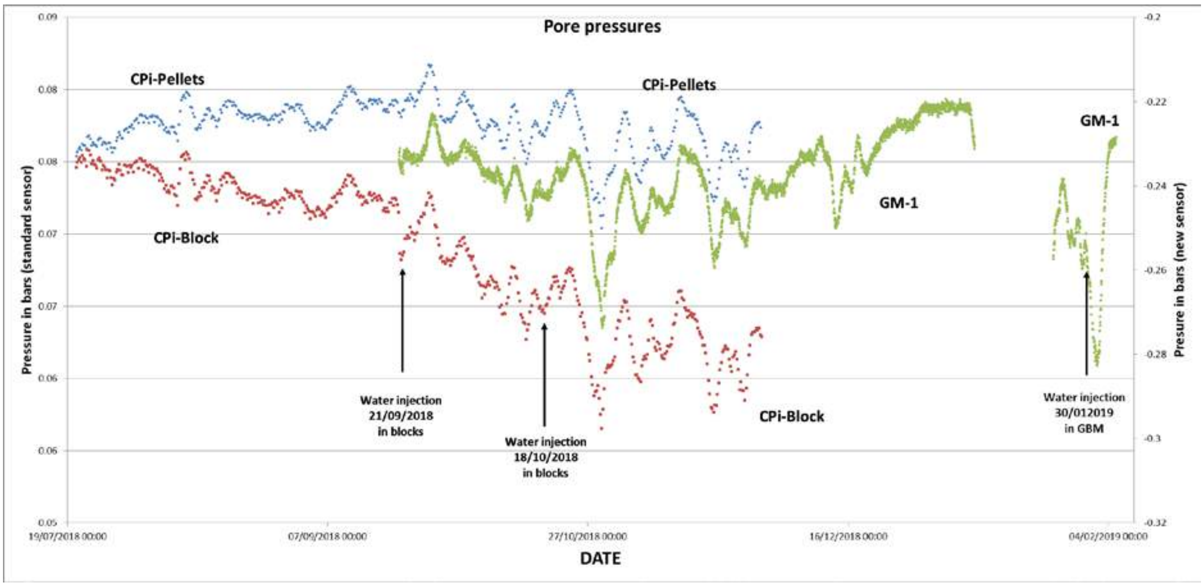

Figure 9: Time series plot showing the evolution a wired standard pore pressure sensor (GM-1) and wireless transmitted pore pressure sensors (CPi-Block, CPi-Pellets).

Table 2: Preliminary report on the performance of new sensors installed in LTRBM. Data quality is defined as follow: 1 – measured data comparable to those obtained from the standard sensors; 2- measured data comparable to those found in laboratory experiments; 3- measured data significantly different from those obtained from the standard sensors; TBD: 4- data quality needs to be determined. The monitoring period correspond to the sensors performance assessment period.

	Sensors	Buffer	Monitoring period	Data quality	Data transmission
New measuring instruments from WP3 to be tested:	**pH**	Precompacted blocks (60/40)	**July 2018 – February 2019**	**2**	**Wired**
	Eh	Precompacted blocks (60/40)	**July 2018 – February 2019**	**TBD**	**Wired**
	Cl-	Precompacted blocks (60/40)	**July 2018 – February 2019**	**TBD**	**Wired**
	Thermocouple Psychrometers	Precompacted blocks (60/40) and GBM	**NW**	**---**	**Wireless**
	THMC smart sensor	Precompacted blocks (100/0))	**NW**	**---**	**Wired**
Other new measuring instruments to be tested:	**Pore water sensors** (vibrating wire based)	Precompacted blocks (60/40)	**July to November 2018**	**1**	**Wireless**
	Pore water sensors (vibrating wire based)	GBM	**July to November 2018**	**1**	**Wireless**
	Total pressure S101 (fibre-optics based)	Precompacted block 1 (60/40)	**July 2018 – January 2019**	**3**	**Wired**
	Total pressure S102 (fibre-optics based)	Precompacted block 3 (60/40)	**July 2018 – January 2019**	**1**	**Wired**
	Total pressure S103 (fibre-optics based)	Precompacted block 3 (60/40)	**July 2018 – January 2019**	**1**	**Wired**
	Total pressure S104 (fibre-optics based)	Precompacted block 3 (60/40)	**July 2018 – January 2019**	**3**	**Wired**

8. Conclusions

The experience gained from the SEALEX in situ tests has enabled project partners to design and safely implement a generic horizontal engineered barrier system destined to test the long term performance of new monitoring sensors and data transmitting units in conditions close to those expected in a real underground repository.
The test was designed to take in to account the needs of each sensor and offer a fast hydration and realistic swelling pressures within the bentonite buffer. The hydration lines were passed through 4 cased access boreholes drilled perpendicular to the main borehole and sealed with a high performance resin to prevent any water flow out of the test. This setup was efficient for three out of four boreholes, however one borehole presented continuous leaks which hampered hydration in the upstream side of the buffer. The leak will shortly be repaired by injecting cement and resin inside the casing and allow hydration from the bottom mats by mid-2019. A second leak observed from the main borehole could have been prevented if a double retaining wall was used between the cement plug and the GBM. The void between the two walls could have been filled with resin to prevent any water flow from behind the cement plug. A plan consisting in building a new resin-based retaining wall in front of the cement plug is underway this should be implemented by mid-2019.

The implementation of the test was longer than expected as great care was taken during each step of the installation. The new backfilling screw conveyor proved to be successful as the targeted dry density of 1.4 g/cm^3 for the granular bentonite mixture was reached.
The preliminary performance assessment of the new sensors and wireless transfer units shows encouraging results. All but one of the new wired sensors were working after the installation and the first hydration phase. Their results are in general close to the ones measured from the standard commercial ones. Though some results differ from the general predicted trend their validity is not questioned as they may be the consequence to heterogeneous swelling in the bentonite buffer. Two out of four wireless transmitters placed in the bentonite buffer worked continuously during the monitoring period. The lack of received signal from the two nonworking units is believed to be related to the sealing (resin) of the electrical components prior to their emplacement inside the buffer. These results indicate that the performance assessment of the sensors should be carried out during each step of the installation in order to prevent possible dysfunctions due to improper handling.

The LTRBM design can be considered as a very efficient and reproducible way to assess the performance of new monitoring technologies. The continuous assessment of these sensors will continue for at least another three years, the data and infrastructure associated with these tests will be available to the partners of Modern2020 during this period.

Acknowledgements

The authors wish to acknowledge the support of the European Commission via the project MODERN2020 'Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal' (Grant Agreement No. 662177-Modern2020- NFRP-2014-2015) under the H2020 Euratom Research and Training Programme (Funding agency ID: http://doi.org/10.13039/100010687). Special thanks are due to Andra, ARQUIMEA, Czech Technical University, ENRESA, EURIDICE, NAGRA, University of Strathclyde and VTT for their support during each step of this project.

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Non-Intrusive Geo-Electrical ERT Monitoring of High-Level Radioactive Waste Experiments in Tournemire URL

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1. Summary

Geophysical electrical resistivity tomography (ERT) is a promising measurement technique for nonintrusive monitoring of an engineered barrier system (EBS) of geological disposal of high-level radioactive waste. Electrical resistivity is sensitive to water content and temperature, which are the key variables characterizing the response of the EBS. In order to assess the technology readiness level of the ERT technique for EBS operational monitoring, ERT survey campaigns have been carried out in two field demonstrator developed at the underground research laboratory (URL) in Tournemire (France) within the project 'Modern 2020', called ERT experiment and LTRBM. Preliminary ERT surveys were carried out to establish the background resistivity of the experimental areas and assess the quality of electrode installation and survey protocols. Monitoring ERT surveys are underway after the installation of both experiments in July 2018 (LTRBM) and September 2018 (ERT experiment). Results of firsts blank test surveys carried out on both experiments confirmed that the resistivity of the host rock around both experiments area is quite homogenous and lower than 100Ωm. Preliminary results of the monitoring period for both experiments are also promising, different materials within the installation are identifiable and changes in resistivity due to water injection and temperature increase are also expected to be noticeable.

2. Introduction

Current radioactive waste management programmes in most countries are focused on disposal of long-lived waste in geological repositories as the most appropriate approach to ensure long-term safety of people and the environment [1]. The combination of a selected host rock and an Engineered Barrier Systems (EBS) to protect and isolate the waste is considered in almost all programmes. A swelling clay is generally used in the EBS as a buffer that surrounds and protects the individual waste packages and/or to seal off the disposal galleries from the shafts leading to the surface. Understanding of the clay barriers behaviour in time is fundamental for a final repository for high-level radioactive waste to be granted license. Therefore, monitoring the EBS could be required to help assessing its proper performance.

During the maturing phase of buffer materials in deep geological repository, water saturation and temperature are two key parameters that have been mentioned in every international collaborative work on monitoring strategies and parameters selection. The EBS is subjected to an inwards water flow from the host rock and an outwards heat flux from the radioactive waste. Changes in water content and temperature are therefore the key to assessing the performance of the EBS. EBS monitoring using wired sensors installed in the buffer should be avoided because wires could provide a preferential pathway for radionuclide leakage as well as for water [2]. Geophysical electrical monitoring is potentially an ideal technique for geophysical diffuse monitoring of the EBS because: (i) it can be designed in a less-intrusive fashion; (ii) it allows local anomalies to be captured that local sensors cannot spot; and (iii) electrical resistivity is very sensitive to changes in water content and temperature, and is therefore very convenient to monitor the EBS [3–9].

Electrical resistivity tomography (ERT) is a well-established geophysical technique that uses the injection of electrical currents and measurements of the resulting voltage differential at the Earth's surface or in boreholes. This generates pseudo-sections displaying apparent resistivity as a function of the location and electrode spacing, which in turn provides an initial picture of the resistivity distribution. An inversion process of the measured data is necessary for the final interpretation of the resistance data. This process transforms the apparent resistivity into 2D or 3D images of the bulk electrical resistivity of the subsurface model, which is discretized into a distinct number of elements of homogeneous resistivity.

ERT surveys have been routinely used in water exploration and contaminant flow detection [10–15], engineering site investigations [16–20], and in the location of buried artefacts or structures in archaeological surveys [21–24] as well as providing geological and hydrogeological site information [25–27]. ERT in boreholes has proven useful for environmental investigations [28–34]. The method has also been demonstrated to be economically efficient when using wells drilled for geotechnical pre-investigation tunnelling sites to obtain information about the geology between the wells [35]. More recently, investigations using ERT in boreholes have been extended to a variety of other applications such as the characterization and monitoring of water infiltration [5–36–37], and in monitoring CO_2 migration [38–39].

Previous researches conducted in repository-like conditions have demonstrated the potential of ERT in monitoring the EBS. ERT [40] could detect the water intake in an experiment conducted in an area at the Aespoe Hard Rock Laboratory (HRL) in Sweden. ERT electrode arrays were installed in the backfill, buffer and rock, and the water saturation changes in those three structures were monitored for a few years. Similarly, the EB Experiment [41] used ERT electrode arrays installed in the Engineered Barrier Emplacement Experiment in Opalinus Clay at the Mont Terri underground laboratory in Switzerland. Several ERT surveys were conducted over the 11 years of operation of the experiment to monitor water intakes in different areas of the experiment. However, in all these experiments, the ERT electrodes were buried inside the EBS and this arrangement is less suitable for long-term monitoring of the EBS in the repository. To the best of the authors' knowledge, there has been no attempt to date to investigate the use of the ERT technique in a non-intrusive fashion: that is, with the electrodes positioned outside the buffer.

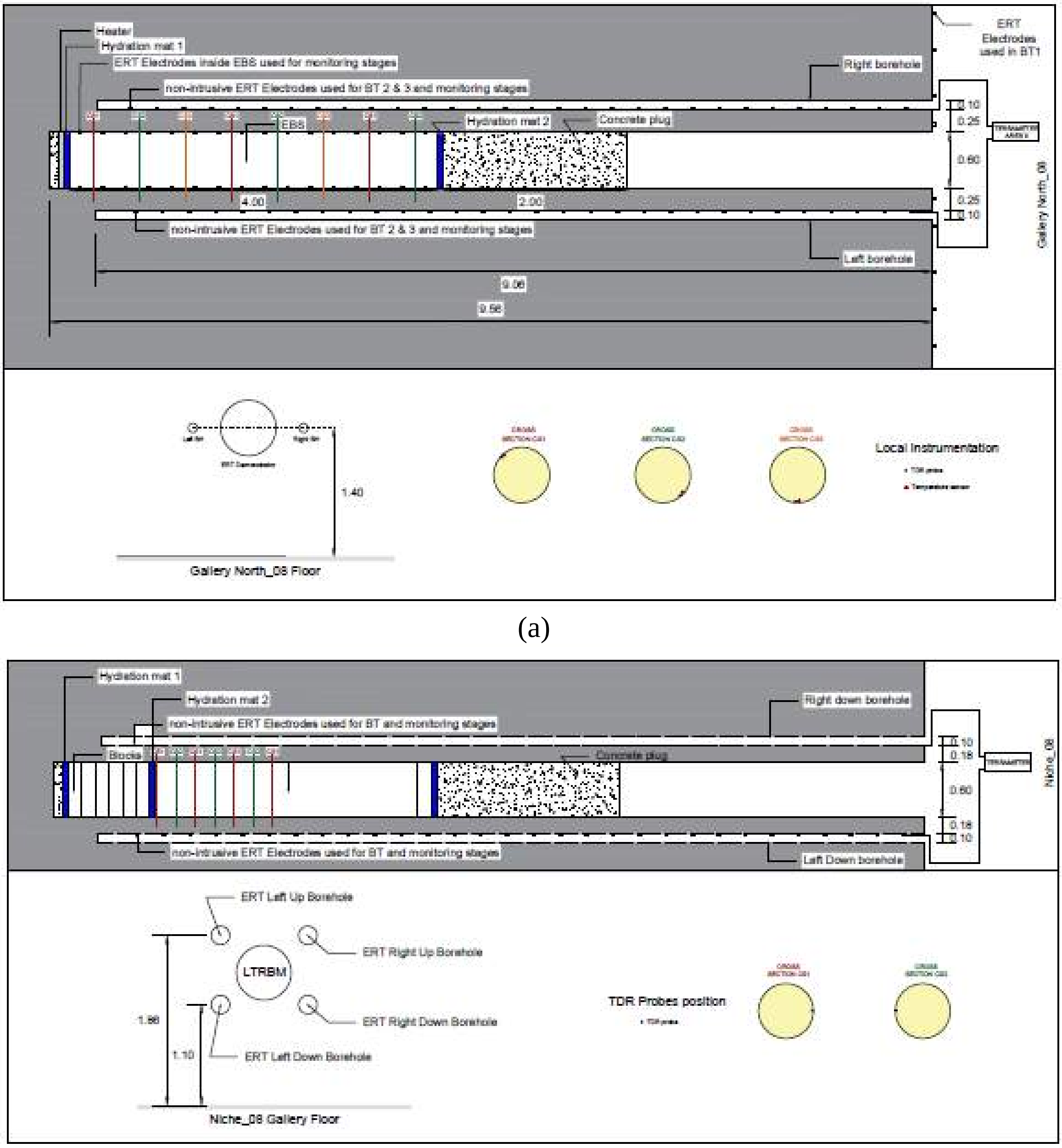
This paper presents preliminary results of the ERT monitoring surveys carried out in two scale tests installed at the underground research laboratory (URL) in Tournemire (France), known as the ERT experiment and the Long Term Rock Buffer Monitoring (LTRBM).

3. Methodology

3.1. Experiments overview

The ERT experiment was purposely designed to assess the capabilities of ERT as a non-intrusive technique of monitoring the EBS under conditions as close as possible to the ones expected in the real repository, while the LTRBM was designed to asses the capabilities of new monitoring devices, mainly wireless devices including long term power supply solutions and new sensors, developed within 'Modern2020' project.

The installation of the ERT experiment took place between June and September 2018, and the installation of the LTRBM took place between June and July 2018, an overview of both experiments are shown in Figure 1. Local sensors were installed into the EBS in both experiments to measure water content (and temperature for the ERT experiment only) as a way of cross-checking the geophysical measurements. For research purposes, electrodes were also buried inside the main shaft in the ERT experiment. Unfortunately, one line of electrodes is malfunctioning since after the installation, a damage most probably caused during the installation activities. After curing of the cement plug, September and October 2018 for the LTRBM and ERT experiment respectively, hydration (and heater tests for the ERT experiment only) started together with scheduled ERT monitoring surveys. A summary of the test's characteristics are presented in Table 1.



(a)

(b)

Figure 19: Overview of (a) ERT experiment and (b) LTRBM

Table 6 : Summary of tests characteristics

Characteristics/ test	ERT Experiment	LTRBM
No. of ERT boreholes	2: One on either side of Main shaft	4: forming an x around the main shaft
No. of Non-intrusive ERT electrodes	64: 32 in each borehole (0.29m spacing)	128: 32 in each borehole (0.27m spacing)
No. of ERT electrodes inside buffer	32: 2 parallel lines of 16 each (0.24m spacing)	None
Blank tests: to measure rock background resistivity	S1 & S2 (Jan 2017) and S3 (Nov 2017)	T1 (Feb 2018)
Size of Main Shaft	Diameter: 0.60m Length: 9.54m	Diameter: 0.60m Length: 9.50m
Installation	June–September 2018	June-July 2018
Length of EBS	4m	4m
Material of EBS	Bentonite pellets and powder [42]	Highly compacted bentonite blocks (HCBB) & 60% Bentonite pellets + 40% Sand (GM)
Local Instrumentation installed inside EBS	8 TDR probes and 8 Temperature sensors	7 TDR probes* within GM
Length of cement plug	2m	2m
Hydration mats	2: one in each end of EBS	5: One in both ends of the EBS, one in the transition between the HCBB and the GM and the last two mats were installed radially around the main shaft in the area of the GM
Heater	Rear of the EBS	None
Hydration started	October 2018	September 2018
Heating started	October 2018	Not possible

* Several other local sensors were installed in the LTRBM, but only TDR probes are worth mentioning for the purposes of this paper.

The non-intrusive ERT electrodes used on both experiments were mounted in PVC tubes at a fixed distance and installed into boreholes drilled in the rock. Usually, water is added within the borehole to ensure contact in these surveys. However, this resource is not an option for the ERT demonstrator and LTRBM experiments since the electrode boreholes in question are horizontal. It is not possible to keep water in horizontal boreholes, thus continuous injection of water would be necessary in this situation, which would perturb the experiment. Consequently, a system described in [43] which injects compressed air in an inflatable balloon at the back of the PVC pipes is used to improve contact between the electrodes and the rock walls. Despite these measures contact resistance is still one of the main concerns which surrounds the surveys on both experiments.

3.2. ERT surveys

Three preliminary ERT surveys were carried out on the ERT experiment area in January and November 2017 before the emplacement of the bentonite, while a preliminary ERT survey was carried out in February 2018 on the LTRBM area before the installation of the buffer. These surveys were aimed at a first assessment of the electrode installation technique, ERT measurement protocols and inversion procedures. Due to restrains of space, we are presenting here two surveys performed on the ERT experiment area and two surveys performed on the LTRBM area, as described in Table 2.

Table 7: ERT surveys performed on ERT experiment and LTRBM area presented in this paper

Survey context	ERT experiment	LTRBM
Blank test	S2	T1
Monitoring stage	S6	T2

Terrameter LS, manufactured by ABEM was used for the data collection of all ERT surveys presented in this report.

Overall, contact resistance, stacking errors and reciprocal measurement errors (for S6 and T2) were the three features used to filter the data collected in the surveys performed. Details on data collection and quality procedure can be seen in [43].

All inversions carried out on the ERT experiment and LTRBM were performed using Res2DInv [44] and Res3DInv [45] respectively. The inversion method used was the L1 norm to account for data sets containing non-random noise.

4. Results

4.1. ERT experiment

Survey S2 occurred in January 2018 and was a combination of data collected from arrays involving in-hole and crosshole quadripole combinations. The data were processed in cross-borehole format, treated in terms of contact resistance and stacking errors and inverted. Figure 2 shows that the resistivity between the two boreholes is somehow homogeneous and less than 100 Ωm. The area of higher resistivity around the electrodes and in the middle of the model (around 5 m depth) is most likely to be due to artefacts created by the noise survey. Figure 3 shows the ERT inversion of survey S6 performed during the monitoring stage in late October 2018. The data for S5 survey were processed, treated in terms of contact resistance, stacking errors and reciprocal errors and inverted.

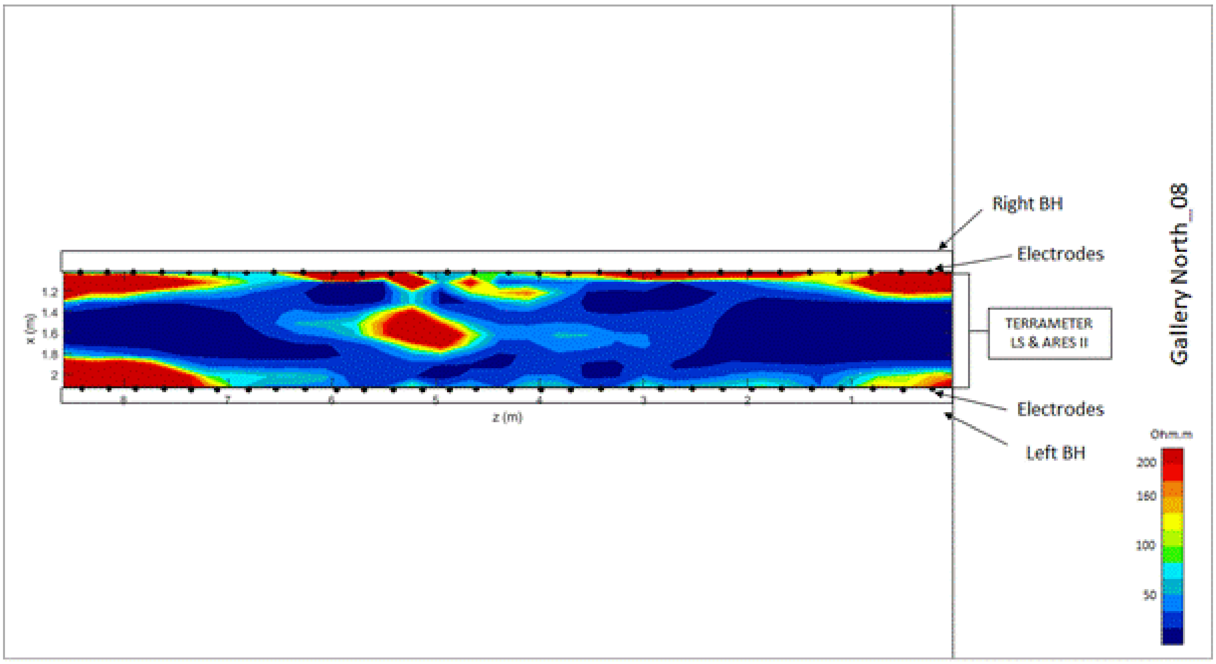


Figure 20: Cross borehole Survey S2 (RMS = 12.7%)

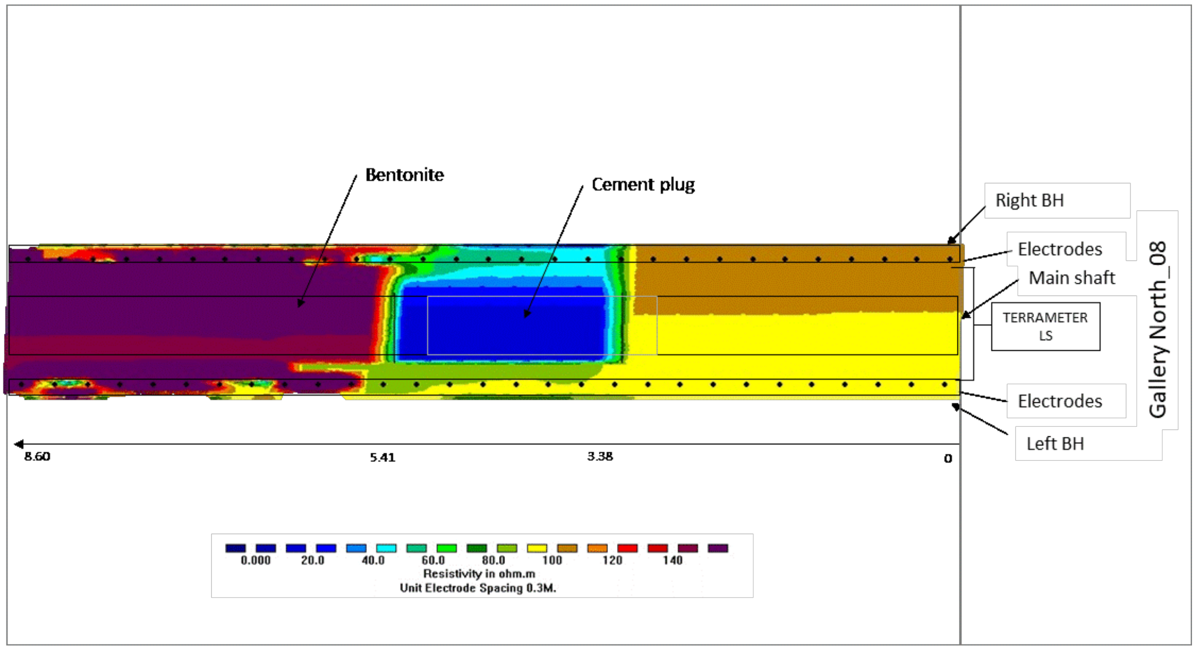


Figure 21: Cross borehole survey S6 (RMS = 1.1%)

It is worth noting that the resistivity shown in survey S6, from depths 0 to 3.4m are not real. The sensitivity in this region was deliberately low in the protocol used in this survey as it envelops the empty shaft of the MB, which is not the area of interest here. Survey S6 distinguishes well the area of the cement plug and the bentonite. Additionally, it seems to be able to detect the narrow rock section between the shaft and electrodes boreholes around the cement plug section but not around the bentonite section. This is a consequence of the high resistivity of the dry bentonite material.

4.2. LTRBM

The data for T1 survey were processed, treated in terms of contact resistance and stacking errors and inverted. The inversion model of survey T1 (Figure 4 and Figure 5) shows that the resistivity between the boreholes area is somehow homogeneous and around 100 Ωm which is consistent with the blank test results obtained in the ERT demonstrator area (S2). In the models below, z is the depth axis of the buffer and xy is the cross section plane from the gallery Niche_08.

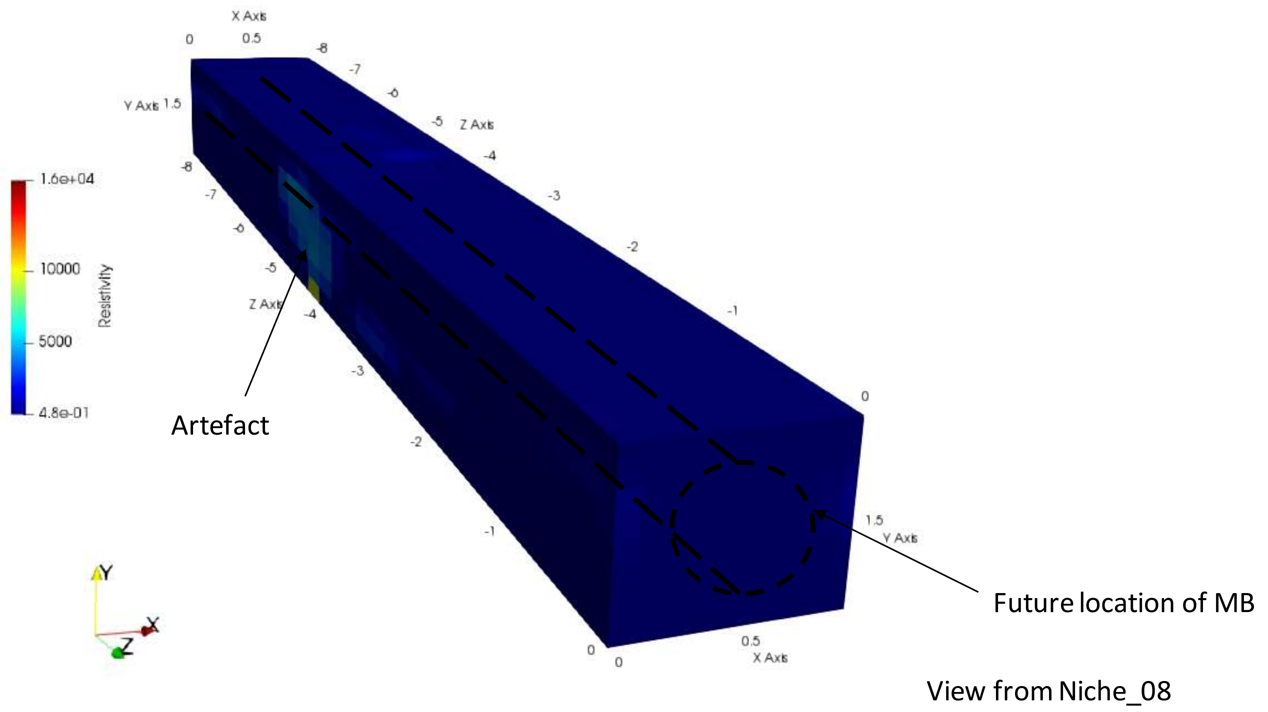


Figure 22: 3D view of inversion results from survey T1 (RMS = 10.7%)

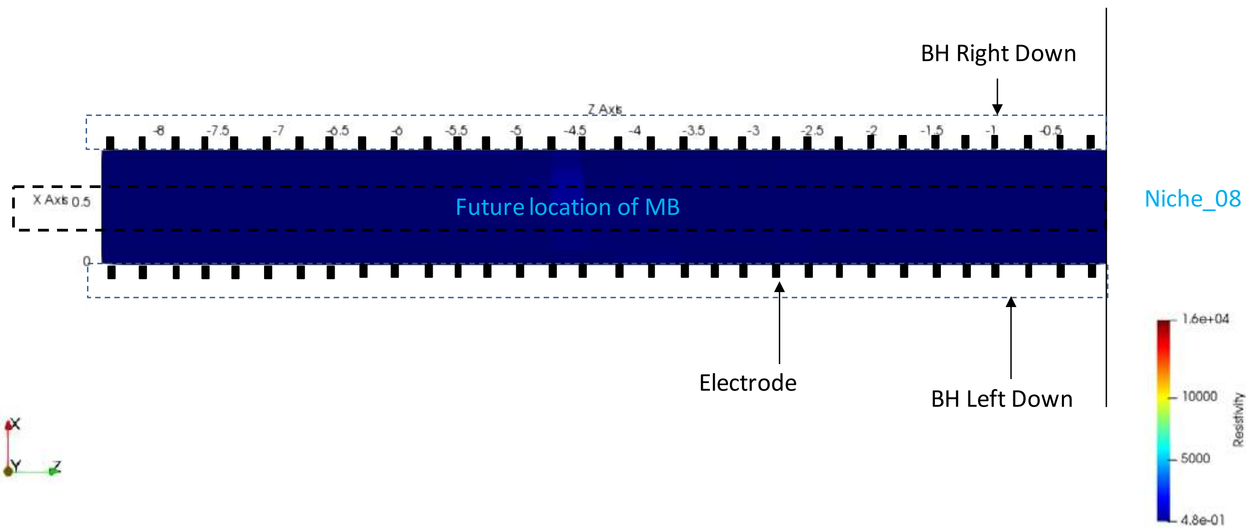


Figure 23: Cross section view of inversion results from survey T1 (RMS = 10.7%)

Figure 6 and Figure 7 show the ERT inversion of survey T2 performed during the monitoring stage in late September 2018 after curing of cement plug. Survey T2 distinguishes well the area of the cement plug and the bentonite. The data for T2 survey were processed, treated in terms of contact resistance, stacking errors and reciprocal errors and inverted.

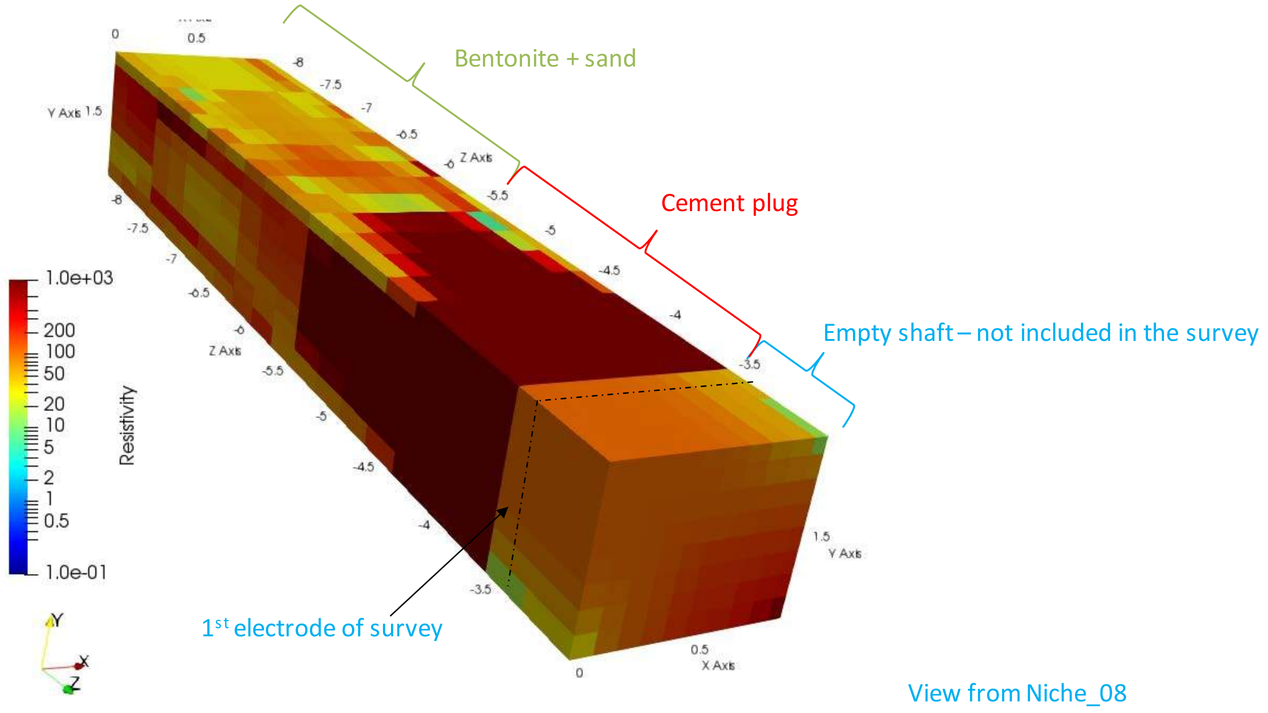


Figure 24: 3D view of inversion results from survey T2 (RMS = 5.16%)

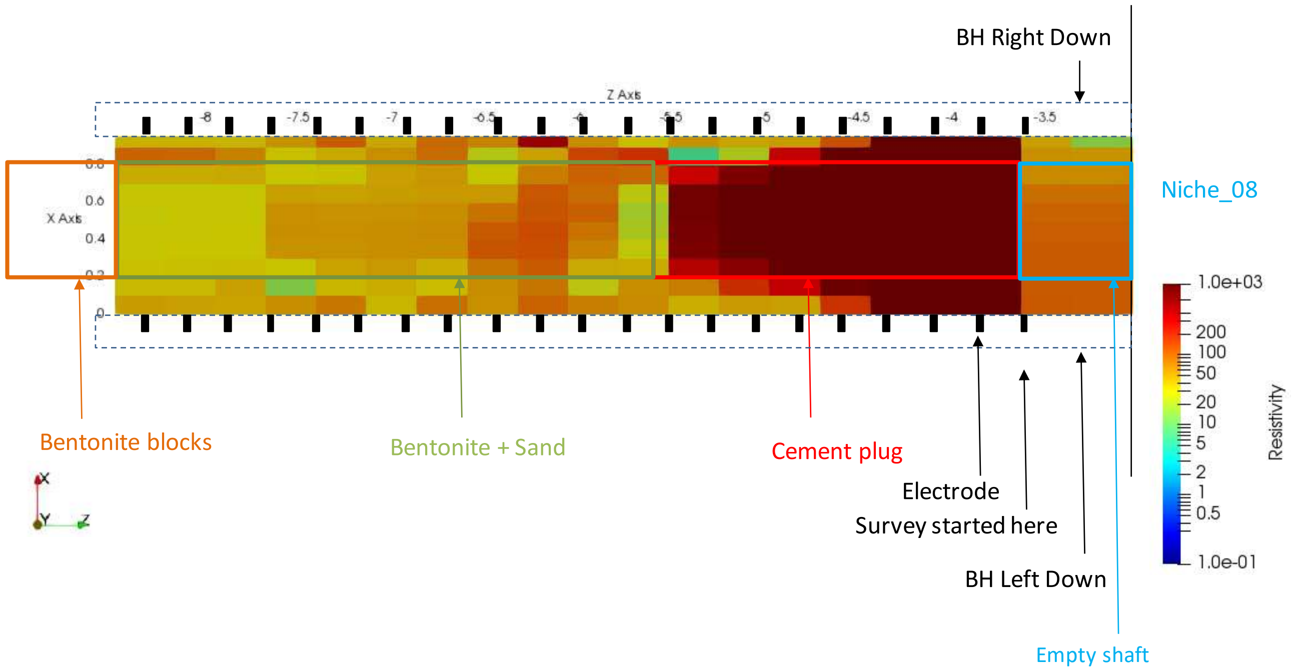


Figure 25: Cross section view of inversion results from survey T2 (RMS = 5.16%)

5. Discussion

5.1. ERT experiment

A considerable number of negative apparent resistivity data were collected during survey S2. This negative apparent resistivity does not appear to be real, since virtually no negative apparent resistivity remained after filtering the data according to the data quality procedure (Figure 8). However, it was evident that the protocol used for data collection during survey S2 was not appropriate since 46% of the total number of data collected were removed during the filtering stage and still the Root Mean Square (RMS) error of this inversion survey was 12.7%. Since then studies have been performed using forward modelling and sensitivity analysis to improve the protocol used for data collection.

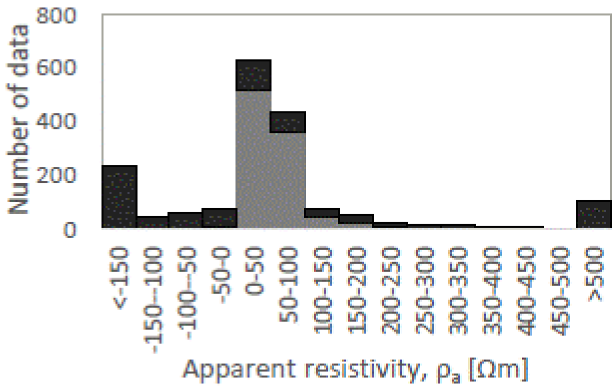


Figure 26: Distribution of apparent resistivity before and after filtering out measurements associated with large geometric factors (black and grey bars, respectively) for survey S2.

Survey S6 benefitted from the new improved protocol. For this survey only 16.5% of the total data collected have been filtered and the RMS obtained was 1.1%. Survey S6 happened 8 days after 26.06L of water had been injected into mat 1 (front of buffer), heater was set at 50°C (rear of buffer) and the temperature recorded by temperature sensors was stable for about 3 days. No changes are noticeable around the rear of the model and it is to be expected as the model only goes around depth 8.65m and the significant temperature change occurred between 8.9 and 9.1m (Figure 9).

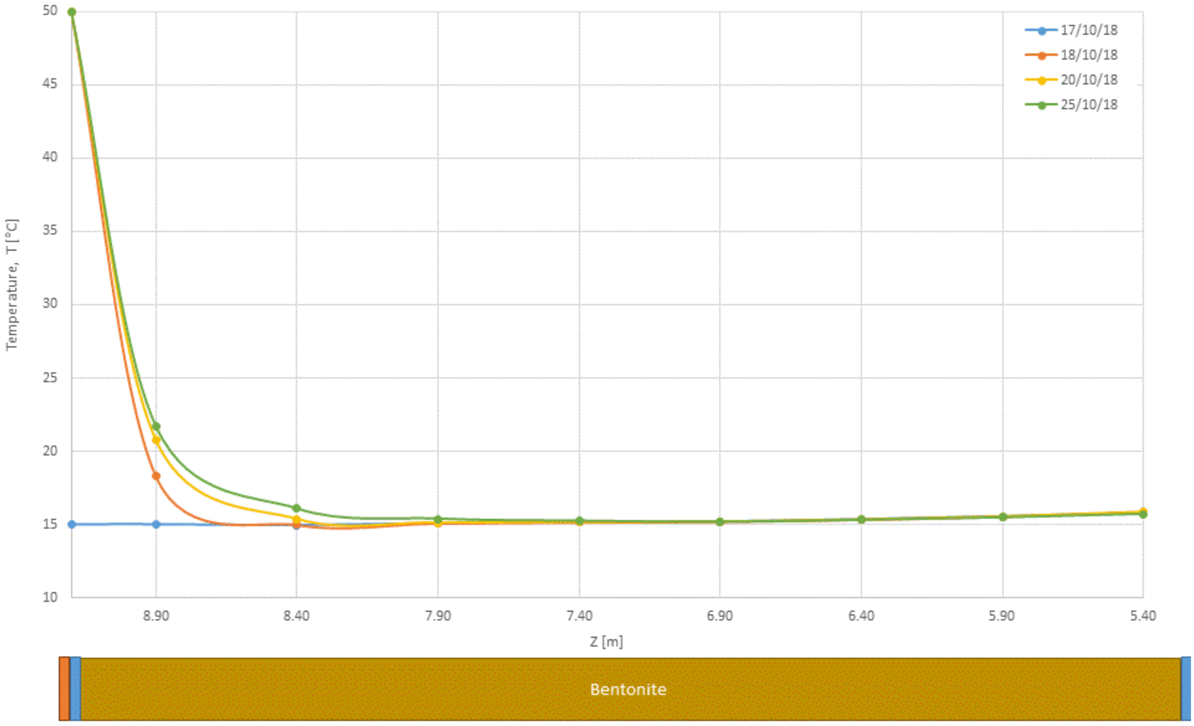


Figure 27: Temperature evolution recorded by temperature sensors installed along the buffer.

In the resistivity model (Figure 3) around the interface between the cement plug and the bentonite, there is a gradual reduction in resistivity. A TDR sensor (E1) located at Z=5.47m appears to be affected by water (resistivity drops recorded by this sensor during these 8 days after water injection) it is reasonable to assume that water has travel from mat 1 (5.1m) up until at least 5.4m depth, which is nicely characterised in the model of survey S6 by a drop in resistivity.

5.2. LTRBM

Measurements for survey T1 were collected in two ways: (1) each electrode in the quadripole was located into one borehole. For instance, the first quadripole of the surface protocol are electrodes 1, 17, 49 and 33, which means that current electrode A is electrode number 1, located in Borehole Left Up (LU); the other current electrode, B, is electrode number 17, located in Borehole Right Up (RU); potential electrode M is electrode number 49, located in Borehole Left Down (LD); and the other potential electrode, N, is number 33, located in Borehole Right Down (RD). (2) in a cross-borehole format where electrodes A and M are in one borehole and electrodes B and N are in the opposite borehole. Although the results obtained were reasonable and RMS error was within acceptable levels, it was clear that an improvement in the protocol was needed.

Thus, studies have been performed using forward modelling and sensitivity analysis to improve the protocol used for data collection in 3D for LTRBM, as well as collection of reciprocal measurements to ensure good data quality. The benefits of the use of the new improved protocol can be noted by the decrease of RMS error for survey T2.

6. Conclusion

Results of preliminary surveys carried out on both experiments confirmed that the resistivity of the host rock around both experiments area is quite homogenous and lower than 100Ωm in accordance with independent measurements carried out in previous campaigns [46]. In addition, the lesson learned from the blank tests allowed identifying key requirements for effective ERT measurements. These include, bespoke measurement protocols designed on the basis of the sensitivity analysis of the geometric factor and the collection of reciprocal data for enhanced data quality control.

Preliminary results of the monitoring period for both experiments are also promising, different materials within the installation are identifiable and changes in resistivity due to water injection and temperature increase are also expected to be noticeable.

The methodology developed for the electrode installation in boreholes and based on the use of PVC half tubes pushed against the borehole wall by inflatable pipes has proved to be successful. However, electrode contact resistance remains a challenge that needs to be addressed.

Interpretation of resistivity results could benefit from time-lapse inversions, which are not currently possible. Res3DInv software used for the 3D inversions does not offer the time-lapse option. Res2DInv does offer time-lapse option but to be able to do that the protocol used by all surveys have to be the same, which is not a possibility since different protocols were used for surveys S1, S2 and S3. Time-lapse analyses are still possible if a different software package is used for inversion and a different time-lapse approach is used based on the model mesh rather than protocols.

Electrical resistivity tomography has been successfully used for several years to monitor, qualitatively, changes in electrical resistivity of materials. Several features of the material (e.g. water content and temperature) are intrinsically sensitive to changes in electrical resistivity and thus could be connected and determined qualitatively by ERT surveys. At this qualitative level, the ERT is at technology readiness level (TRL) 9. The TRL of the ERT approach described here is at level 6. Research is still under development to (1) establish a semi-qualitative relationship between the resistivity measured in the tomography surveys and the resistivity of the material at control laboratory conditions and (2) determine the ideal characteristics of the less-intrusive scenario for EBS monitoring.

Acknowledgements

The authors wish to acknowledge the support of the European Commission via the project MODERN2020 'Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal' (Grant Agreement No. 662177-Modern2020- NFRP-2014-2015) under the H2020 Euratom Research and Training Programme (Funding agency ID: http://doi.org/10.13039/100010687). We also thank ANDRA and IRSN for the funding support.

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What we can learn from a full-scale demonstration experiment after 4 years of DTS monitoring– the FE experiment

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1. Summary

A comprehensive monitoring program using innovative technologies was realized within the framework of the “Full-Scale Emplacement” (FE) experiment - a full-scale multiple heater experiment - at the Mont Terri Rock Laboratory in Switzerland. Here, the work and conclusions related to fiber-optic (FO) distributed temperature sensing (DTS) monitoring are presented. The DTS method provides a continuous temperature profile along a FO cable, which serves as distributed sensor, resulting in unique, detailed insights into the temporal and spatial variations of the temperature field in and around the heated FE tunnel. FO cables are routed in boreholes and along the tunnel wall. After more than 4 years of monitoring, all four FO cables are still providing valuable DTS data. However, a detailed assessment revealed that neither the default nor the standard calibration of the DTS device’s software is sufficient for satisfying the required measurement accuracy. The observed errors became significant over time as temperature differences along the cable rose to 40 °C as a result of heating. The accuracy was greatly improved after installation of a comprehensive calibration system covering the expected temperature range. In addition, we developed the FE Information System (FEIS), which is an internet browser application based on an object-related database that offers fast access to and visualization of all sensor data including the DTS data. This development was necessary to provide easy access to the data for all stakeholders.

2. The FE experiment

The FE experiment was implemented to investigate repository-induced thermo-hydro-mechanical (THM) coupled effects on the claystone host rock at full scale and to demonstrate as realistically as possible the construction, waste emplacement and backfilling processes for a spent fuel / high level waste disposal tunnel according to the Swiss repository concept [1]. The FE experiment is a long-term heating experiment that will run for more than 10 years. The heating phase of the FE experiment was initiated in 2014. The waste canisters and their heat output are simulated using cylindrical heaters (Figure 1), which are placed centrally along a tunnel (2.7 m diameter, 50 m length) and have the same dimension (4.60 m length, 1.05 m diameter) and heat output (1350 – 1500 W) as the planned waste canisters. The space between the heaters and the tunnel wall is filled with buffer material consisting of bentonite blocks, to support the heaters, and a highly compacted “granulated bentonite mixture”.

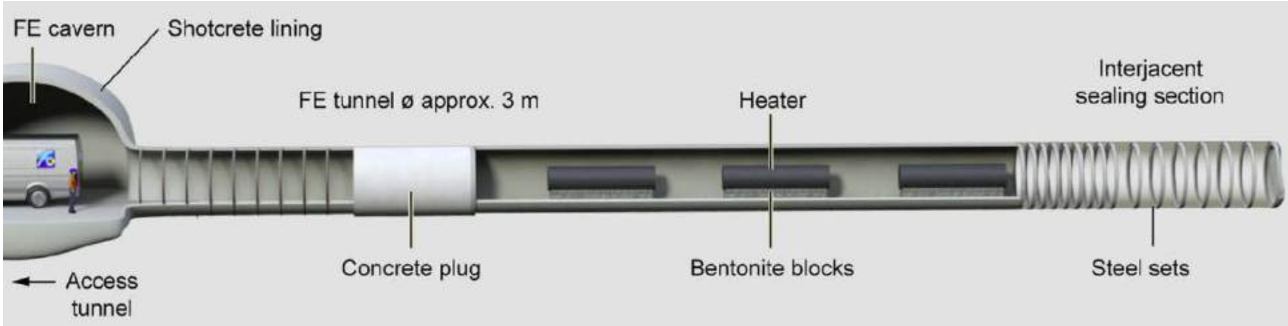

Figure 1: Visualisation of the general layout of the FE experiment and the 50 m long FE tunnel at the Mont Terri Rock Laboratory; sensors, bentonite backfill and rock bolts are not shown. Figure taken from [1].

The entire experiment implementation as well as the THM evolution of this full-scale heater experiment is monitored using several hundred sensors. The main monitored parameters are temperature, mechanical and water pressure, deformation/displacement and humidity/water content. The sensors are distributed in boreholes, in the tunnel lining, in the bentonite buffer and on the heaters. The monitoring environment is challenging because of the long observation period, the high salinity of the pore water and the high temperatures of up to 130 - 150 °C at the heater surface and up to 60 - 80 °C at the tunnel wall. In addition, most sensors cannot be replaced in the case of malfunctioning or failure. Therefore, a careful selection of monitoring systems including sensors, housing materials and cables was needed.

The primary use of the monitoring data is for THM model calibration and validation at full scale. The FE experiment is also a great opportunity to identify issues, to implement developments and to gather experience related to long-term monitoring that will be of importance for the monitoring concept of the future Swiss repository. We therefore focused in our study on what we can learn from this full-scale demonstration experiment after 4 years of DTS monitoring regarding:

- sensor performance and calibration,
- data management challenges and data sharing.

3. Distributed Temperature Sensing (DTS)

The monitoring data of the FE experiment teach us about the reliability and performance of sensors under repository-like conditions. Therefore, multiple sensor types and monitoring technologies were installed to evaluate and compare their performance. Within Work Package 4 of the Modern2020 project, Nagra selected two different sensing technologies for the FE experiment that were both identified as suitable in the previous MoDeRn project [2], namely time domain reflectometry (TDR) for water content measurements as well as DTS for temperature measurements. The focus of our work was mainly on the aspects of installation, calibration, operation and data handling. In this extended abstract we present the DTS related findings.

For DTS measurements the FO cable is the distributed sensor and is connected to the DTS unit, which hosts a laser as well as the detector with signal processing unit. With the DTS technique temperature profiles over several meter to several kilometers in length can be measured with a spatial resolution of 0.25 – 2.00 m. The DTS unit in this study determines the backscatter location via optical time domain reflectometer and uses the Raman backscatter characteristics of light emitted following a laser pulse into a FO cable. The Raman backscatter consists of two components of different wavelength, the Stokes and anti-Stokes signal. A measurement of their ratio in time allows calculation of the temperature along the FO as a function of distance [3]. As compared to other FO sensing techniques, e.g. fiber bragg gratings as well as Brillouin and Rayleigh-based distributed systems, the most prominent advantage of the Raman based DTS is that it is sensitive solely to temperature and not to strain. In general, the temperature measurement accuracy of an DTS unit depends on sampling time (the longer the sampling time, the better the accuracy) as well as spatial resolution, FO cable installation and properties.

Different FO cables were installed within the FE experiment, namely robust armored cables with 4 mm diameter, where the fibers are located loose in a metal tube, and a very flexible cable with 2 mm diameter, which has no armoring and no metal tube. In total four FO cables were connected to a multiplexer for permanent monitoring. Moreover, two different DTS units were used. The DTS unit for permanent monitoring had a spatial resolution (defined as the length over which 10 - 90% of a step temperature change can be detected) of 1.02 m and the DTS unit used temporarily had a spatial resolution of 0.25 m. All DTS measurements were performed in single-ended configuration where only one end of the FO cable was connected to the DTS unit.

For DTS different calibration procedures exist. Besides the default factory setting, pre-installed calibration routines using the DTS device’s calibration software are available to translate the Raman signals into temperatures. With the growing popularity of DTS instrumentation more precise post-processing calibration routines were developed, e.g. [4] for single-ended DTS measurements. Before the heaters in the FE experiment were turned on, we used the default factory setting of the DTS, because no difference could be observed to a standard calibration routine using the DTS device’s software and two water baths (ice bath and ambient temperature bath), which were incorporated in the FO cables’ measurement sections. The water baths were equipped with conventional sensors to determine the calibration parameters and to check the accuracy of the measurements. After the start of heating, the temperature in the FE tunnel close to the heater locations was increasing and over time temperature differences along the cable rose to 40°C. After detailed investigation, we show that errors in temperature measurements became significant over time and that neither the default DTS factory setting nor the DTS device’s calibration software is sufficient for a satisfactory measurement accuracy.

To improve the temperature accuracy of the DTS measurements, a comprehensive calibration set-up was realized covering the expected temperature range. The former simple baths were removed and two very well insulated water baths with a mixing mechanism of the water body were installed including FO cable sections ranging from 10 - 30 m. One bath was at ambient temperature (19 - 20°C) and the other bath had an integrated heating element to keep the temperature stable at 65°C. Both baths were equipped with conventional high precision temperature sensors. Their data and the DTS data of the baths are used for the newly implemented calibration algorithm [4] for single-ended DTS measurement. The FE database (FEIS, see chapter 4) calculates the calibration coefficients “on-the-fly” for every single measurement as the data are imported to the database. Implementation of the database calibration resulted in an average measurement accuracy of 0.1 - 0.3°C depending on FO cable type and DTS unit.

4. Comparison of DTS to conventional temperature sensors

DTS combined with continuous calibration has an advantage over conventional electrical “point-type” temperature measurements. The latter are based on pre-installation calibration; their accuracy is considered to be stable over time and only a small drift is expected, however, cannot be checked during the monitoring period. Changes in the DTS FO cable where the data quality may be affected can be identified and compensated, e.g. light step losses (e.g. at splice connections or due to cable bending) or high strain along the cable. For standard “point” sensors, similar investigations are not possible. However, conventional electrical “point-type” temperature sensors are at the moment the sensors that are used for comparison with DTS and for DTS calibration.

Besides the DTS instrument’s raw data output and calculated temperature data, the calibration parameters are also stored in the FE database. This allows the change in the cable properties to be

investigated over long time periods, e.g. in order to draw conclusions on the suitability of different cable types with respect to cable aging behavior.
Along the boreholes and within the heated tunnel, where temperature gradients of up to 6°C/m exist, a direct comparison with standard electrical point temperature sensors is difficult due to the DTS spatial resolution, which ranged from 0.25 – 1.02 m depending on the DTS device. We could show that in general a good agreement exists between DTS data with about 1 m spatial resolution and data of standard point-type temperature sensors, especially where small to moderate temperature gradients (<1°C/m) prevail along the FO cable. DTS instruments with a high spatial resolution (0.13 – 0.25 m) can even provide reliable data for sections with large temperature gradients along the FO cable. Therefore, DTS provides detailed spatial temperature data at a scale of a repository tunnel, which cannot be realized practically using conventional temperature sensors.

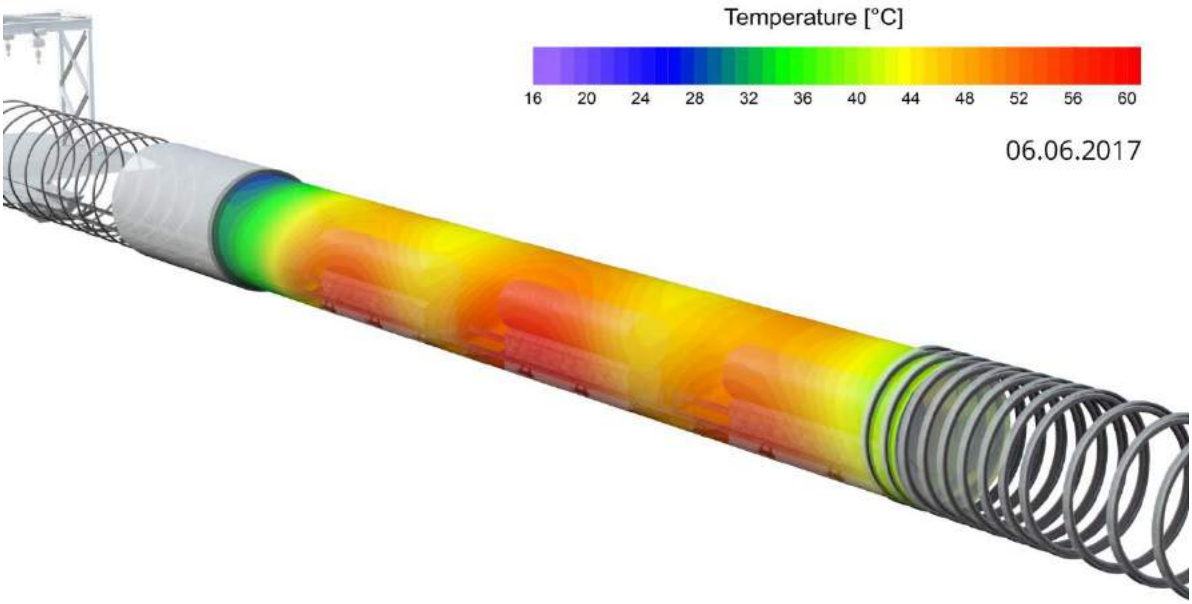

Figure 2: Temperature distribution along the tunnel wall in the FE experiment measured by means of DTS. The measurement data shown were acquired on 06.06.2017, which is equivalent to approx. 2.5 years of heating.

5. Data management and the FE Information System (FEIS)

The acquisition of highly detailed spatial DTS data is of great benefit from the perspective of observation and monitoring; however, it creates new challenges for data management. Compared to conventional point-type sensors, DTS generates significantly more data and the data come in the form of profiles. This specific profile format is untypical for standard databases. We therefore developed the FE Information System (FEIS), which is an internet browser application based on an object-related database that offers fast access to all sensor data (point and profile data) and customizable data visualization. The FEIS relates the location of distributed measurements along a FO cable to FE project locations in 3D-space, even for complex routing of cables. The routines account for varying spatial resolution that can result from different measuring units and instrument settings. The system responds quickly, even with billions of FO measurements. Dynamic calibration coefficients are calculated for each DTS measurement as the data are added to the database. Calibrated temperatures are calculated "on-the-fly" for FEIS graphical output, data listings and exports. DTS measurements can be viewed as a profile (measurements along the cable) or as a time-series (measurements over time at a specified point) and measurements can also be compared with standard sensors.

6. Conclusions

6.1. DTS

Within Work Package 4 of the Modern2020 project we worked on the demonstration and evaluation of the DTS monitoring technology under repository like conditions in the FE experiment. The FE set-up offered ideal conditions for comparing different novel sensing systems with conventional standard systems. For DTS, the focus of our study was mainly on the aspects of installation, calibration, operation and data handling.

According to the obtained results DTS is a promising and advantageous technique for obtaining detailed spatial temperature datasets, opening new insights into the understanding of heat transport in the buffer and host rock as well as providing detailed temperature monitoring within a full-scale high-level waste disposal tunnel (Fig. 2). We show that the spatial and temporal variations of the temperature field within high-level waste disposal tunnels can be determined sufficiently accurately by means of DTS. However, for long-term DTS monitoring under repository conditions, a comprehensive calibration set-up is required covering the expected temperature range. For our single-ended DTS measurements, the calibration algorithm after [4] and step loss correction were successfully applied "on-the-fly" to every single measurement at the moment of data transfer to the FE database.

The different FO cables and the two different DTS units that we used showed different performances. The robust armored FO cables are characterized by a better accuracy due to their more robust structure that is minimizing external influence on data quality in comparison to the flexible cable without armoring. Moreover, in our case the DTS unit with the finer spatial resolution showed a better accuracy.

In general, DTS is a commercial technology that has been used since years for different applications, e.g. pipeline monitoring, fire detection, hydrological research or downhole monitoring in oil and gas industry. However, besides the calibration and data handling issues that were part of our work, further developments are needed for DTS monitoring applications in deep geological repositories, e.g. on radiation and hydrogen resistant FO cables, power supply and data transmission.

6.2. Data sharing

Many internal and external stakeholders are interested in the FE monitoring data. Each stakeholder has a different background, a different interest and uses the FE data in a different way. Therefore, a data sharing concept is important. Although the FEIS offers various access levels for each user and all information and data can be downloaded or viewed, our conclusion after more than 4 years of DTS monitoring is that most stakeholders prefer a condensed summary of the monitoring data (e.g. annual reports and annual data deliveries), rather than having direct access to the database. In addition, modelers using 3D numerical models are not yet accustomed to high-resolution spatial data, because the level of detail is not within the scope of their modeling objectives or the models' grid or cell sizes are insufficient for handling a fine spatial resolution. Although, the users can extract selected point-specific DTS data using the FEIS, this option is hardly ever used by the modelers. Thus, more efforts are needed to promote the advantages of innovative monitoring technologies such as the DTS monitoring and FEIS for different stakeholders.

Acknowledgements

This work was partly funded by the Swiss State Secretariat for Education, Research and Innovation (SERI) as part of the Modern2020 project (Euratom research and training programme 2014–2018, grant agreement No 662177).

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Niches of fibreoptic sensing: from large-strain applications to acoustic emission monitoring

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1. Summary

Fibreoptic sensors (FOS) represent sensing technology with small footprint, low invasiveness, electromagnetic passivity and immunity, plus potential for remote and real-time monitoring. Modern FOS techniques allow truly temporally- and spatially-continuous monitoring over extended distances; a feature not attainable with any other sensing technology. Moreover, depending on their particular material composition and design, optical fibres can be made resistant to high temperatures, chemicals and ionizing radiation. Due to this unique combination of advantageous properties, ever since their emergence, FOS have been attracting considerable attention for monitoring tasks in harsh, hazardous and difficult-to-access locations. The potential of FOS has been recognized also in the field of radioactive waste management and fibreoptic sensors belong to the most promising technologies for nuclear waste repositories (NWR) monitoring.
Vast majority of distributed fibreoptic sensor applications rely on use of silica-based optical fibres as sensing elements. At the same time, distributed measurement of local temperature and strain along the fibre are the most common monitoring tasks addressed by fibreoptic sensors. Nevertheless, FOS offer much larger flexibility both in terms of utilized sensing fibre as well as targeted measurand. In this contribution, we will review some of more alternative implementations of FOS that are being explored at “Fibre Optic Sensors” division of Federal Institute for Material Research and Testing (BAM), in Berlin. The main focus will be twofold. On one side, we will address FOS applications with polymer optical fibres (POF), that may enable monitoring of large strains (>100%) and high-sensitivity radiation detection. On the other side, we will present our activities in the area of distributed acoustic sensing (DAS); one of the most recent developments in the fibreoptic sensing field enabling highly-dynamic vibration sensing with nanostrain sensitivity. We will introduce the principles of the addressed FOS technologies, present application examples from our case studies, discuss advantages and limitations of the techniques and highlight their potential for NWR monitoring.

2. Introduction

Fibreoptic sensors (FOS) have a number of advantageous characteristics such as small dimensions, low weight, electromagnetic immunity and passivity or high durability in harsh environmental conditions. In addition, distributed fibreoptic sensors allow spatially- and temporally-continuous monitoring of extended fibre lengths up to hundreds of kilometres. This constitutes the core advantage over many more traditional sensor technologies that are typically limited to a point sensing. The possibility of continuous monitoring of long distances with a single fibre line makes FOS especially attractive for monitoring of large structures, e.g. bridges, tunnels or dikes. Division 8.6 “Fibre Optic Sensors” is a part of Federal Institute for Materials Research and Testing (BAM). The division has broad expertise in the field of fibre optic sensors, primarily targeting their application for structural health monitoring (SHM) tasks. The division has experience and is equipped with a number of different FOS techniques:

- Fibre Bragg gratings (FBG)
- Fibreoptic Fabry-Perot interferometers (FPI)
- Distributed Brillouin-based fibreoptic sensors
- Raman-based fibreoptic distributed temperature sensors (DTS)
- Optical time- and frequency-domain reflectometry (OTDR, OFDR)
- Distributed fibreoptic acoustic and vibration sensors (DAS, DVS)
- Polymer optical fibre (POF) sensors

Various point or distributed FOS can be used for measurement of strain, temperature, pressure, humidity, vibrations, ionizing radiation and other quantities. Nevertheless, the focus of the division lies on the distributed fibreoptic sensors (DFOS) and their application for condition monitoring of large civil, geotechnical and energy constructions and infrastructures. These include dikes, bridges, tunnels, creeping slopes, dams, power cables, pipelines and others. The competences of the division range from development of novel FOS interrogation techniques, through optimization of application or integration of the sensing fibre into the monitored structures, testing and validation of commercial optical fibre sensors to development of standards and technical regulations for FOS.

DFOS rely on the light backscattering in optical fibres. As the light propagates through an optical fibre, a small part of the light is backscattered back towards the input end of the fibre where it can be detected and used to construct so-called fibre backscattering trace. Fibre backscattering trace can be viewed as a fingerprint of the fibre at given conditions. The backscattering trace is sensitive to fibre external perturbations, most commonly temperature and strain, which can be exploited for sensing applications. Depending on the nature of the utilized light backscattering, DFOS systems can be divided into Rayleigh- [1], Raman- [2], or Brillouin-based [3] techniques. All three types of DFOS techniques have their specific advantages and shortcomings that need to be considered for a particular application.

Potential of FOS has been recognized also in the field of radioactive waste management and fibreoptic sensors belong to the most promising candidates for various monitoring tasks in nuclear waste repositories (NWR) [4-6]. Explored monitoring tasks typically target strain, temperature or radiation measurement in NWR and storage containers. On one of previous MODERN workshops on monitoring technologies [7], we already reported on our general activities with DFOS embedded in technical textiles for monitoring of geotechnical and masonry structures [8]. In this contribution, we will review some of more alternative implementations of FOS that are being explored in our group and highlight their potential for monitoring in NWR. The focus will be mainly on Rayleigh-based DFOS for large strain sensing with polymer optical fibres (POF) and highly sensitive vibration sensing with silica-based fibres. We will also discuss potential of POF for attenuation-based distributed radiation monitoring.

3. Large-strain sensing with polymer optical fibres

In comparison to standard silica-based optical fibres (SOF), typical large-diameter multi-mode POFs are more robust, flexible and considerably cheaper. The cost saving factor does not come only from lower manufacturing price, but in a large part from the easier handling and processing of the fibres. Compared to standard silica single-mode fibre (SMF), typical 1 mm polymethyl methacrylate (PMMA) POF (Figure 1) significantly relaxes alignment requirements for coupling with other fibres and optoelectronic components. This decreases cost for high precision equipment and trained personnel. POF can, thus, yield relatively cheap, user-friendly monitoring systems. Higher flexibility and ductility of polymers makes POF less prone to bending-losses and stress-induced breaking.

Consequently, some POF might withstand straining up to 100% [9], while SOF have typically break limit of few % strain [10]. At the same time, low Young's modulus makes POF attractive for monitoring of compliant structures, where presence of stiff sensing SOF might lead to local reinforcement of the structure disrupting the sensor reading. In addition, high flexibility and low sensitivity to bending losses makes POF also suitable for integration into technical textiles or concreate structures. On the other hand, POF exhibit notably higher attenuation than SOF and their use in distributed sensing applications is therefore limited to several hundred meters.

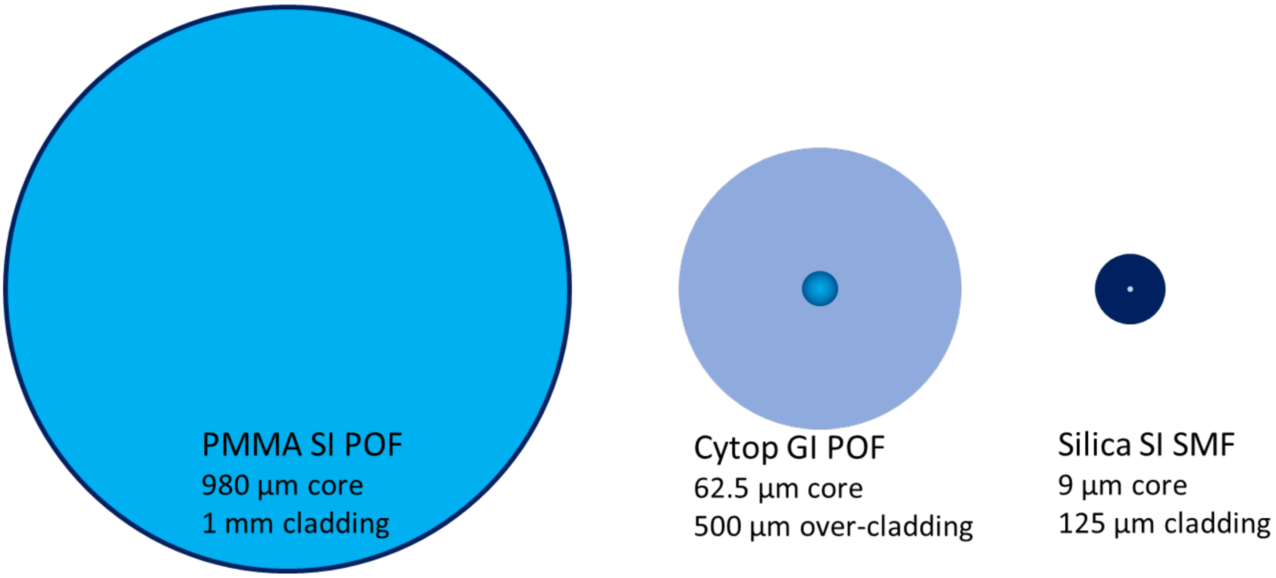

Figure 1: Comparison of cross-sectional geometry of typical multi-mode PMMA step-index (SI) and Cytop graded-index (GI) polymer optical fibres (POF) with standard silica-based single-mode fibre (SMF). Relative cross-sectional dimensions of fibres depicted in the figure are in scale.

Generally, there are two distinct effects that can be used for strain measurement using POF and simple Rayleigh-based optical time-domain reflectometry (OTDR). First, fibre straining leads to an increase of local backscatter level in the strained fibre section. Second, straining is associated with length changes of fibre line that can be observed on prominent features (reflection peaks) of the OTDR trace such fibre end-reflection. Both principles are schematically illustrated in Figure 2. Monitoring of local strain-induced backscatter increase in standard PMMA POF using simple OTDR setup is a cheap and attractive way for distributed large-strain monitoring for geotechnical or SHM applications [11,12]. On the other hand, induced backscatter increase is not a linear function of applied strain and anneals over time. Therefore, potential of this approach for quantitative strain measurement is limited.

The approach based on fibre length change monitoring can yield quantitative strain measurement. However, in the case of standard PMMA POF that have a smooth OTDR trace, it provides only integral length change (strain) information. Artificial scattering centres that will generate traceable backreflection peaks in POF OTDR trace can be created by femtosecond inscription [13]. Alternative solution is the use of specialty graded-index POF based on perfluorinated polymer Cytop, which have typical jagged OTDR trace (inlay in Figure 2). Presence of these inherent backreflection peaks in Cytop POF OTDR trace enables quasi-distributed length change, and thus, strain measurement. At the same time, due to their lower attenuation, Cytop POF enable extension of monitoring length to roughly 500 m, compared to about 100 m achievable with standard PMMA POF [12]. Precise evaluation of local length changes requires higher spatial resolution than the one achieved with common OTDR systems. For this purpose, incoherent optical frequency-domain reflectometry (I-OFDR) system for Cytop POF has been developed at our group and employed in various SHM and geotechnical application [9,14,15]. In addition to increased precision and spatial resolution, the I-OFDR approach enables also dynamic strain measurement [16]. In context of nuclear waste management, POF-based strain sensors can be used for SHM or geological monitoring of repositories in the areas with non-critical radiation and temperature levels.

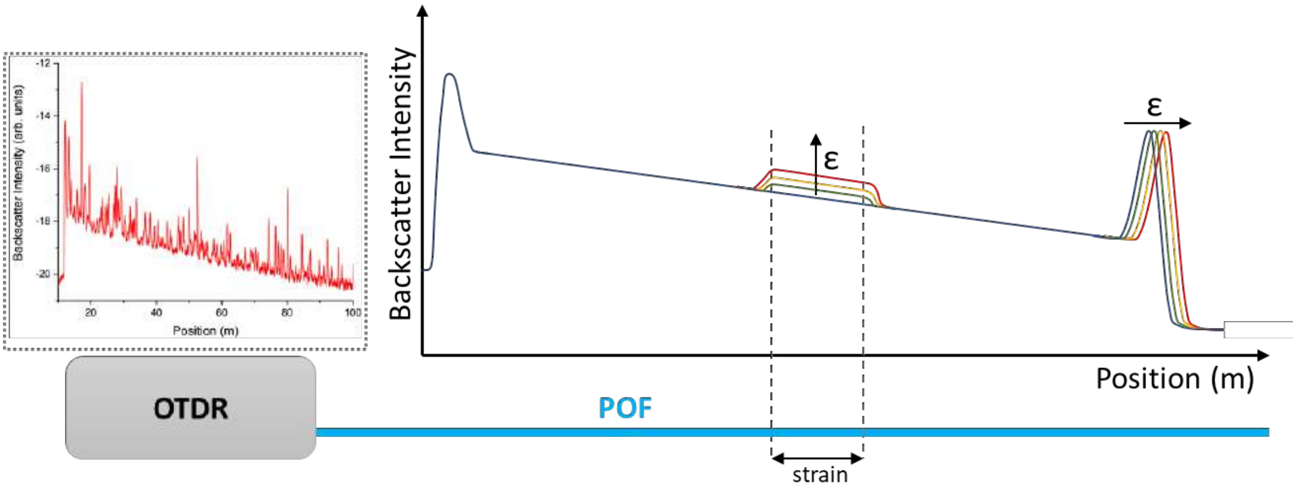

Figure 2: Schematic illustration of working principle of Rayleigh-based distributed strain sensing using POF.

4. Radiation measurement with polymer optical fibres

POF-based strain sensors can be used for repository monitoring only in areas where high radiation levels are not expected. This is due to their high radiation sensitivity, i.e. strong radiation-induced attenuation (RIA) that degrades their transmission properties. RIA sensitivity of standard PMMA POF is at the level of single dBm^{-1}/kGy [17], while it may reach values around 100 dBm^{-1}/kGy for Cytop POF [18]. This allows Cytop POF to detect radiation at single Gray levels. Although this high radiation sensitivity makes POF unsuitable for prolonged operation in radiation environments, it makes them attractive for short-term radiation measurement. The degree of fibre's RIA can be correlated with the total dose that it has received and thus facilitate optical dose measurement. In addition, with help of OTDR or OFDR techniques, fibre attenuation can be measured in a distributed way, which can be used for distributed radiation detection or profiling along the POF [19]. While the approach would not be suitable for long-term radiation monitoring in NWR, it can be potentially interesting for short-term safety monitoring of individual casks and storage units during loading, transportation or placement to verify their integrity and spent fuel position/distribution within the containers. The proposed principle of distributed radiation profiling around the cask with POF is illustrated in figure Figure 3.

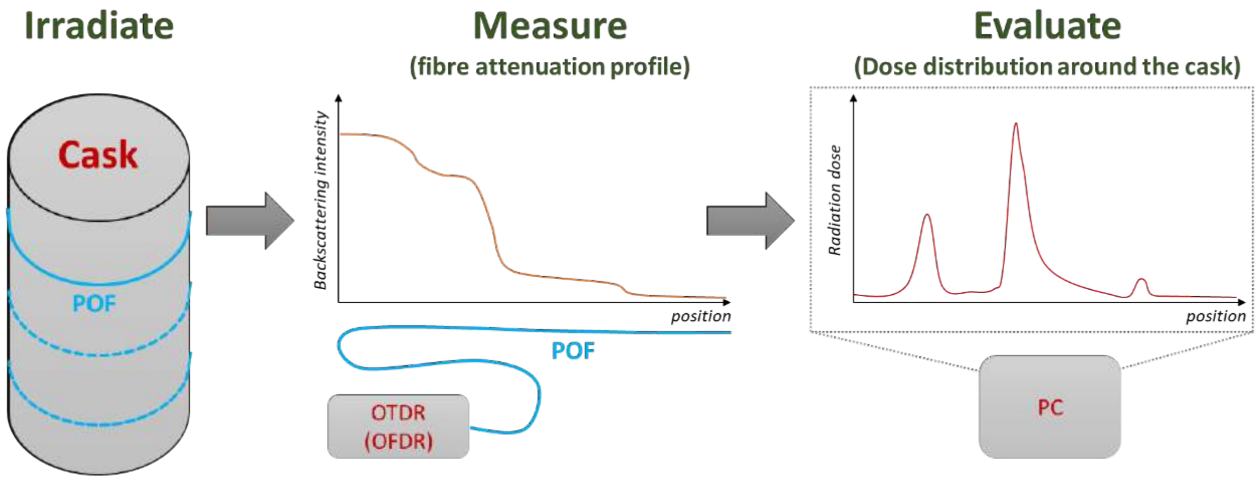

Figure 3: Schematic illustration of working principle of distributed RIA-based radiation measurement using Cytop POF.

5. Distributed acoustic sensing

Distributed acoustic sensing (DAS) belongs to the latest developments in the field of distributed fibreoptic sensing. DAS relies on coherent optical time-domain reflectometry (C-OTDR) [20], which, unlike standard OTDR using incoherent light source, uses highly coherent laser that enables interference of light backreflected from different scattering centres within the fibre. Recorded time evolution of backscatter trace contains information on immediate configuration of local scattering centres in the fibre. Position along the fibre can be inferred from the pulse relative time-of-flight in the fibre and the detected local optical field is a result of light interference from individual scattering centres encompassed in the pulse envelope. Distribution of scatterers along the fibre is a characteristic of individual fibres. Nevertheless, even small changes of local scatterer distribution caused by external perturbations may give rise to notable variation of recorded backscattering trace. The evolution of fibre backscattering trace from pulse to pulses can be monitored at high rates, thus providing dynamic information on evolution of external perturbing factors, e.g. temperature or strain along the fibre. This highly-dynamic (up to MHz range) and highly-sensitive (down to sub-nε level) strain measurement forms the basis of the DAS technology [21]. The working principle of DAS is schematically illustrated in Figure 4.

Different variations of the system have been proposed and developed over the recent years [22-26] and some of the solutions are already available on the market. At BAM, a cost-effective wavelength-scanning C-OTDR has been developed that allows distributed measurement of amplitude, phase and correct algebraic sign of applied dynamic strain [27]. This allows accurate reconstruction of excitation acoustic/vibrational signals causing the fibre straining. DAS holds a potential for numerous monitoring applications in the areas of civil engineering, oil and gas industry, public safety, material and energy infrastructure, geotechnical engineering or seismology. These include boarder and perimeter control [28], pipeline intrusion and leak detection [29], modal analysis of large civil structures [27], power cable monitoring [30] or seismic monitoring of boreholes and other underground structures [31]. With regard to monitoring task in the area of nuclear waste management, DAS technology can be of interest for perimeter control of NWR facility, i.e. detection and localization of unauthorized intrusion of the facility. Even more attractive can be use of DAS system for seismic monitoring of repository geological surrounding and detection of its critical alterations.

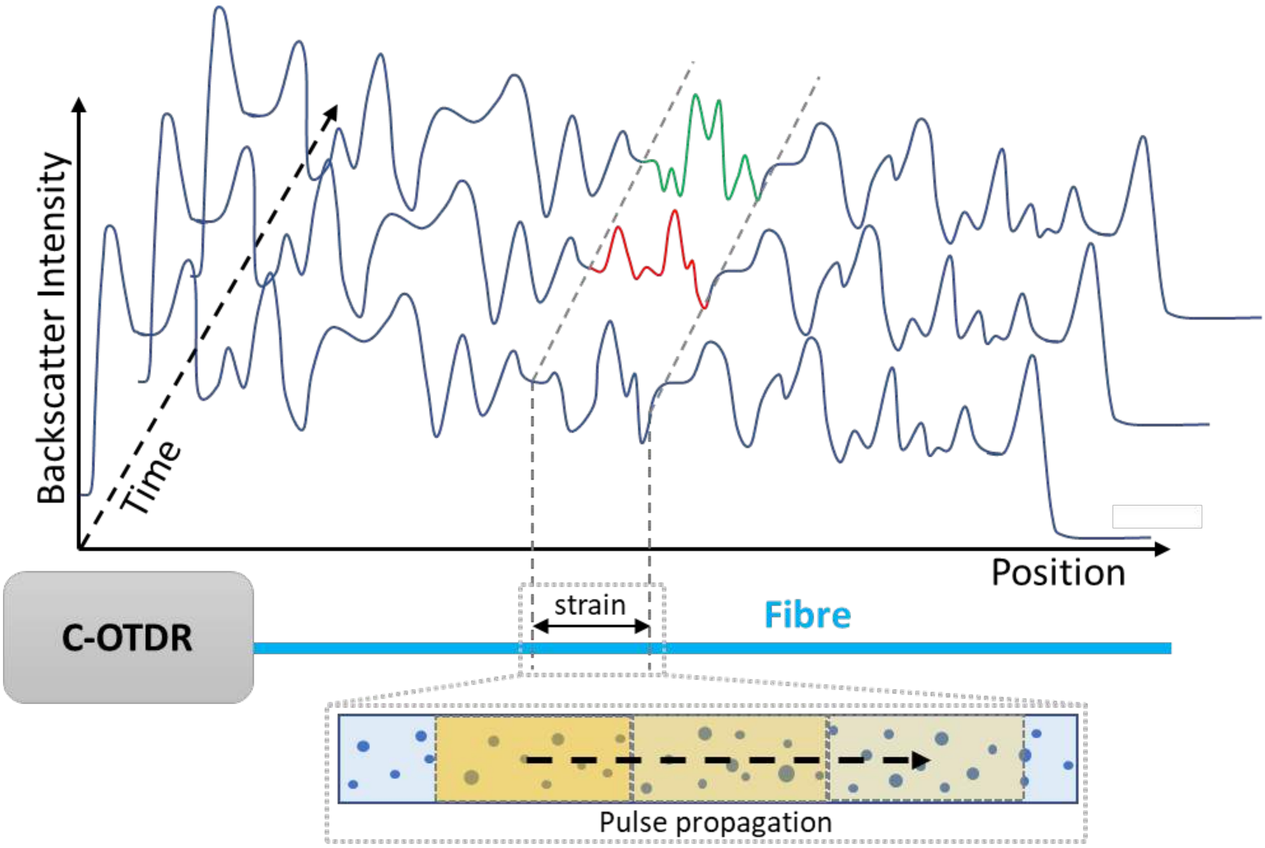

Figure 4: Schematic illustration of working principle of fibreoptic distributed acoustic sensing.

6. Conclusion

Due to their low invasiveness, high resistance to extreme conditions and possibility of remote distributed monitoring, fibreoptic sensors belong to some of the most promising sensing technologies for monitoring tasks in nuclear waste repositories. Most typically, DFOS relying on silica-based optical fibres are being employed for local strain and temperature monitoring for SHM of repository structure or waste containers. In this contribution, we briefly introduced more alternative implementations of FOS technology. We discussed how polymer optical fibres can be used for distributed measurement of large strains (up to 100%) that exceed the breakage limit of standard SOF. POF may be easily incorporated into concrete structures or geosynthetic fabrics. Rayleigh-based distributed strain sensor using POF can be used for monitoring of local strain evolution in repository structure or its geological surroundings. Thanks to their high radiation sensitivity, Cytop POF hold also potential for RIA-based distributed radiation measurement. This approach might be employed for short-term radiation leak detection and profiling during repository construction and commissioning. Finally, we also discussed one of the recent FOS developments; distributed acoustic/vibration sensing, which allows highly-dynamic measurement of local strain changes with sensitivity down to sub-nanostrain levels. DAS system might be interesting for repository perimeter control as well as seismic monitoring of its geological environment.

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C.e – Session on Long-term Integrated Monitoring System

Monitoring the Full-scale Emplacement Experiment (FEBEX) over 18 years: lessons learned for future repository monitoring

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1. Summary

The FEBEX (Full-Scale Engineered Barrier Experiment in crystalline host rock) at the Grimsel Test Site (GTS, Switzerland) provided a large amount of very valuable data and samples after being shut down in 2015 after 18 years of heating at a constant temperature of 100°C at the heater. A carefully-planned monitoring concept, with more than 600 sensors in the buffer and the host rock, provided the necessary data to maintain and manage the experiment, delivered input for modelling, provided the framework for assessing lab-derived sample data and eventually proved and demonstrated the feasibility of the construction of a fully engineered buffer system. A partial dismantling after 5 years in 2002 already served this purpose but with the rather unexpected durability and performance of the sensors, the second part of the experiment was extended for another 13 years. A post-dismantling evaluation and re-calibration of sensors in conjunction with their data revealed good correlation with lab-derived data and useful information for calibration and interpretation. Future sensor and monitoring efforts are already benefiting from the FEBEX findings, not only by its long lifespan but also the valuable data gathered, and performance shown.

2. The FEBEX Experiment

2.1. Objectives of the FEBEX

The FEBEX experiment [1] at the Grimsel Test Site (GTS) in Switzerland consisted of an in-situ full-scale engineered barrier system (EBS) test for the disposal of high level waste (HLW). The experiment was based on the Spanish reference concept for the disposal of radioactive wastes in crystalline rock and was initiated by Enresa in 1995. It was performed under natural conditions in crystalline rock in which two canisters (heaters) were placed horizontally in a drift and surrounded by a clay barrier constructed of highly compacted bentonite blocks. Heating of the FEBEX started in 1997 and was kept at a constant temperature of 100°C, while the bentonite buffer slowly hydrated by the natural supply of groundwater from the rock. The outer part – one canister and the outer part of the bentonite buffer – was dismantled and sampled during 2002. Given that the sensors of the remaining part were still functioning well a continued monitoring of the saturation of the EBS (Engineered Barrier Systems) and related processes could be achieved by closing the second half of the experiment with a new plug [2]. This second, inner part was thus maintained at 100°C for another 13 years and was eventually dismantled in 2015 (the FEBEX dismantling project - FEBEX-DP) with the following objectives:

- Characterisation of the key physical properties (e.g., density, water content) of the barrier and their distribution.

- Characterisation of corrosion and microbiological processes on instruments and coupons resulting from evolving redox conditions and saturation states, including gas analysis.
- Characterisation of macro- and micro level studies of mineralogical interactions at material interfaces (e.g., cement-bentonite or iron-bentonite, rock-bentonite).
- Assessment of sensor performance.
- Increased understanding of the thermo-hydro-mechanical (THM) and thermo-hydro-chemical (THC) processes through integration of monitoring and dismantling results.

2.2. Sensors and Monitoring concept

A total of 636 monitoring instruments were installed in the 12 instrumented sections (spacing ~0.5 – 1 m) of the second half of the experiment, both in the bentonite buffer and in the host rock, to monitor relevant THM processes by measuring parameters such as temperature, humidity, total and pore pressure, or displacements. The measured data were used to confirm and improve the understanding of the THM processes involved and to validate/adjust the available modelling codes.

The following sensors were employed to monitor the experiment: total pressure cells, pore pressure sensors, thermocouples, displacement sensors, moisture sensors of different types as capacitive, psychrometric and TDR (Time Domain Reflectometer), and others. When available, high TRL (Technological Readiness Level) sensors were used, as vibrating wire type sensors, whereas in other cases low TRL were possible only, for instance, a few moisture sensors or prototypes for measuring displacements or clinometers. A Data Acquisition and Control System (DACS) was placed in the service area of the FEBEX drift.

Aside from the continued managing and monitoring of the second half of the experiment/EBS, continued monitoring of the partial dismantling activities in 2002 and any related THM effects were registered by the sensors in the frontal part of the second half of the experiment. These data and a performance assessment of the sensors from the partial dismantling provided very valuable information in combination with the data from the final dismantling of the second part of the experiment.

3. Sensor performance Post dismantling sensor evaluation and re-calibration

The sensors, monitoring system and data acquisition units performed excellently during the experiment, with only a few incidents which were caused by external factors (e.g. power shutdowns) [3]. However, these incidents did not have any real impact on the experiment control or on the continuity of the database.

Sensors and data acquisition systems have typically functioned well beyond the expected lifetime of the experiments (***Figure 1***). A high percentage of sensors was still operational after 18 years. Of the non-operational sensors, most of them were saturated humidity sensors, while other failures occurred either at installation dismantling of Heater #1 and resealing or progressively during the experiment. Results from post-excavation characterization [4] and recalibration further support the quality of the initial design and implementation of the Test. Sensor recalibration has in some cases provided an improvement in data quality and has been retrospectively applied to data.

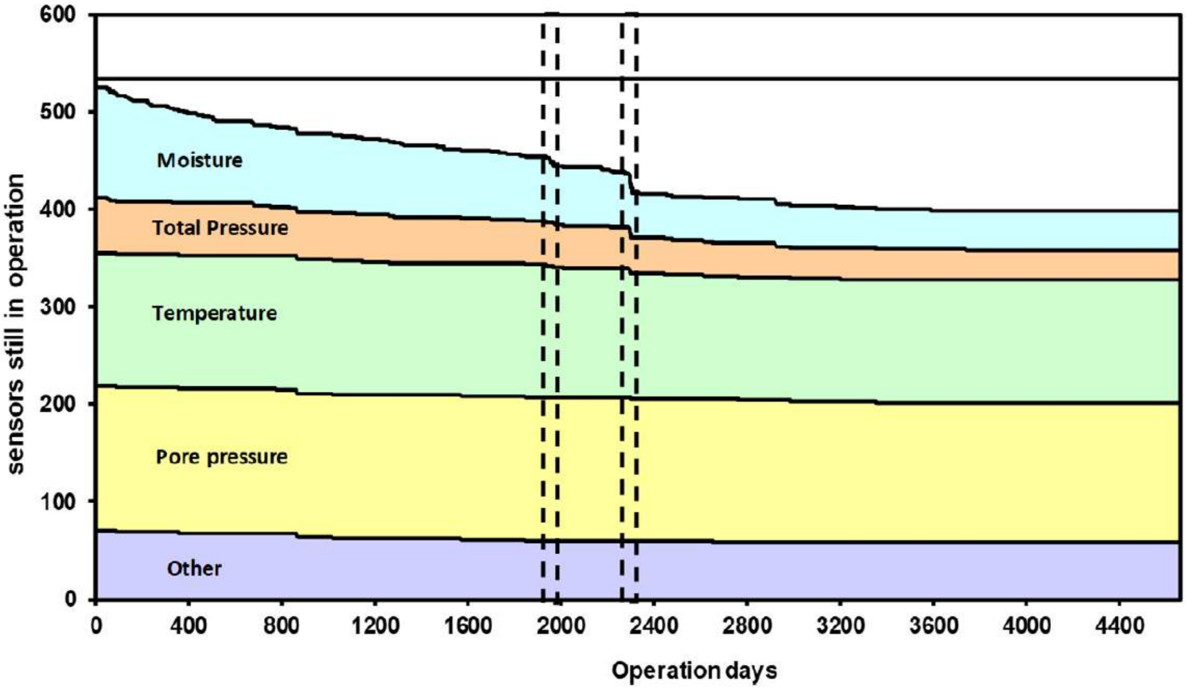

Figure 1: Number of the sensors on duty during the test operation. Vertical striped lines indicate the start and end of the partial dismantling made in 2002

In particular the sensor performance was as follows [5and ***Table 1***]:

a) **Temperature sensors** (thermocouples) performed excellently with an accuracy that did not vary from the installation time (below ±1 ºC).
b) A variety of **humidity sensor** types was installed, with readings matching one another quite well. Capacitive-type sensors substantially surpassed the initially-expected operative lifetime providing accurate readings, whereas psychrometers were shown to be very fragile in a bentonite buffer environment. The TDRs in the bentonite buffer performed well under the harsh environment but became fragile with time and were partially damaged during dismantling, given their length over several bentonite blocks.
c) **Total pressure** cells showed good performance for all the sensors based on the vibrating wire technique.
d) **Pore pressure sensors** were the best surviving ones. They provided very low-pressure readings, showing positive values only at the most humid parts located mainly at the outer ring of the buffer
e) **Heater and buffer displacement sensors** showed manifold damages due to corrosion, mechanical deformation or bending-related blockage, yielding in a poor confidence of the sensors.
f) The custom-made **crack meter** failed quite soon due to the complete flooding and damage of the associated electronics.

Table 1. Summary of sensor´s failure causes (FEBEX final dismantling)

Sensor	Retrieved	Out of Order	Causes			
			Saturated	Flooded	Mechanical	B. Cable
Temperature (bentonite)	62	15			15	
Temperature (heater)	18	2			2	
Humidity Capacitive	52	46	32	11		3
Humidity Psychrometer	24	19	8			11
Humidity TDR	10	3			1	2
Total Pressure Vibrating Wire	6	3			3	
Total Pressure Piezoresistive	10	7		2	5	
Pore Pressure Vibrating Wire	28	11				11
Displacement Heater Vib. Wire	7	6			6	
Displacement Blocks Vib. Wire	4	3			3	
Crack meter	3	3		3		
Displacement of plug LVDT	4	0				
Total	**228**	**118**	**40**	**16**	**35**	**27**
%	**100,00%**	**51,75%**	**33,90%**	**13,56%**	**29,66%**	**22,88%**

4. Lessons learned from the FEBEX

Although there were initial doubts about the durability of some sensors, the performance of the installed sensors was good and significantly better than initially expected, providing valuable information about the THM parameters for more than 18 years. This was largely achieved by the use of sensors with a high TRL or different sensors for the same parameter when the TRL was not high enough, and passive measuring methods (as the vibrating wire technique) were demonstrated to be the best choice. For future usage, cables, if they cannot be avoided (i.e. by using wireless devices), should be routed to provide flexibility when differential movements appear (predominantly in buffer block assemblies). A major weakness in FEBEX was the sensor bodies, which going forward should not be too long in order to minimise mechanical deformations.

Due to FEBEX dismantling, significant information was obtained about the real status of the sensors after more than 18 years of “in situ” operation, in conditions similar to those of an HLW repository except for radiation. The re-calibration results for the surviving sensors indicated that their accuracy remained rather unchanged; they showed negligible or very low drift and confirmed that the obtained data were trustworthy. Therefore, confidence in the recorded data has increased significantly.

Lessons learnt from FEBEX were already taken into consideration for monitoring several large experiments afterwards, for instance EB (Engineered Barrier Emplacement Experiment), VE Ventilation Test Experiment) or HE-E (In-situ heater test) in Mont Terri (Switzerland), GMT (Gas Migration in EBS and Geosphere) and TEM (Test and Evaluation of Monitoring Systems) in GTS (Switzerland), or BPT (Backfill and Plug Test) and Prototype in Äspö (Sweden). Some examples are the wide use of thermocouples, vibrating wire sensors and capacitive-type humidity sensors, the better protection of psychrometers, or the introduction of alternative sensors for measuring buffer humidity close to saturation as the FDR (Frequency Domain Reflectometry) ones.

A number of large scale in-situ buffer tests (e.g., Prototype & MPT (Multi Purpose Test), Äspö; FE (Full scale emplacement demonstration) and HE-E, Mont Terri; KEY (Slots filling experiment) and NSC (Seal Core Investigation), Bure) and mock-up tests (e.g., FEBEX-Mock-up, Ciemat) are currently running and supporting the findings of FEBEX, namely that sensor endurance can be, under certain circumstances, much longer than predicted, despite harsh environments.

Additionally, the FEBEX results will help to design future generic large scale in-situ tests (e.g., HotBENT (High Temperature Buffer Experiment) at GTS; VSEAL (Sealing solution for shafts) at Tournemire; SANDWICH (Large-scale sealing experiment) at Mont Terri) and the related monitoring system of a repository.

5. Future directions of monitoring

After FEBEX, new experiments have already started incorporating new sensing to replace or at least provide alternatives to the classical sensors. Challenges and demands on monitoring in situ experiments will derive from various fields:

- Increased temperature loading (threshold reached of current TRL of sensors)
- Potential presence of radiation
- Higher mechanical and water pressures
- Long cable routing due to real scale gallery type emplacement tests
- Combination and miniaturization of sensors
- Housing of sensors and sensor connections in unfavorable positions over long timescales
- Integration in wireless solutions or MEMs (microelectromechanical system) sensors
- Remote charging and logging in case of wireless transitions with limited experience
- Demands of monitoring chemical and gas evaluation
- Increasing of new Fiber Optics based solutions, which provide multipoint measurements and large amounts of data to be processed
- Variations in buffer type (bentonite based: pellets, blocks, mixed assemblies or bentonite/cement or cement based)
- Time: requirements and demands change over decades of monitoring and developments in WMO programs and performance assessments
- Cost optimization in experiments using as little as possible but as many as necessary sensors.
- Introduction of “Big Data” solutions to handle and manage the increasing amount of data to be gathered.
- Implementation of BIM (Building Information Modeling) as standard for future experiments construction.

Custom-made or new prototype sensors should be supported if feasible by conventional sensors/high TRL sensors in order to compare their performance and extract the right conclusions about their validity as alternative. This is the approach performed, e.g for LTRBM (Long Term Rock Buffer Monitoring) experiment in Tournemire, carried out as part on Modern2020 project.

Previous information from long-term experiments and the lessons learnt from monitoring system should serve for future design and planning of new large-scale tests. Depending on the objectives of such tests, in combination with advanced modelling (e.g., data worth analysis), the types of sensors to be used, the number, their position and range could be better selected. In this respect, any dismantling of experiments should include the careful inspection of the used sensors as did in FEBEX, even if they do not perform as successfully, and should complement the analysis of the experiment components (buffer in particular).

6. Conclusion

The FEBEX experiment is a key example of a large experiment in which the performance of monitoring sensors and the reasons for any failure were considered at the same level as other technical aspects, for example the evolution of buffer or rock properties or the performance of main components of the studied concept. The studies made with the dismantled sensors helped initially to gain confidence in the recorded data, but they will further serve to improve the sensors for future use in similar conditions too, either for new large experiments or for the future repository.

The design of future experiments should consider, at the design stage, the dismantling operation itself, to facilitate the operation and reduce the risk of damaging the samples to be taken; consideration of the monitoring sensors´ analysis is a relevant piece of information about the success and performance of the test.

The combination of sensors with high TRL of high quality and prototypes that are well designed and proposed to cover the existing gaps relating to required parameters, or to provide better alternatives for future use, is the best approach to provide sound data from the relevant processes involved and to continue increasing the monitoring capabilities in this field.

Acknowledgements

The FEBEX project was initially financed by ENRESA, Spain, later on funded by the EC and continued as FEBEXe (NAGRA, Switzerland; CIEMAT, Spain; SKB, Sweden; POSIVA, Finland; and KAERI, South Korea; from 2013). The FEBEX-DP (Dismantling Project) Consortium (with additional partners: US DOE/LBNL, United States of America; Obayashi Corp., Japan; ANDRA, France; BGR, Germany; RWM, United Kingdom and SURAO, Czech Republic) financed the dismantling operation, onsite determinations in 2015 and significantly the laboratory program.

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Lessons learned after more than 7 years of monitoring the Full-Scale Emplacement Experiment at the Mont Terri URL

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1. Summary

Besides the demonstration aspects, the Full-Scale Emplacement experiment at the Mont Terri Rock Laboratory is a long-term heating experiment with the aim of investigating thermo-hydro-mechanical coupled effects on the Opalinus Clay host rock. The first sensors were installed in boreholes in 2011 before the start of construction of the 50 m long FE tunnel. Three full-scale heaters were emplaced on bentonite blocks and backfilled with a granulated bentonite mixture. The experimental setup was heavily instrumented with various types of sensors, particularly also fibre-optic systems. The instrumentation is complemented by geophysical measurements and repeated sampling and analysis of gases and isotopes in the backfilled tunnel. The heating phase started in 2014 and will continue for at least 10–15 years. The monitoring environment is challenging, with temperatures of up to 130–150°C at the heater surface. To date, the overall degree of sensor failure is low, especially with regard to fibre-optic and point temperature sensors. The sensor density is very high, allowing sensor performance and reliability to be compared. A data management system was developed which collects more than one million measurements per day. This experiment offers a great opportunity to gather experience related to long-term monitoring under repository-like conditions. With regard to the monitoring technology, the technical readiness level of the Full-Scale Emplacement experiment was estimated to be 5. The lessons learned will be important for the monitoring concept of a future repository.

2. Experimental setup

The Full-Scale Emplacement (FE) experiment was implemented to investigate repository-induced thermo-hydro-mechanical (THM) coupled effects on the Opalinus Clay host rock at full scale and to demonstrate as realistically as possible the construction, waste emplacement and backfilling processes for a spent fuel / high-level waste disposal tunnel according to the Swiss repository concept [1].

Besides these demonstration aspects, which Nagra handled within the framework of the European Community (EC) project “Large Underground COncept Experiments” (LUCOEX) [2], the FE experiment is mainly a long-term heating experiment. The waste canisters and their heat output are simulated by cylindrical heaters with similar dimensions (4.60 m length, 1.05 m diameter) and a comparable heat output (currently 1,350 W for each heater). The heaters are placed centrally along a tunnel (approx. 2.5 – 2.7 m diameter, 50 m length) in the Mont Terri Rock Laboratory in Switzerland [3]. Within the tunnel, the three heaters were placed on bentonite blocks (Figure 1) and the space between the heaters and the tunnel wall was filled with a highly compacted granulated bentonite mixture (GBM). The heating phase of the FE experiment started in December 2014.

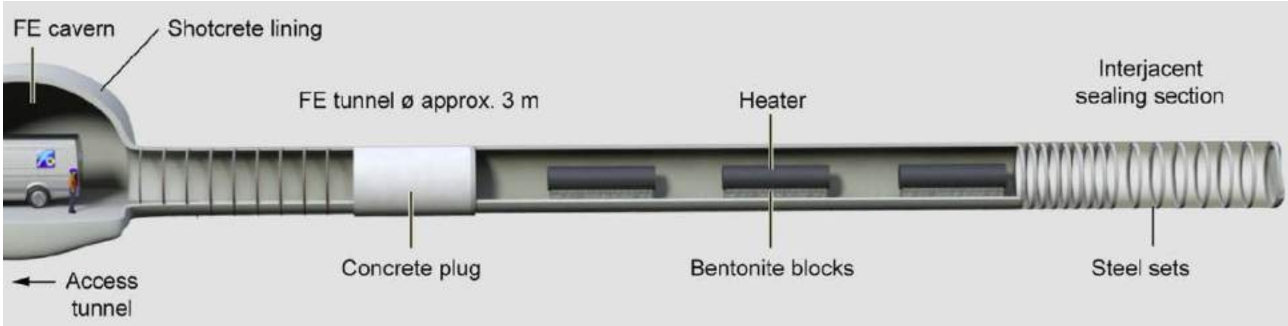

Figure 1: Visualisation of the general layout of the FE experiment and the 50 m long FE tunnel at the Mont Terri Rock Laboratory; sensors, bentonite backfill and rock bolts are not shown. Figure taken from [1].

3. Instrumentation

The entire experiment implementation, as well as the post-closure THM evolution of this full-scale heater experiment, is monitored using several hundred sensors (Table 1). The collected data are used primarily for the validation and calibration of existing coupled THM models. The main monitored parameters are temperature, pressure, deformation and humidity/water content.

The sensors are distributed in boreholes, in the tunnel lining, in the bentonite buffer and on the heaters. Their installation was performed in phases (Figure 2) in accordance with the construction, emplacement, backfilling and closure activities. For baseline monitoring, the first sensors were installed in boreholes in the rock mass in the tunnel far- and near-field, before the start of the construction work for the FE tunnel.

Because most of the sensors are installed in the backfilled FE tunnel, they cannot be replaced in the case of malfunctioning or failure. Therefore, careful selection of monitoring systems including sensors, housing materials and cables was necessary. Details about the sensors and their installation can be found in [1].

The monitoring environment of the FE experiment is challenging because a long observation period of at least 10–15 years is envisaged and because high temperatures of up to 130–150 °C at the heater surface and up to 60–80 °C at the tunnel wall are expected. In addition, the porewater with a salinity or rather conductivity of more than 35 mS/cm[5] may enhance corrosion of metallic sensor components in the rock and in the humid (partially water-saturated) bentonite buffer close to the tunnel wall.

Due to these conditions, in addition to standard state-of-the-art sensors, fibre-optic (FO) sensors, as well as modified and prototype measurement systems, were also installed. The prototype systems were designed to be more corrosion-resistant. They were also constructed to be less heat-conductive, reducing the impact of the instrumentation on the experiment evolution. Information about FO sensors can be found in [4].

First results of the repeated sampling and analysis of gases and isotopes from within the backfilled and heated FE tunnel can be found in [5].

Table 1: Approximate number of sensors installed as part of the FE experiment during the different instrumentation phases. Table taken from [1].

[5] Milli-Siemens per centimetre

Instrumentation	Phase 1 (tunnel far-field)	Phase 2 (tunnel near-field)	Phase 3 (bentonite buffer)	Total
Temperature	480	140	580	1200
RH, TDR, etc.	0	54	119	173
Deformation	80	44	23	147
Total pressure	36	6	30	72
Pore-water pressure	38	27	0	65
Gas composition	0	0	20	20
Total	634	271	772	1677

Not included in this table are the thermal conductivity sensors, the geophysical sensors, the gas sampling lines, the material samples, the plug instrumentation and some fibre-optic systems

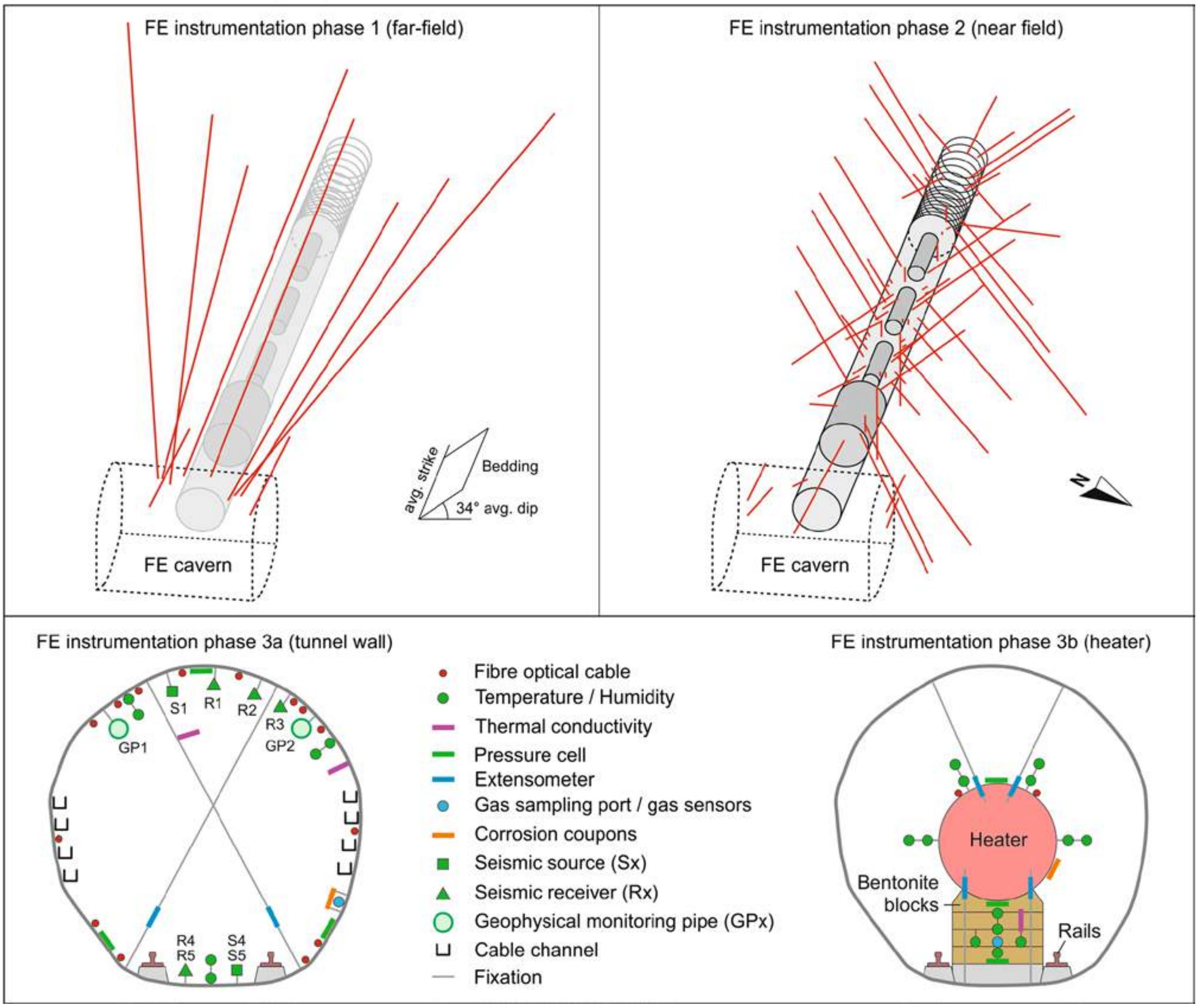

Figure 2: Overview showing the main instrumentation phases of the FE experiment. The graphics at the top indicate the borehole arrangements around the 50 m long FE tunnel. The graphics at the bottom represent strongly simplified overviews of the many different instrumentation cross-sections within the approx. 2.5 – 2.7 m diameter FE tunnel. Figure taken from [1].

4. Geophysical monitoring

Geophysical methods were selected to monitor changes in the bentonite buffer in a quantitative manner with minimal adverse effects on the backfilling procedure or the THM evolution. For this purpose, two gas-tight pipes were installed approximately 1.7 m apart in the roof of the FE tunnel to (1) perform single-hole measurements and (2) obtain tomographic images of the backfill material from crosshole measurements. The single-hole measurements include ground-penetrating radar (GPR) logs, gamma-gamma density and neutron porosity logs. GPR and seismic crosshole measurements were performed between the two pipes. Between February 2015 and May 2018, seven geophysical measurement campaigns were carried out. Finally, a micro-acoustic system was installed in the GBM for semi-continuous seismic recordings.

The gamma-gamma density and neutron porosity logs appeared to be highly repeatable, the latter indicating modest saturation changes between successive experiments. The GPR single-hole data showed considerable variations between experiments, which can be attributed to changes in temperature and moisture content. Joint inversions of the crosshole GPR travel time and amplitude data allowed reliable and consistent images of the electromagnetic properties to be determined.

The initially poor quality of the seismic crosshole data – which was attributed to poor coupling of the measurement pipe to the relatively dry backfill material – improved during the course of the experiment. Tomographic inversions of these data sets showed progressively increasing velocities, likely caused by compaction and swelling of the bentonite backfill. Further research is dedicated to the conversion of geophysical parameters into e.g. temperature and water content / saturation. Once such relationships are established, geophysical data can be used for extrapolating the in-situ measurements of temperature and water content sensors to larger areas.

5. Data management

The implementation of the FE experiment has been monitored in detail since 2011. The FE information system (FEIS) [6] was developed to collect and store all data acquired from the different sensor suppliers and installation companies under one roof. The FEIS allows all data sets to be easily accessed and compared, and the quality of the recorded measurements to be controlled. For this, an open-source object-relational PostgreSQL database is used together with PostGIS and a statistical analysis tool written with the programming language R. Currently the FEIS collects more than one million measurements per day.

In an experiment, a database such as the FEIS should be readily available from the first sensor installation in order to reduce potential errors in sensor naming or missing sensor metadata (e.g. coordinates). Requirements about the data format and the data flow have to be defined and communicated to all involved parties as early as possible. A well planned and executed, and therefore reliably functioning, database facilitates data completeness from the first until the last day of monitoring. Even after the successful implementation of the FEIS, much work is still required to maintain a permanent data flow from all suppliers and to keep the database in an ordered state. Further developments of the FEIS, e.g. towards a mobile version, potentially combined with an augmented reality display of results when visiting on-site, are currently under discussion.

6. Sensor failures

All relevant measurements, including sensor failures, in the FE experiment up to end of August 2018 can be found in [7]. To date, the overall degree of sensor failure is low, particularly with regard to FO sensors [4] and point temperature sensors. Generally, higher failure rates occur for sensors close to the heaters compared to those on the tunnel wall or in the rock mass. Most relative humidity (RH) sensors and total pressure (TP) cells around the heaters either currently provide unreliable data or have failed in the meantime. On the other hand, more than 80 % of the point temperature sensors on and around the heaters are still operational and more than 90 % of the point temperature sensors on the tunnel wall and in the rock mass are still operational.

Table 2: Statistics for functioning sensors in the FE experiment according to [7]

Sensor information			Sensors installed	Sensors in operation	Sensors not working	% sensors in operation	Overall % of operation
Tunnel wall	Temperature	PT1000	53	53	0	100	93
		Thermocouples in RH sensors	47	46	1	98	
		Thermocouples in/next pressure sensors	27	19	8	70	
		Thermistor FDR	9	8	1	89	
	Humidity / water content	Capacitive RH sensors	41	41	0	100	98
		Monolithic RH sensors	6	5	1	83	
		FDR	9	9	0	100	
	Total pressure	Stainless steel	8	8	0	100	89
		Titanium	10	8	2	80	
	Gas sensors	Oxygen sensors	6	6	0	100	100
	Therm. conduct.	KD2 TR1 probes	15	14	1	93	93
Rock mass (Opalinus Clay)	Temperature	Temperature chains	14	14	0	100	90
		Separate PT1000	12	11	1	91	
		Thermocouples in pressure sensors	55	49	6	89	
		Thermocouples in RH sensors	17	7	10	47	
		Thermocouples in extensometers	30	26	4	87	
		Thermocouples in inclinometers	80	80	0	100	
	Pressure	Interval pressure	68	65	3	96	97
		Pore pressure	46	46	0	100	
	Humidity / water content	Capacitive RH sensors	12	6	6	50	40
		Monolithic RH sensors	3	0	3	0	
	Displacement	Extensometer	44	44	0	100	100
		Inclinometers	80	80	0	100	100
In/on/around heaters	Temperature	TERMYA Typ T	127	120	7	94	83
		Thermocouples in RH sensors	49	26	23	53	
		Thermocouples in/next pressure sensors	3	3	0	100	
	Humidity / water content	High T capacitive RH sensors	25	8	17	32	33
		Low T capacitive RH sensors	24	8	16	33	
	Total pressure	High T TP sensors	6	0	6	0	11
		Low T TP sensors	3	1	2	33	
	Displacement	LVDT sensors	19	15	4	79	79

7. Technical readiness level

In order to demonstrate the contribution made by the FE experiment to the readiness of Nagra to implement a repository, a technical readiness level (TRL) assessment was conducted in [8] for different components of the experiment. According to the scale proposed by the EC [9], TRLs are scored on a scale of 1-9, where a score of 1 is the lowest level of readiness and a score of 9 represents a technology that has been proven through operations.

The FE experiment is being carried out in the Mont Terri Rock Laboratory, which is not located in a candidate siting region for a repository. In addition, the FE experiment is being used to develop requirements on the design [8]. For these reasons, and in accordance with the generic definitions of TRL (see Table 3), it was decided that the maximum TRL score assigned in this assessment is 5.

Regarding the monitoring technology, the TRL of the FE experiment was estimated to be 5, because the experiment has extended the options available for monitoring the THM evolution of the engineered barrier system (EBS) and the host rock, for example by gaining experience and improving FO sensors and dielectric probes for GBM density measurements as described in [10] and [11].

In the coming years to decades, Nagra will have the time and opportunity to increase the TRL for all relevant aspects of a repository. The way forward is described in Nagra's Research, Development and Demonstration (RD&D) Plan [12].

Table 3: Definition of TRL level 5 according to [9]

• Level	• Description	• Definition
• TRL 5	• Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).	• At TRL 5, thorough testing of the candidate materials or prototype machinery is undertaken in a relevant environment (e.g. a URL in a representative geological environment) in order to develop detailed requirements and understanding of how the individual components perform in an integrated setting.

8. Discussion

The initial design of the monitoring programme for the FE experiment was based on experience from previous and similar underground experiments and their findings regarding long-term sensor behaviour. Valuable information also came from exchanges with the scientific community and sister organisations and from EC-supported research programmes. Before implementation, THM scoping calculations were performed to optimise the spatial distribution of sensors and to specify their measurement range and operating conditions.

To date, the monitoring programme for the FE experiment has been successful, as it demonstrably allows monitoring of the THM evolution of the EBS and the host rock. Monitoring began with measurements of the baseline conditions prior to construction and continued through all experimental phases. In terms of spatial discretisation, the heating phase is monitored using a series of similarly instrumented cross-sections within the FE tunnel, complemented by measurements in boreholes drilled into the host rock. This setup allows not only a comparison of the THM response for each of the three heaters, but also a comparison of sensor performance and reliability.

Together with the FO systems, the sensor density in the FE experiment is large enough to plot measurement results in unaliased cross- and longitudinal sections, as well as on 3D surfaces such as the tunnel wall for any point in time.

The FE experiment offers a great opportunity to identify issues, to implement developments and to gather experience related to long-term monitoring under repository-like conditions. It also allows the evaluation and comparison of different sensor types and monitoring techniques in a more general sense. In any case, the lessons learned from the FE experiment will be important for the monitoring concept of the future Swiss repository.

Acknowledgements

The FE experiment was implemented at the Mont Terri Rock Laboratory, which is operated by swisstopo. The initiator and lead organisation of the FE experiment is Nagra (Switzerland). We thank ANDRA (France), BGR (Germany), DOE/LBNL (USA), FANC (Belgium), GRS (Germany), NWMO (Canada) and RWM (UK) for participating in the ongoing THM monitoring of the FE(-M) experiment. We thank ANDRA (France), NWMO (Canada) and RWM (UK) for participating in the ongoing gas monitoring of the FE(-G) experiment.

The engineering and demonstration components of the FE experiment were also part of Nagra's participation in the EU project 'Large Underground COncept EXperiments' (LUCOEX); parts of the research leading to these results have therefore received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under Grant Agreement No. 269905.

Last but not least, we are grateful to Linda McKinley for improving the English of the manuscript and to Simon Norris (RWM, UK) for the constructive feedback which helped to further improve the quality of this extended abstract.

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Feedback from more than 20 years of monitoring in Andra Underground Research Laboratory

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1. Summary

The Cigéo project (Industrial Center for Geological Disposal), developed by the French National Agency for Radioactive Waste Management (Andra) aims to store the ILLW and HLW in a deep clay formation. The Cigéo project is located in the Eastern part of the Paris Basin, on the border of the Meuse and Haute-Marne departments, near the Bure Underground Research Laboratory (URL) where, for more than 20 years, Andra has been conducting research in the Callovo-Oxfordian argillaceous formation. The URL, located at a depth of 490 m, has led to scientific experiments to characterize the geological environment and the evolution of its behavior over time with regard to i) URL excavation and construction, ii) the imposition of a heat source to mimic the thermal output of waste, and iii) the behavior of engineered barrier systems (EBS) (metal, concrete, glass, bentonite…) at different spatial scales. Numerous technological demonstrations have also been conducted, to test industrial solutions to operate Cigéo.

Andra URL is currently monitored with thousands of sensors, and data has been collected since the beginning of its construction. Sensors made it possible to acquire multiple measurements (coupled THMC data). Sensors are also the subject of research and development, with the objective to qualify the sensors installed, to test in situ new sensors and data transmission systems, and to evaluate the durability and the different sensor technologies used.

The Andra URL and the collaboration with other foreign laboratories allows the development and testing of the technical means of disposal monitoring (sensors...), with a long-term objective of demonstrating the ability to monitor the operating of Cigéo as part of its reversible and progressive development over time.

2. Introduction

In the context of radioactive waste disposal, a URL is a facility in which experiments are conducted to establish and to be able to demonstrate the feasibility of constructing and operating a radioactive waste disposal facility within a geological formation. Experiments in URL meet two sets of needs:

- characterization, that is, acquiring knowledge of the geological, hydro-geological, geochemical, structural and mechanical properties of the host rock and of its response to perturbations and,
- construction and operation, that is, developing equipment to acquire know-how about the construction of all the components of a disposal facility up to its closure, and the emplacement and/or retrieval of the waste.

The development of measurement devices in Andra URL followed those of the Cigéo project (see Section 2, below) and the laboratory itself (excavation and construction phases). Today, Andra URL includes 2 access shafts and 1800 meters of drifts; 1250 wells have been drilled (including 12 km of cores available in the clay foramation), 80000 samples have been taken, and more than 70 experiments and technological tests have been conducted.

During 18 years of monitoring developments in the URL, significant progress has been made on the design and implementation of complex monitoring devices and the development of specific parameter measurements. Some measuring devices / sensors have been directly implemented in the URL, because they are already adapted to the needs and available on the market. Others have been modified with a particular attention to the technology, robustness, repeatability, resolution and complementarity sought between the sensors. Others have been developed and continue to be specifically developed in a prospective / innovative manner.

3. A monitoring stepwise development in the URL linked to Cigéo milestones

The construction of Andra URL started in 2000 and, until 2005, most of the experiments and monitoring systems were dedicated to the characterization of the geological environment and its behavior over time with regard to excavation and construction. The results obtained have confirmed that the properties of the geological environment are favorable to the implementation of deep geological disposal [1]. From 2006, while continuing the study of the geological formation, the experiments focused on the development of the first monitored demonstrators of the future Cigéo underground structure in reduced scale (sealing experiment, demonstrator of ILW and HLW cells…). Experiments were also dedicated to host rock / EBS material interactions and the mechanical damage of the Callovo-Oxfordian clay in the vicinity of underground structures and the evolution of its HM properties with time. In 2016, the knowledge acquired allowed Andra to submit the Safety Options reports (DOS) which stabilized the safety strategy and requirements, the safety methods, and design options [2, 3]. Since then, URL experiments have continued with a technological programme and R&D studies dedicated to the preparation of the licencing application and the industrial pilot phase [4]. The monitoring strategy is one of the priority objectives.

The development and the implementation of the monitoring devices that have been carried out make it possible to test and implement various means / devices for measurements of all types of parameters (thermal, hydraulic, mechanical, chemical and radiological) and for different environments (rock, concrete, reworked clay materials, metals ...) to meet the following scientific and technological objectives:

- To monitor seismicity around the URL and characterize site effects;
- To specify the geological, hydrogeological and geochemical characteristics and the thermo-hydro-mechanical parameters of the Callovo-Oxfordian clay, a pillar of the long-term safety of Cigéo;
- To characterize the damage of the Callovo-Oxfordian clay in the vicinity of underground structures as caused by their excavation, and by the evolution of the Callovo-Oxfordian clay properties (mainly the hydraulic conductvity) over time, in particular according to the type of lining/support;
- To evaluate the constructability of underground structures, particularly disposal cells and closure structures, in agreement with Cigéo's design;
- To evaluate the mechanical behavior of the structures after excavation according to the type of support and / or the lining in relation to the direction of the major horizontal stress;
- To evaluate the physicochemical processes within the Callovo-Oxfordian clay that could be induced by ventilation, exothermic wastes, gas production, and different EBS materials (steel, concrete, glass ...), including evaluation of their sustainability;
- To develop / test integrated devices for monitoring Cigéo underground structures, including drifts, ILW and HLW disposal cells.

4. Monitoring of the geological environment

The first experiments conducted at the Andra URL aimed to confirm the basic characteristics of the Callovo-Oxfordian clay, in particular its ability to contain radionuclides. Experiments and monitoring systems concerned the study of the composition of the water contained in the clay rock, the permeability of the rock and diffusive properties.
On a larger scale, and since 2003, Andra has installed and developed on the surface and deep in the URL a seismological monitoring network from accelerometric and seismometric broadband stations. The objective is to know, during the occurrence of an earthquake, the amplification or attenuation of seismic waves as a function of the depth in the specific geological context of the site. The parallel measurement of the same earthquake at different depths makes it possible to identify the effect of the geological structure and the structure by comparative analysis. Currently, 6 stations are installed on the laboratory: two stations on the surface, two stations at -490m depth, a station at -445m and a last station in a shaft at -254m.

5. Monitoring of thermal phenomena

Various temperature sensors were used to study the evolution of the characteristics of the rock in response to an increase of temperature (platinum probes, and optical fibers interrogated in "Raman"). The results obtained in the URL have shown that a "mix" of technology makes it possible to respond effectively to the need to know the temperature at many points in the URL, in the concrete structures and near the cells. Platinum probes are used for reference and give readings accruate to hundredths of a degree in a few locations. Optical fibers, associated with platinum probes, provide measurements along its cable with a resolution of one-tenth of a degree. This device can operate over several hundred meters. The accelerated ageing tests of these two types of sensor are in progress.

6. Monitoring of hydraulic phenomena

The monitoring of the water pressures in the rock is carried out with the installation of piezoresistive pressure sensor in saturated boreholes. The distribution of these measurements around the drifts makes it possible to describe the shape and the evolution of the zones of hydraulic gradient induced by the creation of the structures and their ventilation.
Various types of water content sensors have been implemented in the URL in concrete and bentonite and all are functional. Sensor types are represented by (i) capacitive moisture sensors that monitor relative humidity over a wide range of values (up to 95- 99%), (ii) psychrometers that complement capacitance measurements for high humidity values of (> 95%) and (iii) antennae probes with two or three stems interrogated in the time or frequency domain (TDR or FDR probes), which make it possible to derive the water content. All URL sensors, installed in the bentonite and the concrete (especially in the sealing experiment), are functional.

7. Monitoring of mechanical phenomena

Strain/stress measurement is commonly used in civil engineering to track the deformations of concrete structures. They allow measurement in a measuring range of 3×10^{-3} m/m with an accuracy of about 1 µm/m. More than 2100 vibrating wire deformation sensors were used at the URL. These sensors are installed before projection or concrete pouring, or on the frames of precast concrete arch segments. Most of these sensors are emplaced in such a way as to be able to follow orthoradial strains. In addition, Andra is evaluating the potential of newer techniques, such as optical fibers to monitor mechanical phenomena [5]. Some systems using this technology have the advantage of providing "fully continuous" distributed measurements over several kilometers. Such systems have been implemented in the laboratory, in concrete liners, in boreholes and on the upper surface and lower surface of the metallic liners of an HLW cell demonstrator. In collaboration with foreign counterparts, Andra has also implemented optical fiber sensors in clay (HADES in Belgium) and in bentonite (FE

Experiment in Switzerland). Strain is obtained with a sensitivity of 30 µm / m; such results are in very good agreement with the measurements acquired by the spot measurement sensors placed nearby. However, optical fibers have highlighted the inhomogeneities within materials or structures, which reinforces the necessary interest in distributed measurement technologies.
Stress measurements are tested with sensing plates. This technology was developed in the 1980s for biomedical applications and consists of a matrix network of ultra-thin resistive sensors (of the order of 0.1 mm) embedded between two polymer parts. The main advantage is to have access to the distribution of the stresses / forces on a given section (with a resolution of the order of a cm^2), which makes it possible to measure the contact forces for example between the rock and the liner or to measure orthoradial stress gradients in a concrete liner. The adaptability of this technology to the concrete and steel structure have been tested in Andra URL since 2013.

8. Monitoring of Chemical phenomena

The chemical and isotopic composition of the water produced by the rock is followed most often by off-site analyses of samples taken in the absence of an atmosphere. In the URL, sensors for physico-chemical measurements allow the monitoring of the pH, the redox potential and the electrical conductivity of the rock water.
For monitoring of the atmosphere evolution in the HLW disposal cells, a micro-gas chromatographic measuring device is used for H_2, O_2, CO_2 and CH_4 monitoring. A gas circulation module connected to lines positioned at different locations within the cell allows the gas to be withdrawn. The different constituents of the gas are separated there, and then the processing of the signal recorded by a thermal conductivity detector (TCD) makes it possible to quantify them. The gases can be monitored for contents ranging from a few tens of ppm to several tens of % vol.

9. Monitoring programme of underground structure demonstrators

In support of the definition of Cigéo's monitoring programme, Andra set itself the objective of testing different monitoring technologies and comparing them in such a way as to provide all the elements of a convincing choice for the licencing application, and then for the pilot industrial phase. To do this, each system / monitoring device envisaged is tested in a controlled environment before being tested in an environment close to that of Cigéo. These last tests concern either a sensor / measuring device alone or fitted into the overall framework of a demonstrator.

These demonstrators dedicated to monitoring mainly make it possible to: (i) check the behavior of the sensors over time, (ii) test different technologies and compare them with each other and with the measurements in a controlled environment, (iii) validate the implementation protocols and (iv) contribute to the evaluation of costs and interfacing with overall operations.

9.1. The ILLW disposal cell

The definition of demonstration tests dedicated to the monitoring of drifts or the ILW disposal cell with a concrete lining was carried out in the framework of two experiments. The main objective is to study the mechanical strain.

These demonstrators, with a standard selection of thermo-hydro-mechanical measurements (THM), allowed the verification of the implementation of sensors, both already tested and innovative, in the rock and the concrete liners in situ (Optical Fibers), interstitial pressure cells, vibrating wire extensometer ...). They allowed, for drifts excavated according to major or minor horizontal constraints, the validation of the ability to implement instrumentation for THM monitoring in rock and concrete liners in situ. This instrumentation provides exhaustive information on the rock and the liners, to understand their behavior. The good survival rate of the sensors reinforces confidence in the technologies chosen. More particularly, the demonstrators allowed the validation of the devices to follow the temperature in drilling and in the concrete liner by local (platinum probe) and distributed sensors (OF), and the orthoradial deformation in the concrete coating by local (ECV) and distributed (OF) sensors.

9.2. The HLW disposal cell

Since 2009, an important programme of HLW disposal cell demonstrators has been implemented at the URL, most of them equipped with sensors dedicated to monitoring. Some have been the subject of durability studies to the environmental conditions of the HLW cell. In the field of surveillance, the experiments that have been carried out and those to come allow the development of devices:

- To evaluate the mechanical strength of the liner by characterizing the maximum amplitude of deformation (increase and decrease convergence)ovalization and the time required to reach the steady state (AHA1604, ALC1605 demonstrators);
- To evaluate the impact of a thermal load (ALC1604, ALC1605 demonstrators);
- To evaluate the kinetics of corrosion;
- To follow the evolution of the atomosphere in the cell (Cf. Chapter 7) and the gas exchanges between the drifts and the HLW disposal cell;

R&D development is continuing on some technologies (OF, electrochemical probes for corrosion monitoring, Lidar Raman, robots, etc.) to reach a demonstration level in a representative and operational environment of cell monitoring.

10. A robust scientific data management system

With the implementation of monitoring systems, Andra has developed a management and information system for georeferenced scientific data. This system gathers in a single tool all the acquired data, to ensure in the long term the traceability, the capitalization and the provision of the data and to homogenize the working method between the various stakeholders. Their number, their diverse nature and the large areas of space and time of their acquisition characterize these scientific data.

The data acquisition and management system (SAGD) enables the acquisition and consultation of measurements from sensors installed on surface and in the URL. The objectives of SAGD are:

- To provide in real time and on a single system all the experimental data currently being acquired on site;
- To visualize recorded data over specified time windows and measurement steps;
- To allow remote control of experiments;
- To ensure traceability of all recorded information;
- To ensure the archiving of information in a database.

The data are acquired, stored and managed on specific software (Geoscope). This software, the result of a continuous computer development for more than 15 years, manages and stores information currently from around 200 acquisition centers and more 12000 sensors (including more than 10000 installed in the URL). This represents more than 1.6 million values / day recorded on average and more than 3 billion values already recorded.

If the management and information system of scientific data was initially aimed at knowledge, it is also today a tool prefiguring the one that will be implemented in Cigéo.

11. Conclusion

Since the first experiments realized in the URL in 2000, significant progress has been made concerning the design and implementation of complex monitoring devices. These concern the development of specific measurement instruments, the installation of several types of sensors in structures and boreholes taking into acount the operational constraints (management of cables, available space, co-activity...) without forgetting the system of continuous monitoring of sensor functionality and the recording of data via specific scientific databases. Today, most tested devices are functional with an average failure rate of 8%. This feedback is well recognized and shared with French and European actors.

Such feedback is also largely driven by Andra's participation in the Mont-Terri Consortium (since 1995), in foreign laboratories (HADES in Belgium, Grimsel Test Site in Switzerland, Aspö in Sweden ...) and the information shared within the IAEA's URF network.

Development and optimization work on sensors continues in a prospective / innovative manner, to have in the long term a monitoring system adapted to the constraints of Cigéo. Progress is also being made in terms of measurement resolution, energy usage of monitoring equipment, wireless transmissions, constituent materials, drones and robots.

The extension of Andra URL in the next 4 years and the planned R&D and technological testing programme, partially focused to developing and optimizing the monitoring devices for the various demonstrators (sealing demonstrators, ILW cells and HLW disposal cells) will allow the provision of all the elements of a convincing case for both the licencing application and aubsequently for the pilot industrial phase of Cigéo.

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Rock Mechanics Monitoring At Olkiluoto, Finland. Case Study: Monitoring Strategy Of Repository Temperature Evolution

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1. Summary

Since 1995, Posiva Oy has been responsible for the final disposal of spent nuclear fuel of its owner companies Teollisuuden Voima Oy and Fortum Heat and Power Oyj. Excavation of an underground rock characterisation laboratory ONKALO© was commenced in the repository site at Olkiluoto Island, in western Finland. The construction of the final disposal facility started in 2017 by expanding ONKALO facility. The final disposal concept, applied by Posiva, is based on the KBS-3V multi-barrier concept developed by the Swedish Nuclear Waste Management Company (SKB). The first canisters are planned to be disposed underground during the 2020's.
The final disposal activity needs a long-term monitoring programme in order to assure that the selected site retains its suitable properties over long timespan for final disposal of spent nuclear fuel. The monitoring programme should primarily rely on a strategy in order to select the relevant processes to be monitored, and to develop a monitoring network layout of measurement devices to sufficiently capture the relevant processes. At Olkiluoto, a temperature monitoring strategy has been established based on predicted thermal load occurring due to excess heat flow from the deposited canisters during operational phase of the repository facility. The monitoring network layout takes into account the locations of different temperature magnitudes (minimum and maximum) and the predicted maximal extent of the thermal load.

2. Introduction

2.1. Background for monitoring programme at Olkiluoto

Posiva Oy is responsible for the final disposal of spent nuclear fuel of its owner companies Teollisuuden Voima Oy (TVO) and Fortum Heat and Power Oyj. The final disposal approach is based on a multi-barrier KBS-3 concept, developed initially by the Swedish Nuclear Waste Management Company (SKB). According to the KBS-3 concept (both KBS-3V as vertically disposed and KBS-3H as horizontal), the spent nuclear fuel assemblies are deposited in excavated tunnels in a selected geological domain of crystalline rock at 400-500 m depth, and further protected by several natural and engineered barriers (EBS), such as the copper canister, bentonite clay barrier and natural bedrock (Fig. 1). Between 1983 and 2000, TVO proceeded to preliminary and detailed site investigations in order to select the most suitable site for the final repository of the spent nuclear fuel. In 2001, the Finnish Parliament approved the Government's decision-in-principle permitting the final repository site to be located at Olkiluoto and the excavation of an underground rock characterization laboratory named ONKALO© was started in 2004 at Olkiluoto. In 2015, Posiva was granted a construction license for the repository on the Olkiluoto site. Olkiluoto is situated in south-western Finland, where the bedrock consisting of stable crystalline rock conditions being part of the Fenno-Scandian shield (Fig. 2).

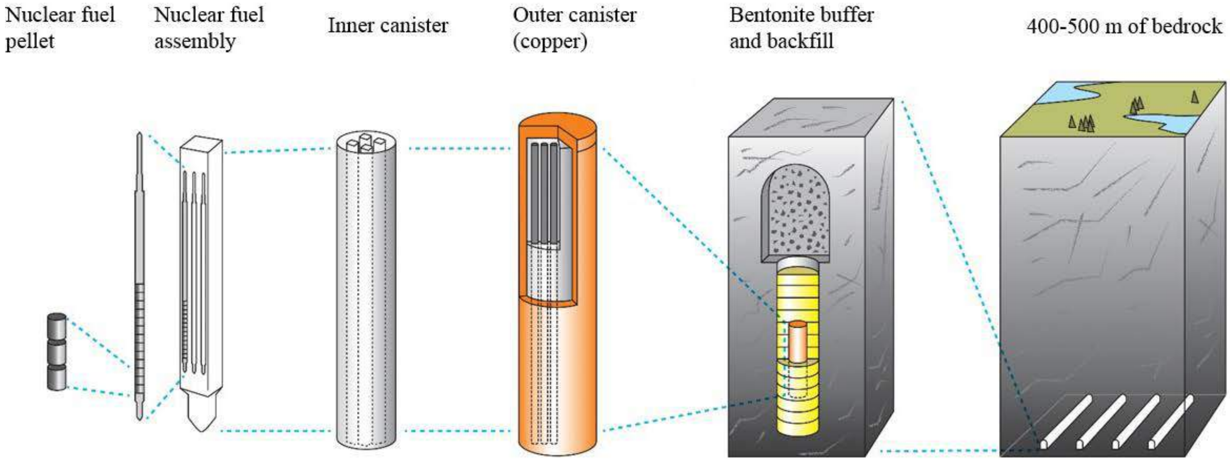

Figure 28: Illustration of the KBS-3V multi barrier concept where the spent nuclear fuel is disposed in a geological final disposal facility. This concept is executed by Posiva at Olkiluoto in Finland.

Since the disposal site was selected to be located at Olkiluoto, Posiva commenced a monitoring program for the Olkiluoto site several years ahead prior to the construction of ONKALO© facility. The monitoring program consisted of both surface and underground monitoring systems, utilising mainly deep drillholes but also tunnel spaces after the ONKALO excavation began in 2004. The monitoring program aimed at gathering sufficient data set for the characterization of the undisturbed conditions of the repository site, before the starting of the construction activities on the site. This data set of the undisturbed state could later on be compared against the disturbances observed in the monitored data during ONKALO and the repository construction, in order to assess the impact of repository construction disturbances. The commenced monitoring program of Olkiluoto consists of multiple different scientific disciplines such as observations of geochemical, hydrogeological, environmental and rock mechanics processes. In the future when the repository is operating, the monitoring programme will also containthe monitoring of the EBS components [1].

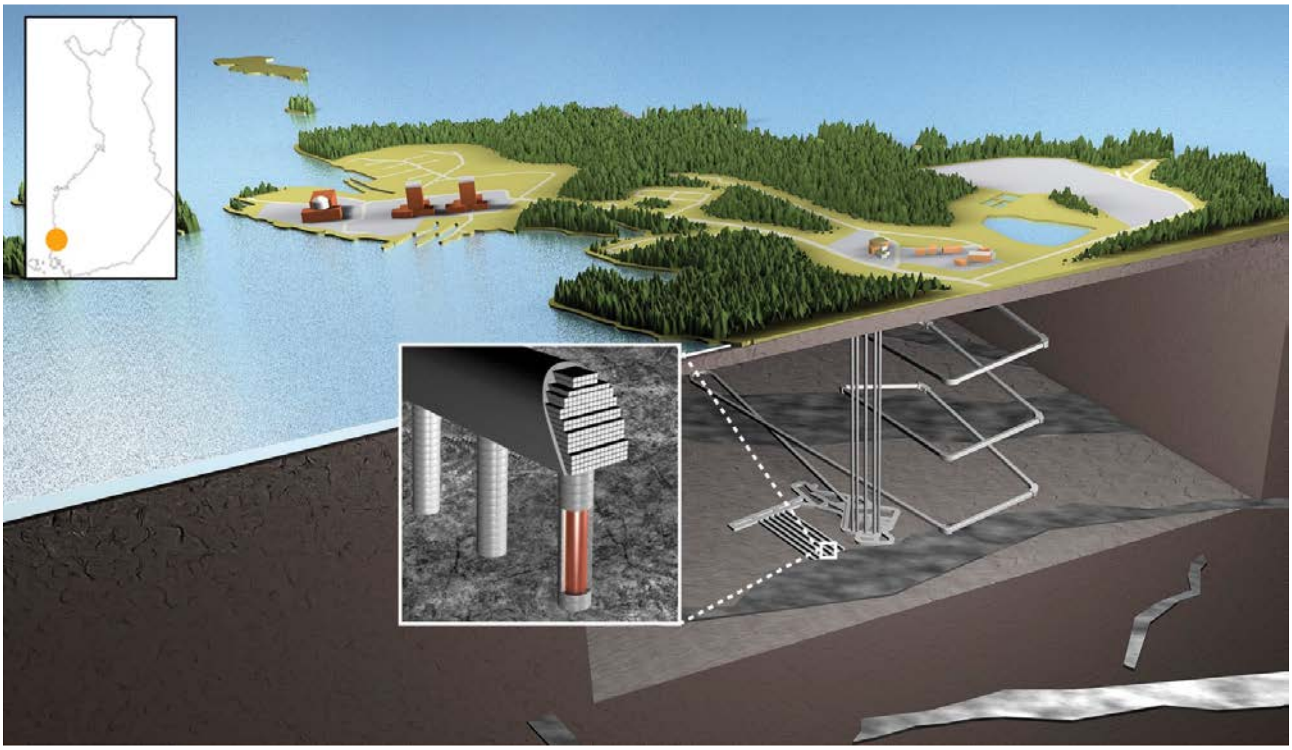

Figure 29: Conceptual model of the final disposal facility at Olkiluoto, Eurajoki (situated in south-western Finland).

2.2. Rock mechanics monitoring network at Olkiluoto

The purpose of rock mechanics part of the Olkiluoto monitoring program is to verify that Posivas development of the repository spaces is influencing the surrounding bedrock conditions only to a minimum but an acceptable degree, and does not cause irreversible changes in the areal stability. Currently, perturbations in the stable bedrock conditions are imposed by the excavation of the ONKALO facility and the regional tectonics (e.g. post glacial isostatic rebound). However, during the operational phase of the repository, the heat flow caused by the radioactive decay of the deposited spent nuclear fuel canisters will cause perturbations in the bedrock stability at Olkiluoto due to the thermal expansion of the rock mass.

Data collected as part of the monitoring program has been used during the Olkiluoto site characterization [2], while also determining the baseline properties of the Olkiluoto site before the repository operation in order to compare eventual anomalies to this baseline. The rock mechanics part of the monitoring program acts also as part of the safety guard principle, such as observing that no undocumented spaces are excavated or that no unplanned access tunnels to the repository can be excavated from outside. Since 1990's, Posiva have installed and expanded its rock mechanics monitoring network on the surroundings of the Olkiluoto Island and on the underdoing spaces associated with ONKALO facility. Currently, the following processes are monitored as part of the rock mechanics monitoring network. Tectonic movements are monitored by GPS- and microseismic stations, in addition to precise levelling measurement campaigns. The baseline temperature of the bedrock, tunnel displacement and associated stability observations, and displacement of various deformation zones are monitored by extensometers and thermistors installed in drillholes in addition to visual observations gathered during construction activities [3]. The current extent of rock mechanics monitoring network of Olkiluoto site is presented in Fig. 3.

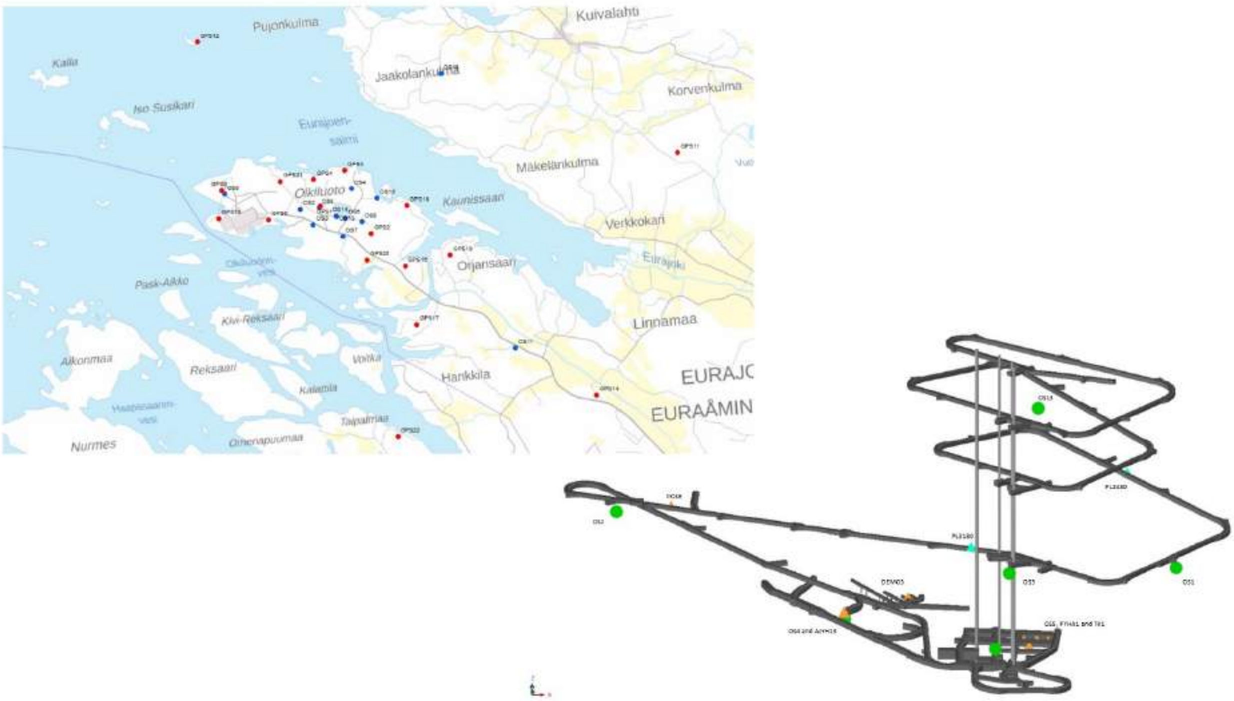

Figure 30: Rock mechanics monitoring network in Olkiluoto in 2018 at surface (left image) and underground (right image). The network is composed by GPS stations (red points), microseismic stations (blue on surface and green underground), extensometers (orange and turquoise triangles). Only precise levelling bolts are missing from the images.

2.3.Monitoring strategy and network layout

The monitoring programme can be roughly divided into three phases along with the repository lifespan: monitoring during site characterization, monitoring during the operation of the repository facility, and monitoring after repository closure. Each of the phases is associated with a unique monitoring strategy, as the objectives of the different phases vary. For example, the aim of the monitoring during site characterization is to establish a sufficiently accurate baseline for understanding the undisturbed site conditions. The monitoring strategy, developed for each phase separately, is necessary for deciding the layout and extent of monitoring network for each scientific discipline, so that the objectives of each monitoring phase can be fulfilled. In the next chapter, monitoring strategy of temperature evolution during repository operation is used as an example to present a case study, when monitoring of a process is advancing from establishing an undisturbed baseline condition towards monitoring a transient disturbance caused by repository operation.

3. Case Study: Monitoring strategy of repository temperature evolution

3.1. Thermal model of Olkiluoto

Radioactive decay of the highly active spent nuclear fuel assemblies will continue throughout the entire operational period of the repository lifespan [4]. The heat generated by the deposited canister will increase the temperature of the bedrock, while also inducing thermal stresses in the rock mass. Therefore, the thermal load of the canisters can have impact on the stability repository facilities, such as deposition tunnels and holes. In addition, the safety functions of EBS barriers can be affected with increasing temperatures, along with ageing of tunnel reinforcements.

In order to establish a quantitative prediction of the repository temperature evolution, a thermo-mechanical model of Olkiluoto was developed by Clay Technology AB during 2018. The thermo-mechanical model of Olkiluoto takes into account the estimated canister deposition sequence, in addition to the heat output of different fuel types and current layout protocols applicable to Olkiluoto repository [5]. The objective of the thermo-mechanical model is to highlight the areas where the maximum temperature is reached, and establish an approximation of the timing when this temperature maxima is reached given the abovementioned factors (Fig. 4).

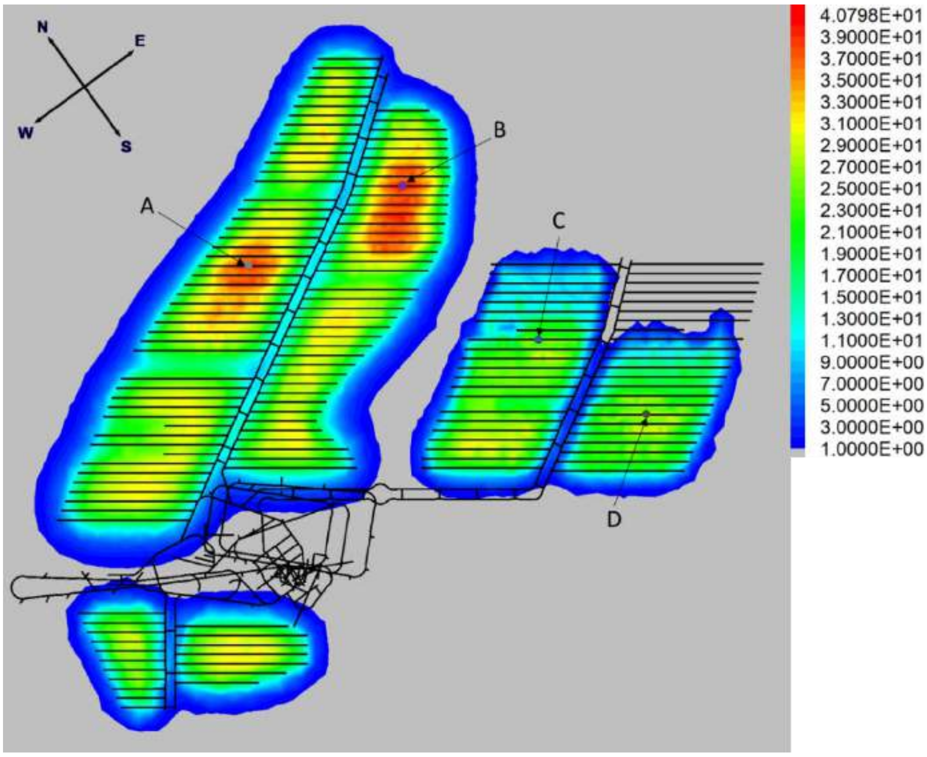

Figure 31: Bedrock temperature increase (> 1°C) at year 160 after deposition of first canister. Horizontal section from depth level -420 m. Coloured dots, marked with A, B, C and D, act as local maximum query points for obtaining estimate of the local temperature maxima.

The thermo-mechanical model of Olkiluoto does not take into account the EBS components of the KBS-3 system, as the layout protocols are implicitly designed to constrain the achieved temperatures at different parts of the repository being on acceptable level. The model only shows the location of the maximum temperatures and the volume of the heat load after the closure of the final disposal repository. For instance, from temperature evolution point of view, the most important design requirement relates to the bentonite clay buffer and backfill, stating that the temperature of the installed buffer shall stay below 100˚C, [5, 6]. This design criteria then leads onwards to canister spacing, controlling the heat load and achieved maxima of the temperature evolution, as presented in Fig. 4. However, the heat is currently being optimized for all components of the KBS-3 system, as part of the thermal optimization work [7].

3.2. Monitoring strategy of temperature evolution

Based on the temperature evolution prediction of Olkiluoto repository (Fig. 4), a preliminary strategy for monitoring the temperature evolution during repository operation has been established during 2018. Constrains related to the strategy of monitoring of the temperature evolution results to following conditions:

- Temperature increase should be measured in locations of the repository facilities where the temperature is predicted to increase at the earliest stage during the repository operation.
- Temperature increase should be measured in locations where maximum temperature changes are predicted.
- Temperature increase should be measured in locations where temperature changes are predicted to be minor.
- Temperature increase should have sufficient lateral and vertical coverage, in the direction of predicted anisotropy (foliation).
- Temperature changes should be monitored in locations relative to water bearing features
- Long enough baseline monitoring for ambient temperature of the bedrock should be established.
- Due to the long timespan of the temperature evolution and repository operation, the monitoring system must have easy maintenance of the instruments and continuous data collection.
- The locations of the temperature monitoring network should be selected as such, that the possibility to replace measuring devices can be achieved as long as possible during the repository operation.

A preliminary schedule, with suggested installation layout for the temperature evolution monitoring points, is presented in the Chapter 2.3. The actual schedule of monitoring instrument installation is directly linked to the canister's installation sequence, as the process of temperature evolution occurs due to canister deposition and associated heat flow. Hence the installation of monitoring instrument will change according to the canister deposition schedule.

3.3. Suggested layout for monitoring of repository temperature evolution

Following the monitoring strategy established in Chapter 2.2, a preliminary layout for instrument installation could be established based on the thermal evolution prediction (Fig. 4). In order to assure the correct understanding of the temperature evolution and it extent, some measuring points need to be installed at the boundaries of the thermal load area. The planned measuring points are located as follows (Figures 5, 6 and 7):

1. Early detection of increased rock temperature from first deposition holes
2. Early detection of increased rock temperature from first deposition holes
3. Monitor the development of temperature at the deposition tunnel with a local maximum (query point A, Fig. 3)
4. Monitor the development of temperature at the deposition tunnel with a local maximum (query point B, Fig. 3)
5. Monitor the development of temperature at the deposition tunnel with a local maximum
6. Monitor the speed of heat flow at the boundary of the panel
7. Early detection of increased rock temperature from first deposition holes
8. Monitor the development of temperature at the deposition tunnel with a local maximum (query point D, Fig. 3)
9. Monitor the development of temperature at the deposition tunnel with a local maximum (query point C, Fig. 3)
10. Monitor the speed of heat flow at the boundary of the panel

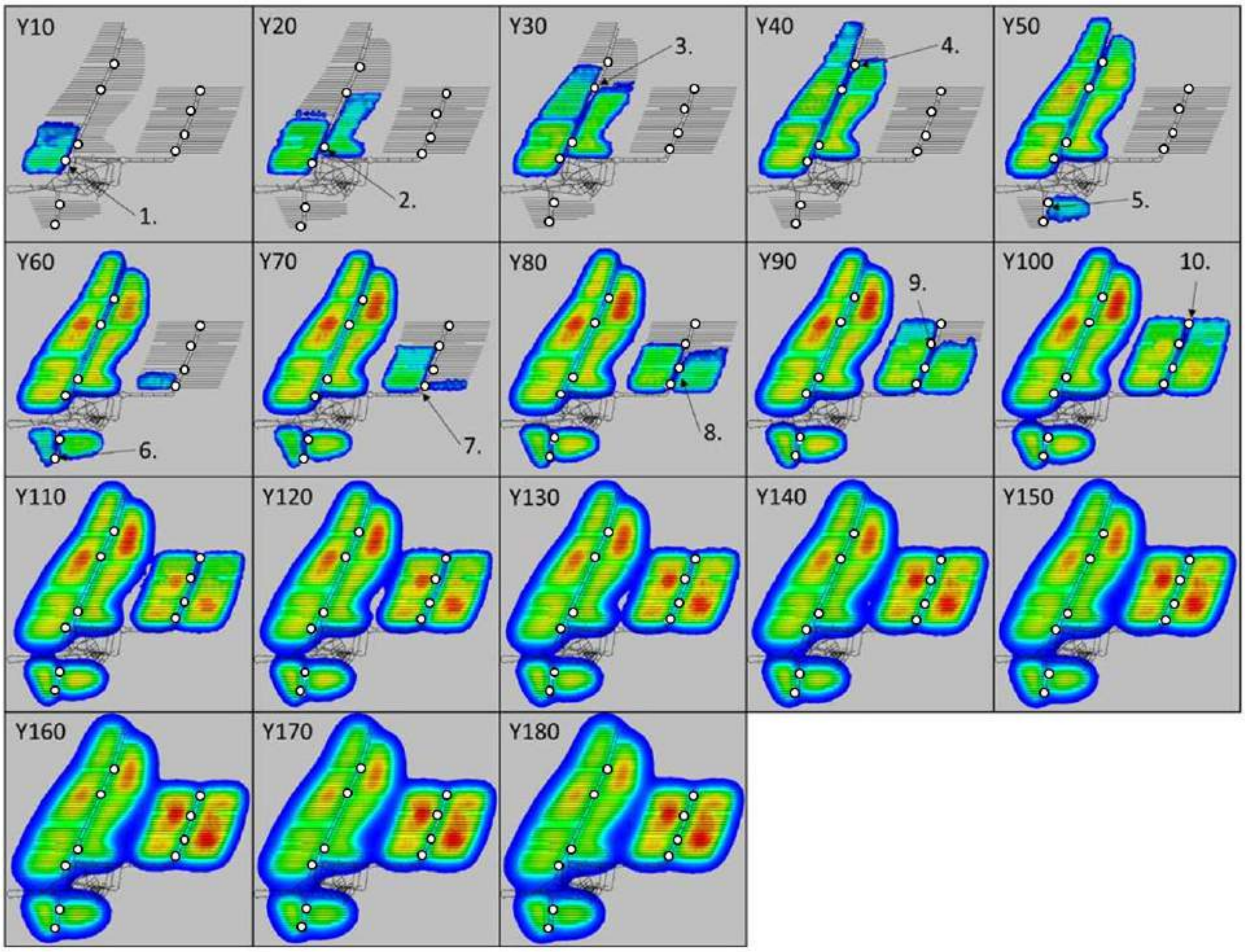

Figure 32: Preliminary suggestions for temperature monitoring points in deposition area (white dots) at different stages (XX in YXX means year) (Contour lines, temperature increase > 1°C, horizontal section from level -420).

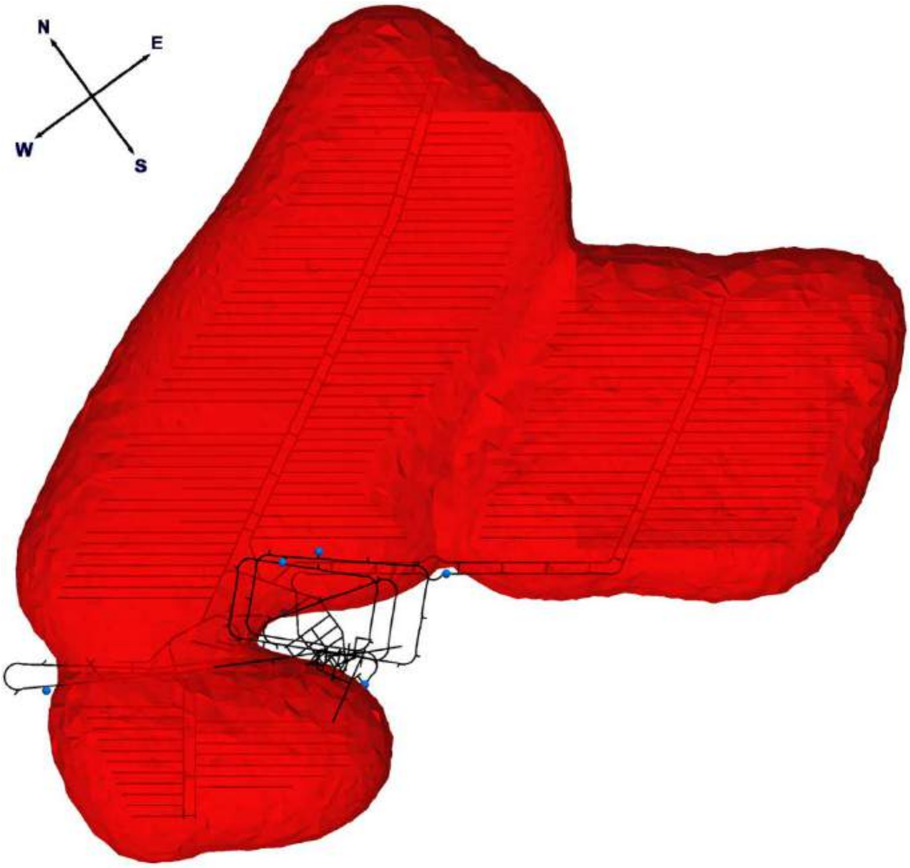

Figure 33: Preliminary suggestions for temperature monitoring points for temperature increase extent verification (blue spheres) (Isosurface temperature increase > 1°C (Year 180)). Plan view.

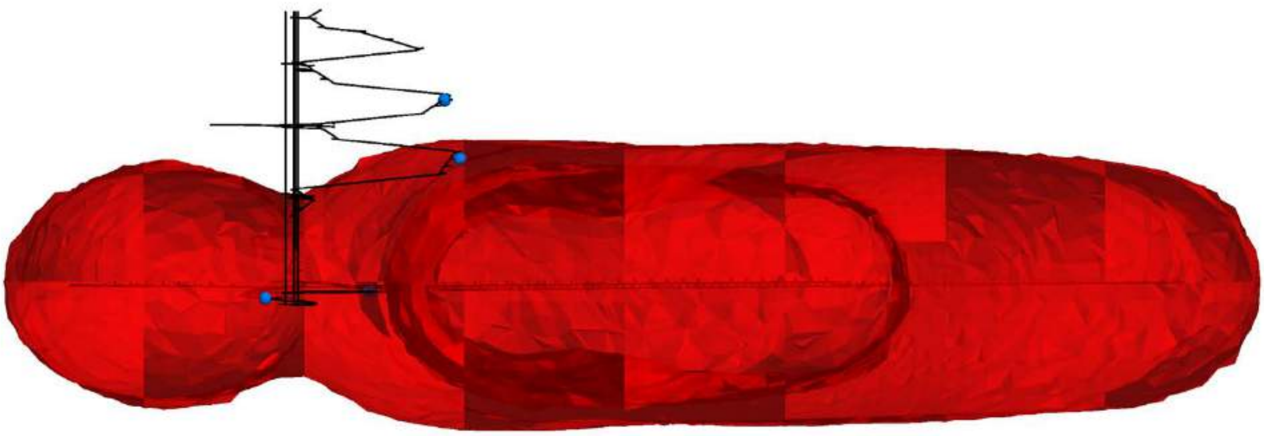

Figure 34: Preliminary suggestions for temperature monitoring points for temperature increase extent verification (blue spheres) (Isosurface temperature increase > 1°C (Year 180)). View from South-West.

4. Discussion

Besides modelling, monitoring strategy needs also take into account the technical aspects and limitations, both from repository property point of view and from those associated with repository operation. These limitations might occur due to deposition tunnel closure, limitations on foreign materials that can be installed within the repository volume, or limitations within the conflicting schedules of monitoring instrumentation and canister installation. Each repository site has its particular limitations from sites property point of view, and in order to assure the suitability of the site during the entire final disposal activity, the monitored processes should be selected to reflect the limitations set by the site properties.
The main philosophy in the establishment of monitoring strategy is to predict the extent and magnitude of the selected processes to be monitored by modelling. The prediction can be based on modelling, using the data collected during site characterisation as an input. Predictive modelling yields the information on the magnitudes (minimum and maximum) and the extent of the monitored process on the site. This information can be used to design the network of measurement devices (for example for the temperature Fig 5, 6 and 7). By estimating the magnitudes and extent, and further monitoring their development, fulfilment of long term safety requirements can be estimated during operation (eg. maximum temperature of bentonite) based on the predicted estimations against observations. Finally the validation of the model can be conducted by using the monitoring data, and the modelling can be iterated further in case of major discrepancies between predictions and observations.

5. Conclusion

Formulating a suitable monitoring strategy is a process that needs to take into account multiple aspects. However, it is important primarily to identify the stage of the repository project, which sets the objective for extent and scope for the overall monitoring. Posiva is currently advancing from the detailed site characterisation phase where the amount and the type of collected data is much larger and possibly done in a wider spectrum, than is necessary during construction and operational phase of a repository facility. Every monitoring strategy should take advantage of previously collected data sets in order to summarize an undisturbed baseline for the repository site, and for identifying the processes which are significantly invoked due to the construction and operational activities. The identified processes should drive the direction for the overall monitoring strategy, while the impact of the processes can be modelled in order to form a prediction on the extent and magnitude of the expected changes. If the identified processes are extremely small from magnitude point of view or slowly occurring, the monitoring should be concentrated in areas where the largest changes are predicted to occur, for increasing the chances of success on detection within limits of instrumentation capabilities. Lastly, it is important to keep in mind that a construction site of a final disposal facility is not a common construction site, resulting in long-term safety aspects which be taken in consideration during planning of actual instrumentation installation such as drillhole locations or foreign materials used in the measurement devices.

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C.f – Session on Decision Making Process

Planning for Evaluating and Responding to Monitoring Results, and Use of Monitoring in Decision Making

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1. Summary

The Modern2020 Project focused on monitoring during the operational period to support decision making and to build further confidence in the post-closure safety case, as this is where the greatest challenges lie in terms of strategy and technology, and where the greatest gains can be made through international collaboration. The Project aimed to develop methods to support disposal programmes close to licensing in the design of monitoring systems suitable for deployment in the next decade, and to support programmes less close to licensing and other stakeholders.

One aspect of the work focused on generic approaches and methodologies for monitoring data evaluation criteria and response plans, decision making, and, in particular, developing collective opinions on planning for evaluating and responding to monitoring results.

The Modern2020 Project identified the following collective opinions on planning for evaluating and responding to monitoring results:

- It is not possible to define a direct link to safety for any specific monitoring parameter.
- Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the monitoring dataset.
- Response plans should be developed to describe actions that could be taken following some specific parameter evolutions.
- Response plans need to be adaptable and should consider the system behaviour.
- Assessment of monitoring results might need to consider processes that have not been previously recognised or identified as being significant.
- Usually, the first response to unexpected results is to check the data and consider the implications for safety.
- The results from monitoring each parameter should be compared to the range of expected evolution of that parameter in time and space.
- Continuous evaluation would occur in response to parameter values being inconsistent with their expected evolution.

- Periodic evaluation might occur in response to the outcome of a continuous evaluation or at regular intervals.
- Monitoring programmes should include the organisational set-up for responding to monitoring results.
- The response to monitoring can be guided by consideration of a generic action list, comprising desk-based actions and physical actions.

A range of thermal, hydraulic, mechanical and chemical (THMC) processes are typically monitored in underground research laboratory (URL) experiments, and associated parameters might be considered as candidates for monitoring during repository operations. These parameters might include:

- Temperature.
- Porewater pressure.
- Gas pressure.
- Groundwater flow rate.
- Swelling pressure.
- Strain.
- Displacement.
- Relative humidity.
- Water content /saturation.
- Water chemistry, including pH and Eh.
- Density.
- Corrosion.

It is possible that a range of these parameters will be monitored to provide specific information on processes and to check the results against criteria identified prior to commencement of the monitoring programme. However, monitoring of single parameters cannot provide conclusions regarding repository long-term performance. To develop an understanding of process evolution it may be necessary to monitor several parameters, convolving the acquired data to derive process understanding. It is possible that a range of the parameters listed above (and others) will be monitored to provide information on coupled THMC processes and to check the understanding presented in the most recent iteration of the post-closure safety case. Therefore, evaluating monitoring results will consider both individual results (i.e. monitoring of the same parameter, potentially in multiple locations and/or with multiple types of sensor) and also integrated consideration of the range of monitoring data.

Evaluation of individual results will be undertaken on a continuous basis, whereas integrated evaluation would be undertaken periodically. For continuous evaluation of specific parameters, the main aspect will be to compare results to the range of their expected evolution. For this evaluation, three scenarios are envisaged:

- Monitoring values and trends are consistent with the range of expected evolution.
- Results are inconsistent with the range of expected evolution, but insignificant to safety.
- Results are inconsistent with the range of expected evolution and require further evaluation, in particular to evaluate their significance to safety.

In some circumstances, results that are inconsistent with their expected evolution could act as a trigger for undertaking a periodic evaluation, which considers the integrated data set. Periodic evaluation could also be triggered by the needs of a periodic update to the safety case or as the result of an external decision (e.g. a request from the regulator or other Government agency).

In all cases, it would be expected that periodic evaluation of monitoring data would confirm that the repository was performing in a manner consistent with the safety case. Should there be a need for further investigation as a result of the periodic evaluation, three generic types of response are recognised:

- Desk-based responses: these responses relate to the evaluation and understanding of the monitoring results and discussion with stakeholders (it will always be necessary to first undertake a desk-based evaluation of monitoring results, and the outcomes of such an evaluation would have a bearing on other responses).
- Monitoring programme responses: these responses relate to responses to monitoring results focused on acquisition of monitoring data.
- Disposal programme responses: these responses relate to physical intervention in the disposal programme as a result of decision supported by monitoring data.

Further elaboration of the responses envisaged, and an explanation of each response is provided in Table 1. In addition, the Modern2020 Project has developed examples of generic decision-making processes. Responding to monitoring results is viewed as a stepwise process that considers both independent monitoring results and periodic evaluation of integrated datasets. This process first involves data acquisition on a parameter-by-parameter basis, followed by the comparison of this data to its expected evolution, and the integrated evaluation of the full range of monitoring results. From this, decisions can be made about whether to a) continue monitoring in the same way, b) change the monitoring programme, c) change the disposal process, or d) end the monitoring programme.

Data Acquisition

All monitoring data gathered during the operational period will be subject to rigorous quality assurance and quality control (QA/QC) as pursuant to the implementer's documented / published procedures. This will ensure that they can be trusted and therefore used as inputs to the decision process. Data quality will be checked at all stages of the monitoring programme for errors, as a stakeholder needs to be confident in relation to the veracity of any data. Where uncertainty exists in data quality, this should be made evident. Using such an approach for reporting data will ensure obvious instances of monitoring device failure are clear. Raw data might be made available to stakeholders for independent analysis.

Once monitoring results are assured, the raw data will need to be interpreted and converted into information, which would include adjusting and calibrating the data for the in situ environmental conditions. This process will yield parameter values and time-dependent results that can be compared to their expected evolution.

Comparison with Expected Evolution (Continuous Evaluation)

A "base case" for the expected evolution (spatially and temporally) for specific components of the near field will be proposed prior to monitoring on the basis of existing knowledge and with the input of modelling and experimental data. This base case will include an "envelope" of responses, perhaps related to variant scenario evolutions, that can also be bracketed as "expected". The expected evolution needs to consider an understanding of the performance of monitoring devices and will be an a priori prediction of the suite of information to be provided subsequently via the repository monitoring programme.

Monitoring information will be compared to the expected evolution. Comparison will follow internal processes laid down in company procedures which will allow assessment as to whether or not information derived from monitoring is essentially consistent with the expected evolution or inconsistent.

The process of comparison may be straightforward, for example in the case where consistency with the expected evolution is judged based on the comparison with one data point, or more complex, with consistency judged based on the trend of information over time.

The implementer's procedures in relation to maintaining interaction with e.g. regulatory bodies, the host community, citizen stakeholders, academia, governmental oversight bodies, independent advisory panels will continue, possibly requiring extraordinary meetings dependent on the nature of the situation at hand. This ensures communication of information, and also ensures the derivation of any responses subsequently to be enacted by the implementer are subject to scrutiny and oversight, and can be informed externally as decided on a case-by-case basis.

Integrated Evaluation of Monitoring Results (Periodic Evaluation)

There are three main reasons that an integrated evaluation of monitoring results could be triggered: at a planned interval; in response to results that are inconsistent with their expected evolution; and as a result of an external decision.

Regardless of the reasons for undertaking an integrated evaluation of monitoring data, it is expected that the processes for evaluating the data will be the same. During periodic evaluation of monitoring results new data collected during the monitoring programme will feed into an update of the post-closure safety case. This update could manifest in several different ways, including:

- Inclusion of a new scenario or new sensitivity calculation with the safety assessment, should the new data from the monitoring programme change the screening arguments made during previous safety assessments.
- Inclusion of new processes in underpinning models (e.g. THMC coupled models) or in the safety assessment calculation, should the monitoring data indicate that processes not previously included in models are potentially significant. This might include revising the expected evolution of monitoring parameters.
- Revision of data used in the underpinning models or in the safety assessment calculations based on the extended operation of the monitoring system.

Any periodic update to the safety case will not only rely on monitoring data but will also incorporate new information from the operation of the repository, from the wider waste management organisation (WMO) research, development and demonstration programme, from collaborative research undertaken by the waste management community, and from the wider scientific community.

Once the new information and data have been used to update the safety case, the significance of it can be assessed, in particular to decide if any data inconsistent with the parameter-specific expected evolution is insignificant or significant to safety, and whether the overall system is behaving within the bounds assumed in the safety case. This will provide a basis for deciding to continue monitoring in the same way, to change the monitoring programme or to change the disposal programme, as discussed below.

It is envisaged that WMOs will record detailed information of the process that led to a decision (including references where appropriate) as part of the justification for the decision undertaken. This would provide long-term traceability and enable decision justification.

Continue Monitoring

Once monitoring data are measured, if they remain within the expected evolution, the monitoring could continue as planned. However, the implementing organisation may have to face some decisions, e.g. on the need for further monitoring and the duration of further monitoring. These decisions would be considered as part of a periodic evaluation of monitoring data.

Change Monitoring Programme

The outcome of a periodic evaluation might be a decision to continue the monitoring programme albeit with a modification to the details of data acquisition. This could, for example, be a decision made in response to collecting data that was inconsistent with the expected evolution but not judged to be significant to the safety case. Continuation of the monitoring programme under this circumstance would be caveated, for example the frequency of data collection might be enhanced, and re-analyses of data gathered to date – including more broadly than in relation to any one specific repository component - might be undertaken, to assess whether additional information can be derived.

Furthermore, a programme of potential future action could be derived. This further action could be undertaken if further data gathering confirms the information available to date, or allows an inference to be drawn that the evolution of the specific repository component is becoming more removed from the safety case assumption with time.

The above does not preclude further analyses of the data gathered to date, and assessment of its potential significance, being undertaken. Such analyses could well include a re-consideration of how the specific repository component could evolve in the post-closure period, including related coupled THMC processes. It must be recognised that the evolution of components in the repository is itself linked – the effects of such coupling also need to be recognised and considered.

The actions above would most probably not be undertaken as a single-pass process, and indeed numerous iterations could be necessary. The importance of implementer interaction with a range of stakeholders cannot be overstated – confidence in the capability of the implementer will not be enhanced, and could well be damaged, were the implementer to act in "going it alone" mode. More than one specific repository component could be the considered subject, and a conceptualisation of the evolving repository component – both temporally and spatially – can be built up. A 'So What?' question remains – is the unexpected performance of a specific repository component, if negative, significant enough in consideration of the robustness of the post-closure safety case (and possibly the operational safety case) to necessitate action, and at what point does action move from desk-based to repository-based?

Change Disposal Programme

Should the implementer and other organisations (e.g. regulatory bodies, the host community, citizen stakeholders, academia, governmental oversight bodies and/or independent advisory panels) reach a conclusion that the nature of information available to date is significant enough to mandate new repository-based action – the options to be pursued could be wide-ranging, and could be influenced by the advancement of the respective repository programme.

If the data gathered through monitoring suggests that the engineered barrier system (EBS) and emplaced waste is evolving in a manner that is irrevocably inconsistent with the currently-accepted post-closure safety case (and possibly the operational safety case, too), it may be concluded that reversal of the EBS emplacement and retrieval of the emplaced waste is necessary.
Whether or not both the EBS and emplaced waste would be affected is something that would be determined on a case-by-case basis. It could be the case that data gathered by monitoring of a specific component of the repository shows significant unexpected behaviour, implying that limited dismantling and analyses – not extending to the emplaced waste – could be necessary only (perhaps to be followed by re-emplacement of a revised EBS, updated on the basis of analyses and updating of the disposal concept).

Retrieving emplaced waste – which would itself still require subsequent disposal in the longer term (if this were to remain the national policy) – would potentially expose workers to an operational radiological dose. The implications of retrieval and workers receiving a dose at the present time, in comparison with a decision to potentially reduce a radiological dose that could be received in the post-closure period were waste retrieval not to proceed, should be considered as part of the response. Depending on the specific programme, such a decision could again involve the implementer and, for example, regulatory bodies, the host community, citizen stakeholders, academia, governmental oversight bodies, independent advisory panels.

Intervening in the repository programme could have significant consequences on a repository programme overall, including cost and duration. Confidence in the implementing organisation may be affected. Furthermore, there is a possibility of a knock-on reduction in confidence affecting other repository programmes (domino effect). However, intervention may be essential and unavoidable, dependent on the situation at hand and on weighing up the pluses and minuses of "doing nothing" compared with "doing something".

End Monitoring Programme

If the implementer is sufficiently confident in its understanding of the evolution of the specific EBS component that is the subject of monitoring, the implementer might propose that no further information is now needed, and related monitoring can cease. Review and acceptance of this proposal would most likely be subject to regulatory approval in consultation with other stakeholders.

Table 1: Generic responses to monitoring results identified in the Modern2020 Project.

Generic Response	Explanation
Desk-based responses	
Evaluate sensor performance	Re-checking of the raw data from sensors to check that the sensor readings are valid.
Check results	Re-checking the analysis of sensor readings to check that the interpretation of the raw data is valid.
Record, document and/or publish results	Archiving and making monitoring results available for further use.
Report results	Notifying stakeholders (including regulators) of particular results.
Root cause analysis	Evaluating the reasons behind particular monitoring results, focused on results that are not consistent with expectations.
Revise models / safety assessment	Modifying THMC and safety assessment models to incorporate new process understanding and/or parameter values.
Update monitoring plan	Revising the monitoring programme, taking into account the results from the monitoring programme to date (and any other information generated during the period since the monitoring programme was last updated).
Monitoring Programme Responses	
Continue monitoring in the same way	Continuing the operation of the monitoring programme using the same method (e.g. using the same number and type of sensors, in the same locations, and with acquisition of data at the same frequency).
Change monitoring	Changes in the monitoring programme could relate to changes in the frequency of data acquisition using the current monitoring system, monitoring the same parameter(s) with additional sensors of the same type (additional redundancy), monitoring the same parameter(s) with different sensors (increased diversity), or monitoring of different parameters.
Disposal Programme Responses	
Change operations	The emplacement of waste could be altered by, for example, placing a temporary halt on emplacement operations, or only emplacing waste of a specific type.
Change design	Evaluation of the results from the monitoring programme may be used to underpin decisions to change the design of the repository.
Engineering intervention	Changing the properties of the repository near field through engineering measures such as grouting, *in situ* vitrification and construction of new barriers.
Reversal / retrieval	Reversal is removing the waste from the disposal location by reversing the original emplacement process (the term is also used to denote the ability to reverse decisions). Retrieval is removing the waste from the disposal location by any means.

Acknowledgement

The Modern2020 Project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 662177.

The IAEA prospective on use of the monitoring programmes in the safe development of geological disposal facilities for radioactive waste

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1. Introduction

The International Atomic Energy Agency (IAEA) has developed Specific Safety Guide entitled 'Monitoring and Surveillance of Radioactive Waste Disposal Facilities' (SSG-31). According to this guide, during the period between the decision to develop a waste disposal facility and closure of the facility, decisions will need to be made about how, when and whether to grant a licence and implement the various stages of the development of the disposal facility. One of the objectives of monitoring and surveillance, and of the analysis of the data thus obtained, is to provide information that can assist in making such decisions. An aspect that must obviously be considered is the likelihood of monitoring and recording changes that are unexpected. This implies that the range of expected results for each monitoring activity needs to be evaluated and discussed at the earliest stages of a monitoring programme.

2. The IAEA project on use of monitoring programmes in the safe development of geological disposal facilities

In 2017, the Working Group (WG) on the Use of Monitoring Programmes in the Safe Development of Geological Disposal Facilities for Radioactive Waste was established by the IAEA to support the use of technical monitoring information when taking decisions regarding the safe development of geological disposal facilities (including both operational facilities and those that have been closed). The key objective of the Working Group is to evaluate the role of monitoring in decision-making in relation to other inputs, and how decisions can be justified on the basis of such monitoring. The outcomes from other related international projects (MODERN2020, GEOSAF) are considered in this regard.

A draft IAEA report on use of Monitoring programmes in the safe development of geological disposal facilities for radioactive waste was prepared by the 'core group' of experts:

- *Sylvie Voivis*, Agence Nationale pour la gestion des Dechets Radioactifs (ANDRA), France;
- *Johan Andersson*, Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden,
- *Jiri Svoboda*, Czech Technical University, Czech Republic;
- *Michael Jobmann*, Deutsche Gesellschaft zum Bau und Betrieb Endlagern fur Abfallstoffe m.b.H. (DBE), Germany;
- *Jaakko Leino*, Radiation and Nuclear Safety Authority (STUK), Finland.

This IAEA draft of report was presented and reviewed during the second meeting of WG in December 2018. The following relevant topics were discussed during this meeting:

- Terms and definitions to be properly understood and used in the area of ‘monitoring’ (e.g. monitoring programme, monitoring strategy, monitoring data, monitoring results, and ets) and need to be consistent with definitions from other relevant projects (e.g. GEOSAF project and ‘safety envelop’, ‘design target’, ‘as-built state’);
- Role of monitoring to build confidence on the safety of deep geological facility on the different stages of its life time including relation of monitoring to post-closure safety and design requirements.
- A ‘Screening Methodology’ to identify the safety relevant parameters to be monitored;
- Use of monitoring results (in this project it means use of ‘an interpreted monitoring data, which will be used in decision making process’), objective of ‘monitoring’ and range of possible decisions, application of principle of ‘graded approach’ in decision making process based on the results obtained during the implementation of monitoring programme(s);
- Interface between ‘monitoring’ and ‘site characterization’, ‘quality assurance’, ‘quality control’;
- Some constrains (limitations) in use of monitoring results considering the fact that ‘monitoring’ cannot be used as a control tool to completely check the overall behaviour of geological disposal facility at any time (such constrains are discussed for two main applications of monitoring that are relevant for the safety case: verifying of proper long-term behaviour of the host rock and the demonstrating of proper functioning of the engineered barriers);
- Use of Underground Research Facilities to evaluate and reach of some monitoring objectives (research, development, demonstration and verification of monitoring strategies, methods, methodologies, tools and equipment; training and maintaining of competence of staff involved in monitoring; evaluation of impact of ‘monitoring’ to facility elements performance’).

3. IAEA ongoing projects related to the safe development of deep geological facilities

Following the great practical interest of Members States to the deep geological disposal facilities, the IAEA initiated and continue implementation of a set international projects in this regard:

GEOSAF III project (the International Intercomparison and Harmonization Project on Demonstrating the Safety of Geological Disposal). The main objective is to develop practical guidance for the safety case illustrating through practical examples and case studies how the integrated safety case covering both operational and post-closure safety is to be built by waste management organizations and evaluated by regulatory bodies and technical support organizations.

Working Group on Interaction and Roles of Regulators and Operators in the Licensing Process for the Development of Safe Geological Disposal for High Level Waste and Spent Fuel. The **o**verall purpose is to increase understanding of and to develop guidance on, the types of preparation that a regulatory body should consider at the different stages of a programme leading to geological disposal of radioactive waste and spent fuel.

Working Group on Liabilities and Long-Term Responsibilities for all Phases of the Development of a Geological Disposal Facility. The first consultancy meeting was held in November 2018 and the following areas for future development in considering the question of liability related to geological repositories have been identified:

- Given the importance of clear communication surrounding both the safety philosophy for geological disposal and the role of the operator in relation liability conventions, it was

recommended that a review is made of how the expression “institutional control” is used in current safety requirements and safety guides.
- The potential need for explicit recognition of the State’s responsibility and liability, once there is no longer an operator for the facility, through national legislation.
- The potential need for a specific system of assurance relating to the nature of the State’s ultimate responsibility after closure of a repository, and thereby outside of the application of a strict international nuclear liability regime, once it has been determined that an operator for the facility no longer exists.
- Ensuring of international confidence in decisions taken at the national level to relieve the operator of a geological repository from their obligations and thereby take the facility out of the remit of liability conventions.

Projects within the URF Network (IAEA Network of Centres of Excellence on Training in and Demonstration of Waste Disposal Technologies in Underground Research Facilities (URF)) to develop the following IAEA documents:

- *‘Roadmap for Developing a Geological Disposal’* which primary objective is to provide practical guidance to the interested Member States striving to develop or elaborate national geological disposal programmes including 1) defining the key phases in a geological disposal programme as they occur in time, from early initiation of the programme, through siting, disposal implementation, and closure; 2) developing a Work Breakdown Structure that relates individual activities to phases of the programme in a matrix format and 3) identifying the major categories of activities or elements necessary in the disposal programme;
- *‘Compendium of Research, Development and Demonstration (RD&D) Results Carried Out at Underground Research Facilities for Geological Disposal’* to support Member States that would like to initiate their geological disposal programmes, by providing a reference allowing finding the more in-depth information and reports on URF RD&D results. The objectives of this document are to make an overview of the existing URFs around world and to summarize information available on RD&D results from URFs, presented with an understanding on how this contributes to the scientific and technical basis for feasibility and safety of geological disposal, in a range of host rocks.

4. Conclusions

The safe development of deep geological disposal for radioactive waste is still a great challenge in many countries using nuclear and radiation technologies. Considering the practical interest of the Member States, the International Atomic Energy Agency has been initiating and implementing several projects that covers different safety issues of disposal of radioactive waste in deep geological formations and creation of deep geological disposal facilities. The IAEA efforts addressed to elaboration and sharing of experience about the use of monitoring programmes in the safe development of geological disposal facilities will support the Member States on the stages of planning, construction, operation, closure and post-closure of this facilities.

Acknowledgements

Considering quite big number of the international projects and studies related to the different issues in the safe development of geological disposal facilities, there is a need to exchange the experience, outputs and lessons learned obtained during the implementation of international activities in this area: it may support countries with necessary information and data and, probably, can help to save time and resources.

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Passive Trust or Active Mistrust? The Finnish and French Approaches to Monitoring of Radioactive Waste Repositories

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1. Summary

Among forerunners in developing final disposal of high-level nuclear waste, Finland and France differ strikingly in terms of two crucial features for radioactive waste management (RWM) policy: requirements for reversibility and monitoring of the repository, and the degree of public trust in RWM institutions. In the Finnish 'high-trust society', the disposal concept is based on the idea of passive safety, i.e. no monitoring is required in the future after the closure of the repository. By contrast, in France – called sometimes a 'society of mistrust'– legislation stipulates that the project must be reversible, and the repository and its environment remain under constant monitoring for a period of several centuries. These countries have therefore adopted different means of building trust in the waste disposal solution and trust in the organisations responsible for RWM.

This paper reports on intermediary results from a critical analysis of the dynamic interplay between waste disposal concept, its monitoring, trust, and mistrust in these two countries' RWM policies. We examine the minutes of parliamentary sessions and news articles from the countries' leading daily newspapers – *Helsingin Sanomat* and *Le Monde*, especially the ways in which these news media and the various societal actors represented in the debate have defined problems and solutions relating to safety, trust, and repository monitoring. Our analysis illustrates the context-dependence of the roles of trust and monitoring in RWM policy, the interdependence between trust and monitoring solutions, and suggests that the potential virtues of mistrust have been underestimated, notably in literature on companies' "social licence to operate".

2. Introduction

This paper compares safety argumentation concerning the role of monitoring in national decision-making on radioactive waste management in Finland and France from the viewpoint of institutional trust. Our analysis spans the boundary between two aspects of monitoring, which are often addressed separately: the technical monitoring, designed to ensure appropriate functioning of a waste repository, and the "societal" monitoring activities concerning collection and dissemination of information on societal and economic impacts of the repository. We focus in particular on debates concerning reversibility, retrievability, and preservation of memory as key aspects of monitoring. Indirectly, our analysis is relevant to "oversight" – a term that covers both long-term (post-closure) monitoring and preservation of Records, Knowledge & Memory (RKM) across generations [1]. For simplicity, we will in the following employ monitoring as an umbrella term covering these various aspects.

As frontrunners in high-level radioactive waste management, Finland and France, have adopted diverging approaches to monitoring of the deep geological repository. In Finland, the KBS-3 final disposal concept is based on the idea of passive safety, i.e. no monitoring would be needed once the repository for spent nuclear fuel would be closed. In France, by contrast, the principle of reversibility – enshrined in law – governs the disposal project. Even after its closure, after some 150 years of operation, the repository and its environment are to remain under constant monitoring for several centuries. The Finnish and French approaches hence appear as two opposing ends of a spectrum, ranging from a view that sees monitoring as a means of building confidence in the technological solution and trust in the waste management organisations and institutional arrangements, to a perception of monitoring as merely an unnecessary and potentially harmful impediment to long-term safety.

To examine the foundations for this divergence between the two approaches to monitoring, we draw on concepts developed in social science to examine the dimensions and roles of trust and mistrust.[6] We adopt a typology distinguishing between three mutually interacting dimensions of trust – social, institutional, and ideological – that structure our analysis concerning the argumentation on monitoring in the two countries' radioactive waste management (RWM) policy. Our analysis will focus on argumentation by policymakers and key stakeholders, especially in national parliaments. We link our analysis to the recent literature concerning the "social license to operate" (SLO) – especially the role of safety issues in building and maintaining trust. SLO has been described as a *"soft contract that is usually based on trust and mutual understanding between the involved parties"* [2] – typically a company and the local host community. Boutilier and Thomson [3], in their oft-used framework for analysing SLO, consider achieving "full trust" or "institutionalised trust" as the ultimate objective in the attempts of a company to achieve an SLO.

We contribute to this field of scholarship by providing a more nuanced and critical treatment of the virtues and vices of trust and mistrust. Our comparative analysis helps to better understand how characteristics of the wider societal context interact with technological and institutional choices and transformations, and how institutional and ideological forms of trust interact in debates over safety and monitoring. By analytically separating the parliamentary debates from the actual policy responses – i.e. societal pressure and the corrective measures adopted as a consequence – our paper also offers insights into the anatomy of societal pressure, which may or may not lead to improvement of control and stakeholder engagement concerning technological choices. We suggest that in a high-trust society citizens are more prepared to give an SLO for a final disposal project based on passive safety, whereas in a context of mistrust, there is greater pressure to subject the technological concept to democratic debate and continuous stakeholder engagement. The debate on the chosen monitoring approach has significant feedback effects on institutional trust, as for example the shifting frontlines in the French debates on reversibility demonstrate.

3. Trust and the role of long-term monitoring

In our analysis, we treat institutional trust as a central variable. Surveys consistently show Finland as a society in which institutional trust is high, whereas in France mistrust towards institutions and authorities is widespread. We consider institutional trust as a pivotal feature that at the same time shapes and is shaped by the choices relating to monitoring.

3.1. Finland: legalism and trust in institutions as the backbone of society

[6] For the sake of simplicity, we do not here distinguish between trust and confidence – two sister concepts that are sometimes treated as separate.

The Nordic societies, including Finland, are generally considered high-trust societies. While surveys measuring trust levels have given Finland slightly lower scores than for its neighbouring Norway and Sweden, the country still features as among the most ‘trusting’ in the world. This goes equally for trusting other people, i.e. generalised social trust [4], trust in institutions such as the national government, parliament, and political parties [5], and the news media [6]. This high trust especially in public sector organisations and societal institutions have been identified as particular strength of the Finnish society [7]. However, Finns have not always fully trusted the safety of the final disposal. In 2000, when the government adopted a Decision-in-Principle (DiP) on final disposal of spent nuclear fuel (SNF) (ratified in 2001), an attitude survey showed that only 26% of the Finns trusted final disposal to be safe - however, at the same time, as many as 45% of residents in the planned host municipality, Eurajoki, trusted in the safety of the project [8]. Yet, a Eurobarometer study from 2002 showed Finns to be among the least worried amongst the Europeans concerning the way radioactive waste was handled in their country [9].

3.2. France: a society of mistrust?

France, by contrast, has been described as a “society of mistrust” [10; 11]. According to the World Values Survey, generalised social trust reaches only about 20% – about a third of the level in the Nordic countries [12]. On this measure, France ranks 24th among the 26 surveyed OECD countries [13]. Yet, trust is difficult to measure, and results are sometimes surprising: the latest Edelman trust barometer places France in the low-to-mid range, close to classic high-trust societies such as Sweden.[7] The apparent discrepancy may be explained by the fact that the measure used by Edelmans hides behind a single composite index trust in entities as different as government institutions, enterprises, media and the NGOs.

In the nuclear sector, mistrust is prevalent. According to an annual survey conducted by IRSN, the nuclear safety expert authority, only 13% of the French citizens trust that the authorities tell the truth about the risks of nuclear waste, and 21% trust in the ability of the authorities to deal with the waste problem [14]. Only about 5% would be willing to live close to a repository – a figure down from the 12% in 1983 [14]. The radioactive waste agency, Andra, and the nuclear industry enjoy high (>70%) trust when it comes to their competence, but less than 40% of the trust them to tell the truth about the risks of nuclear energy and waste management [14]. Moreover, this trust has declined in recent years.

4. Data and methods

To examine monitoring methods and approaches in these diverging contexts of institutional trust and mistrust, we analyse public debate through the lens of the parliamentary discussions and newspaper articles concerning long-term safety of final disposal of radioactive waste. We draw further on information from sources such as the print media and parliamentary committees, notably in order to account for the differences in decision-making processes between the two countries: in Finland, Parliament’s approval[8] for the repository project (or any other nuclear installation) is mandatory, whereas in France, the government remains the ultimate decision-maker.

The analysis of the French case will combine two elements – a historical overview of the trajectory of debates on reversibility, and a focused analysis of parliamentary and societal debate in preparation for the 2016 law on reversibility. The historical overview will build primarily on earlier research [e.g.

[7] https://www.edelman.com/sites/g/files/aatuss191/files/2018-10/2018_Edelman_Trust_Barometer_Global_Report_FEB.pdf
[8] i.e. ratification of the Decision-in-Principle issued by the government.

15; 16; 17], and places the contemporary discussion on monitoring within the context of the longstanding debate on reversibility, including notably the debates in the National Commission on Public Debate (CNDP)[9] and the 2014 consensus conference on the project for deep geological disposal of the country's medium- and high-level radioactive waste – the Cigéo project.[10] The preparation of the 2016 law will be examined via the minutes of the parliamentary debates, reports and publications of ANCCLI (the national federation of Local Information Committees and Commissions); the IRSN (the technical safety support organisation), OPECST (the parliamentary office of scientific and technological choices), the major associations opposing the repository project. Newspaper articles (mainly from *Le Monde*) from the period of the parliamentary debate 2016 will provide supplementary information on stakeholder views. To focus the analysis and limit the number of documents to be analysed, keywords relating to reversibility, trust and monitoring will be applied.

The Finnish case draws on material from parliamentary debates, previous studies [e.g. 17; 18; 19], and articles from the country's leading daily newspaper, *Helsingin Sanomat*. Our analysis will concentrate on discussions preparation for the Decision-in-Principle on the repository project, adopted by Parliament in May 2001. In addition to the minutes of parliamentary sessions, we also analyse statements by the various parliamentary committees on the topic.

5. Retrievability, reversibility, and monitoring in Finnish and French RWM debates

5.1. Finland: passive safety instead of monitoring

The Finnish Posiva submitted the application for DiP regarding the final disposal facility in May 1999. The adopted KBS-3 concept is based on passive safety – in other words, no monitoring would be needed after the final closure of the repository, to ensure its safety to humans and nature [20, Appendix 3, p.3]. However, retrieval of spent nuclear fuel would be possible, should a justified reason emerge in the future.

The demand for retrievability was brought to the Finnish RWM policy debates at the end of the 1990s. A local citizens' movement opposed to the construction of a disposal site in Loviisa was probably the first to raise the issue [21].[11] A longstanding demand by the Greens [22], retrievability was subsequently brought to parliamentary debate by the then Minister of the Environment, Pekka Haavisto from the Green Party [23]. Although against geological disposal, the Finnish Association for Nature Conservation [24] further argued in favour of the concept, referring also to the French research programme on reversibility and to the statement by the Swedish authorities on Posiva's EIA programme. Hence, the emerging international debate on retrievability (the technical possibility to retrieve waste once it has been disposed of) and reversibility (possibility to return to earlier stages in the decision-making process), including work undertaken by the EU Commission in the mid-1990s, contributed to the emergence of these demands. A more immediate contributing factor was the opinion poll conducted by the regional newspaper, *Keskisuomalainen*, among the Finnish parliamentarians in 1998, which revealed that most were in favor of retrievability. As a result, the Finnish Radiation and Nuclear Safety Authority, STUK, started to prepare for what it foresaw as an "unavoidable" debate.[12] Retrievability was then introduced in the government decision on safety of final disposal in March 1999. The decision was unanimous [25]. Monitoring was not included in the concept. The retrievability requirement was added to the government DiP in December 2000.

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[9] Commission nationale du débat public, established in 1995 to organise consultations on large projects expected to have significant impacts on society.

[10] Centre industriel de stockage géologique.

[11] Personal communication by a Posiva radioactive waste management expert, June 1, 2009.

[12] Personal communication by a Posiva radioactive waste management expert, June 1, 2009.

In preliminary debate in Parliament on the application concerning the DiP a number of parliamentarians referred to retrievability. The then Minister of Trade and Industry, Sinikka Mönkäre (the Social Democratic Party), argued that retrievability should be sufficiently difficult to implement, in order to facilitate efforts to control proliferation, prevent unwanted intrusion into the repository, and limit potential environmental impacts. However difficult in practice, retrievability would be useful in view of possible future development of technology that might allow the utilisation of spent nuclear fuel for useful purposes in the future. Many parliamentarians seemed satisfied with the sole existence of technical option for retrievability in the future. Others called for further information concerning retrievability, criticising the narrow framing of impacts and insufficient attention to costs and technical aspects. Resource utilisation, rather than safety, was generally seen as the primary motivation for a possible retrieval, as opposed to safety reasons.

Parliament ratified the DiP in May 2001 (votes 159–3). Safety was discussed but final disposal was seen as "better" and "safer" option than interim storage [26], which would require continuous maintenance and control. The binding safety guidelines issued by the safety regulator (STUK) underline that retrievability shall not compromise safety [27].[13] Authorities and industry nevertheless continue to follow international discussion on the topic.

The government decision of 1999 [28] was replaced in 2008 by the government decree on safety of final disposal. The decree does not impose requirements related to opening of the disposal facility [29]. In its subsequent statements, STUK has merely taken note of the fact that Posiva's disposal concept allows the retrieval of waste although at substantial cost [30, 31]. Posiva's construction licence application from 2012 included a legally mandatory statement on reversibility. In the safety assessment STUK [32] argued that retrievability shall not impair post-closure safety, and underlined that geological disposal was not designed to facilitate retrievability but to isolate the waste from the living environment. Yet, in a 2015 parliamentary debate the then Minister of Economy, Olli Rehn (the Centre Party of Finland), responsible for nuclear waste management, considered retrievability as a key criterion for the disposal solution.

5.2. France: reversibility and monitoring as means of building trust

The principle of reversibility was enshrined in the French law with the National Waste Act 1990 [e.g., 16; 33; 34], which did not, however, clearly and unambiguously define the concept.[14] Indeed, the French case differs from those of most other countries in that reversibility, instead of retrievability, constitutes the central term. Following the national debate on the country's nuclear waste management policy, organised in 2005–2006 by the National Commission on Public Debate (CNDP), Parliament adopted the "Planning Act" of 2006, which established reversible geological disposal as the reference option and defined reversibility as an umbrella term that covers both the technical and political aspects of the term: ability to retrieve the waste and the possibility to change and reverse decisions. Reversibility was again debated as part of the 2013-2014 CNDP debate on the disposal project, Cigéo, proposed by the national agency for radioactive waste management, Andra. As required by the Planning Act of 2006, Andra then made its proposal for the practical application of reversibility in the context of Cigéo – a proposal that was debated in Parliament and integrated in July 2016 in the law on reversibility of geological disposal.

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[13] The guidelines require that "*no monitoring of the disposal site is required for ensuring long-term safety" [27].*

[14] The Law did not define clearly whether reversibility obliged the waste management authority to examine two altogether alternative disposal concepts or to consider reversibility as an early step in a process ultimately leading to irreversible disposal [16].

Concern and societal debate concerning the various aspects related to monitoring were institutionalised, for instance, in the ‘technical dialogue’ on intermediate and high-level waste jointly led since 2012 by ANCCLI, IRNS, and CLIS – the local information and liaison committee for the repository and underground research laboratory. This collaboration sought to anticipate key issues that might arise during the 2013 public debate on Cigéo. The key topics of debate included reversibility, safety, radiological protection, and environmental and health monitoring. In 2007, Andra had already established the Permanent Environmental Observatory (OPE) in the area of the planned repository. Especially the local stakeholders regularly demand information on issues of monitoring and memory preservation. The topic of memory preservation, in which local communities are seen as central actors, can indeed be seen as an extension of monitoring to a period when institutional monitoring has been discontinued [35].

The trajectory of French debate on reversibility has been characterised by a shift in the use and users of the reversibility demand. This demand emanated mainly in the civil society, but progressively lost its prevalence in the argumentation of anti-nuclear groups as the term became appropriated by the dominant actors and integrated into legislation. The main objective in relation to RWM remains opposition to geological disposal, and the concept of reversibility has come to represent for them just another way of justifying geological disposal and the continued use of nuclear energy. These groups criticise reversibility as impossible to implement in practice. By contrast, both reversibility and the associated elements of monitoring have taken an increasingly prominent position in the argumentation of local-level actors. Reversibility and long-term monitoring have therefore become one of the major means for remediating the chronic mistrust that prevails between the local and national-level actors. The success of this trust-building strategy is far from certain, as the ‘unrealistic’ nature of reversibility has become a major argument used by the opponents.

6. Conclusions

The narrow framing focusing on retrievability, and the relatively limited debate on the topic, clearly distinguishes the Finnish case from the French case, characterised by enduring discussion on the meaning and practical implementation of reversibility. These differences reflect the highly distinct contexts of high institutional trust in actors responsible for waste management in Finland, and an enduring mistrust amongst the French stakeholders. In Finland, the possibility and requirement of retrievability – without the need for monitoring – served to further ensure high degree of institutional trust. The extensive debate on reversibility in France was originally designed to strengthen trust, especially by satisfying the demands from civil society, yet the concept has since then come under attack by various civil society groups. Our analysis suggests that monitoring – including long-term post-closure monitoring and preservation of memory – are necessary requirements for a successful repository project in a low-trust context, whereas in the Finnish high-trust environment, a need for monitoring might rather undermine institutional trust.

Acknowledgements

This work was funded by the Finnish Research Programme on Nuclear Waste Management.

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Do We Need a Nuclear Steward? Monitoring as Task for a Long-term Governance Institution

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1. Summary

A central challenge in nuclear waste governance is the long time frame over which institutional control of the waste is needed. Responsible actors and institutions will be needed once handling the waste in the underground becomes necessary during the operation phase as well as to take new decisions regarding its safe disposal. Most countries favor some kind of underground storage of the high-level wastes, but have not proceeded far with the implementation, yet. For example in Germany, according to the current schedule it is planned to close the repository sometime between 2130 and 2170. Until then, many generations of professionals and citizens willbe involved in dealing with the waste and possibly occurring problems. Considering this, a central question is how the responsible actors, such as political decision-makers, public administration etc. can work together over such a long period of time. With regard to monitoring, this means that institutions will be needed that can interpret the data, including its validity and reliability, take decisions based on the evaluation, take action at the site if necessary, as well as interact with the local public at least.

2. Introduction

A central challenge in nuclear waste governance is the long time frame over which institutional control of the waste is needed. Responsible actors and institutions will be needed once handling the waste in the underground becomes necessary during the operation phase as well as to take new decisions regarding its safe disposal. Even in the countries most advanced in the siting process, many generations of professionals and citizens will be involved in dealing with the waste and possibly occurring problems. Scientific knowledge as well as societal and political preferences will develop and change over time. Considering this, a central question is how the responsible actors, such as political decision-makers, public administration, industry and the interested public can work together to responsibly “govern” the waste over such a long period of time.

With regard to monitoring, this means that institutions will be needed that can interpret the data, including its validity and reliability, prepare and in some cases take decisions based on the evaluation under their responsibility, take action at the site if necessary, as well as interact with the local public at least. It can be assumed that the public will want to be involved in decision-making in order to be able to contribute to the quality of decisions taken by questioning scientific results and enriching the debate with their knowledge [1].
In literature, two concepts can be found that address long-term tasks based on the idea of “stewardship”: First, a long-term stewardship model developed by the US Department of Energy [2] and second, a more general debate on stewardship of ecosystems [3]. Based on a discussion of their strengths and weaknesses as well as drawing on governance theory [4], [5], [6] we argue that for complex tasks of this type functioning checks and balances will be needed. This means that several institutions have to be involved in the decision-making process, but that one institution takes the

responsibility for organizing it – esp. in the post-closure period or in times close to it. For these times in the more or less far future it can be assumed that political interest and public attention will decrease and these trends probably have the fatal side-effect of unsecure resources in terms of money and knowledge. For this we suggest that a new 'hybrid organization' will be needed that can fulfil technical tasks as well as keep links with political decision-makers and the interested public [7]. Our intention is to open the debate on central characteristics of long-term governance institutions[15] that are capable of organizing a high-quality monitoring process which is steered by the aim of actionability under complicate conditions.[16]

3. Why plan for the future?

Many would say that it does not make sense to plan for the far future, i.e. several decades or even centuries from now. Societal preferences can change, ways of governing can change, laws and regulations can change. Context conditions can change, too, due to environmental conditions, such as climate change. Technological development takes place and might lead to new solutions being available for the nuclear waste disposal problem. Still, we would like to argue that precisely because of the impossibility to know under which conditions nuclear waste management will take place a few centuries from now, having a plan is essential. There are several reasons for this: (1) If not properly managed with a certain degree of attention, the waste can be a hazard to society and the environment for a very long time. If control of the waste is seized before an underground repository is declared sealed, the waste might not be stored safely and securely. (2) At the moment, it is not conceivable that a technology will be available, which renders the waste completely harmless. It has irreversibly changed the environment in which we live. (3) Radioactive waste management can be interpreted as a socio-technical system, in which a multitude of actors shape the system and at the same time standards of technology are influenced by technological developments. Regulations are part of this dynamic system and it cannot be foreseen how the actors involved react to any change in regulation brought about by other actors.[17] Czada [10] argues that any technology that exhibits those criteria should be subject to long-term planning to avoid adverse consequences for society.

It could be argued that functioning societal institutions are well capable of reacting to changes and protecting citizens from technology induced risks and that planning for a major disruption in societal structures is futile anyway. Research has shown that also in functioning societies it cannot be assumed that striving for safety is at the core of any risk-involving technological endeavour due to the inner working logic of companies or institutions [11]. Furthermore, it is often assumed that it would be sufficient to make a plan for the implementation of safety procedures without considering how they will be institutionalized [12].

When it comes to monitoring, the challenge will be to set up an institution that is capable of interpreting the monitoring data as well as preparing and coordinating decision-making on whether they point to a problem underground that would necessitate action being taken [8].

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[15] Institutions in our understanding are the result of functional differentiation in the sense of N. Luhmann and his conceptual idea of modernization. They can stabilize social processes and interests (like safety and security in nuclear waste management).

[16] The talk and this abstract are based on an article published in the Journal of Risk Research [8].

[17] For a first debate on nuclear waste management as socio-technical system see [9]. One example for such a change in regulation is the new site selection law in Germany (StandAG). While the law is clear about the procedure of how to identify a repository site, several civil society actors disagree and refuse to participate. Further, many aspects are not regulated in detail and their implementation will depend on how the actors involved interpret the regulatory text (e.g. what is transparency?).

4. What is a nuclear steward?

In literature, particularly one concept can be identified that deals with nuclear institutions that have the task of taking care of the long-term future. This is the stewardship concept, which has been developed regarding nuclear waste management by the US Department of Energy [2] and in a broader context on ecosystems for example by Steffen et al. [3]. The long-term stewardship model developed by DoE aims at consolidating management over all nuclear sites with a focus on the next 100 years from now. It focuses on managerial tasks that require human action and range from proactive (monitoring, information management) to reactive tasks (e.g. land use control) [8]. The concept highlights the need to develop an idea on tasks to be carried out so that resources and trained staff can be planned for. Following this definition a steward would be an organization that has the task of keeping nuclear sites safe and secure e.g. by maintaining infrastructure and monitoring the waste disposed at the site. A major omission in the concept is that it does not address the institutional requirements in a multi-level system necessary for being able to carry out such tasks over a long time-span [8]. The institutional implementation is thus treated as a black-box. In the context of climate change and the analytical finding that current societies are in the middle of an Anthropocene, different authors underline the need of an ecosystem stewardship to control human impacts on the stability of the Earth System [3],[13]. The challenge is to understand "planetary dynamics" and to support resilience in resistance to widespread biodiversity loss and similar global trends. Under this perspective the implementation of a stewardship system is classified as an absolute necessity, and an "effective architecture of a governance system" for planetary stewardship has to be installed quickly, polycentric and multi-level based [3: 757]. In our interpretation these characteristics can only be reached if the wisest experts and scientist became the stewards in this system.

5. Long-term governance

When attempting to open the black-box of implementation, two aspects should be considered: First, how can it be ensured that safety and security do not fall prey to routine? Second, how can robust decision-making take place? The first question refers to debates in organisational psychology that address the difficulty of implementation an institutional culture that in fact promotes the uncovering of errors and problems. This includes several aspects, such as attaching a positive meaning to the uncovering of errors and problems from the highest levels of management [10]. It is the second aspect, i.e. decision-making, on which we focus in our work on long-term governance. Governance here is used as an analytical category that allows analysing political decision-making not only by government, but also in networks and similar arrangements with other actors through cooperation and coordination [4], [5]. Decision-making in those networks is based on deliberation [1]. At the same time, power relations play a role, particularly as the rules according to which the networks function, are decided upon in classic government procedures ("shadow of hierarchy") [14: 111].
In such a governance network checks and balances can be installed that help prevent routine errors and can increase robustness of decisions taken. Such checks and balances would mean that multiple actors can contribute their knowledge, expertise and point of view to the decision-making process, e.g. when monitoring data suggest that "something is going wrong down there".
The tasks that need to be carried out at a waste storage site can be categorized as managerial, scientific, technical (engineering) tasks, data management, decision-making, and collective deliberation with central collective actors [8]. Those tasks will need to be carried out under changing context conditions. We assume that the following changes will take place in the long-term: "The attention of official politics and 'governmental organisations' decreases. [...] At least the residents at a local site of the repository need to be involved in the long-term [...]. The importance of functioning checks and balances increases as the political and societal attention decreases over time. The possibilities of nearfield monitoring decrease over time. [...]" ([8]: 9]. In such a situation, the standard tasks that need to be fulfilled at each point in time would be fulfilled by the stewardship institution,

i.e. it would be responsible of carrying out maintenance and monitoring tasks at the site. To maintain the knowledge necessary for fulfilling those tasks the steward it seems natural that it would also need to conduct scientific research in this field. On top of this, it would need to be able to communicate with the public and raise attention among decision-makers if the site is not developing as planned [8]. This way, the steward would be a technical "fast response" institution with a larger governance network behind it responsible for taking deliberated decisions on general management issues as well as on high-impact decisions, such as whether to retrieve the waste.[18]

6. Conclusion

Learning from literature in this case means to open up possibilities for reflection about necessities arising with planning a nuclear underground repository for "uncomfortable" time spans. Uncomfortable, as they open temporal spaces with unforeseeable events in the future. The interested public wants to know whether the experts are prepared to deal with developments that can be expected. First, the relevant literature shows that an idea exists of the wide range of duties that come with managing waste disposal sites that need to be kept safe and secure for more than some hundred thousand years. In terms of organising management structures, Metlay [12] highlights that is a mistake to expect a self-implementing process. Rather, a proactive institutionalisation process for the stewardship organisation has to be initiated. This is necessary as a wide range of duties has to be identified and competences developed to deal with an open future, esp. if monitoring is a component for final disposal. Second, the debate on ecosystem stewardship gives an incentive to think about modes of governance, which integrate the state, stakeholders, neighbourhood groups, and national NGOs in a problem-oriented network. This network would have to provide a balanced ensemble of care, reflection, and productive urgent action, if necessary. Furthermore, organisational and regulatory principles need to be defined that guide decision-making processes and define responsibilities within those networks. Organizing collective action in this field that meets the requirements of civil conflict resolution and fair decision-making would have to build up dialogic structures starting from now. Those structures would need to include different stakeholders such as science, implementers, the interested public, and controlling authorities. Those stakeholders would be involved not only in monitoring, but also in preparing deliberative formats of decision-making in the case of unexpected events, as well as in mobilizing resources and competences for consequent action to minimize unexpected hazards. Stewardship in this sense is far away from the service aspect on an ocean liner.

Acknowledgements

The work presented here is closely connected with the Project SOTEC-radio funded by the German Federal Ministry for Economic Affairs and Energy (funding number: 02E11547B). SOTEC-radio stands for "Methods and measures to deal with socio-technical challenges in radioactive waste management".

[18] Such a twofold institutional structure is also discussed in the field of climate engineering, where it is suggested that one body is needed that decides on the general course of action to be taken and other background decisions that can take time and need to be consensual. Another body would be responsible for the technical and scientific supervision of any implementation processes as well of fast response action to be taken in case of emergency, both by following guidelines defined by the consensual decision-making body [15].

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Community Modelling Making Sense of Monitoring Data

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1. Summary

Monitoring undertaken as citizen science often lose momentum as the objectives change from scientific research to continuous sampling. In many cases the use of collected data is not transparent to participating publics, leading to deterioration of data quality and meta data. Developed to increase the ability of local stewardship groups to participate in environmental risk governance the Community Modelling (CM) technique also helps to maintain a sense of purpose of ongoing monitoring.

Convened by two academics, a facilitator and a modeller, a CM project involves a small group of local participants. Together the academics and local participants use extant computer modelling software to address local matters of concern and set it up for continued use after the completion of the project.

The potential of the CM technique came to light in a project using a water quality model to analyse the impact of local river modifications by the charity Thames 21. CM groups of Thames 21 volunteers use their own measurements together with data generated by new monitoring technologies in the model to analyse the efficacy of the wetlands they built. Being able to use a computer model to visualise and examine local processes has increased the interest in monitoring.

2. Introduction

Monitoring is a key aspect of environmental governance as it is necessary to know the status of an environmental system before making decisions about how to manage it. Advances in digital technology have provided small, cheap sensors that can be placed in the environment and provide extensive measurement data. The series of numbers generated by digital monitoring devices require expert interpretation in order to yield information about environmental processes. To make the most of the big data sets generated by digital sensors scientists and technical experts use computer models. In a reciprocal relationship environmental computer models are also a driving force for monitoring because they depend on large data sets that can only be generated by digital sensors.

The historical shift from collecting data by observation to using digital instruments has in many cases removed the need to involve local 'observers' trained to use mechanical instruments, such as weather stations, to collect data. In a parallel process computer modelling provides the decision-making process with seemingly objective, or value-free, analysis of possible future consequences of management actions. This digitalisation of environmental risk governance establishes practices with very little need for scientists or decision makers to involve local lay people in knowledge production and decision making.

Running counter to the closing down of environmental management and expertise is the increased political recognition of the concerned communities' right to participate in environmental governance affecting them. Contrary to the digitalisation of monitoring is the growing interest in citizen science.

Environmental scientists in many fields still need large numbers of field observations and measurements to investigate processes. Citizen science is a form of public participation that engages people with local environments, but it is rarely connected to local decision making when the research projects finish. The challenge is to maintain public involvement with monitoring and to promote public engagement with local environmental decision making.

3. Citizen Science – public engagement with monitoring

The term monitoring is often associated with decision making by formal authorities and advanced technical remote sensing. However, monitoring also refers to the observation of change over time in processes in nature, for example, biodiversity or flood risk. When associated with scientific observation monitoring is a common feature in citizen science.

Many scientific fields rely on citizen science monitoring to generate large amounts of data for research questions to be answered. Examples range from astronomical observations, to light pollution, to biodiversity, to water quality. Citizen science involve a degree of mutuality as the scientists designing and organising the activities have to recruit, enthuse and train participants with diverse knowledges. In many scientific research projects recruiting and retaining participants' motivation is not a problem as they are time limited with clear objectives. When monitoring needs to be continuous to inform risk management and long-term governance processes the transparency of goals is easily lost and the lack of purpose presents a challenge to retain lay participants.

Environmental monitoring in which local publics collect measurement data, for example in the form of water samples, tend to be ongoing because they provide information about potential risk. Risk such as water pollution may, or may not occur, the only way to determine whether risk is turning into actuality is by monitoring. Such routine monitoring is of little scientific interest and it becomes the responsibility of local communities, often a task for volunteers organised by environmental charities. After a while this type of environmental monitoring, which often has no tangible outcome, is challenged by participants' loss of interest.

The participatory technique 'Community Modelling', developed to enable local groups to use expert computer models to use monitoring information to engage with local environmental management and governance has also been found to reduce participants' loss of interest in monitoring.

4. Community Modelling – a technique for participation

Community Modelling (CM) is intended for use in any area of environmental management in which computer models play a role [1]. The technique uses scientific computer modelling to increase the ability of local communities to participate in the governance of environmental problems in their locality. In the process leading to increased local capacity to participate CM projects collaboratively generate computer model representations with relevant for local matters of concern.

CM originates in the Environmental Competency Groups (ECGs) methodology underpinned by poststructuralist, more-than-human philosophical notions [2]. This means, among other things, placing more emphasis on the role of objects in the process and thinking of expertise as a distributed achievement. The ECGs methodology has been successful in enabling the combination of local and scientific knowledge to improve local FRM in the town of Pickering, Yorkshire [3, 4]. Differently from the research focussed ECGs, CM is a technique that can be deployed in response to local requests and that delivers a bespoke computer model supporting local people in engaging with expert bodies and decision-making authorities in the locality.

The CM technique is based on four core elements: resource minimalism, strategic participant recruitment, standardised software and making connections with decision makers.

4.1. Resource minimalism

A CM project is comparatively short, six to eight months, including preparation and reporting time. CM projects are set up in the locality with the environmental problem and run by two people with backgrounds in social science and natural science modelling respectively (acting as 'the facilitator' and 'the modeller'). Aiming to put existing scientific knowledge and tools to use in ways that take local people's knowledge into account, rather than create new scientific knowledge or models, makes it possible for one natural scientist to lead the participatory modelling. The ambition is to make it possible for local communities, in the guise of e.g. city councils, to cover the cost of expert assistance. The participatory activities comprise three to four meetings over a three to four-month period, a relatively short period to make it easier for local participants to attend all sessions.

4.2. Strategic recruitment

A CM project begins with a qualitative social science mapping of the community affected by an environmental problem. This provides an understanding of the social dynamics and power relations shaping the articulation of local environmental matters of concern. The mapping includes the identification of potential local participants for the modelling group. The aim is to engage a small number (four to eight) local participants who are selected based on their interest, suitability and potential for long-term commitment demonstrated by past involvement. The recruitment process involves individual interviews with potential participants by the social scientist, to clarify expectations on behalf of both parties. The interviews also establish that participants can attend all the scheduled sessions and that they have a commitment to future involvement with the local management of the environmental problem.

The selection of participants for CM is based on the ECGs methodology (Whatmore, 2009) and it appreciates self-selection and participants with a previous interest in the topic. Focussing on what interviewees would like to do after the end of the project the identification of potential participants contrasts with social science-based approaches aiming for representativity. The aim is to involve people who have the potential to involve other local residents and to continue to engage with the local environmental management process after the project has ended.

Local participants who are members of environmental groups usually have practical experience of environmental processes and are committed to enduring engagement. Local environmental groups can also make the local model and its results available to interested local people after the end of the project, supporting ongoing local public engagement. Participants involved with local environmental groups also have access to the knowledge resources generated by such groups, which can add to the quality of the modelling.

CM considers local participants in the modelling sessions to be partners who take responsibility for conveying the knowledge gained and the results to the wider local public. They also contribute knowledge about the local environmental matter of concern and learn about how computer modelling, central in environmental management, works.

4.3. Standardised software

CM uses 'off-the-shelf' modelling software that is established and known among the technical experts in the relevant field of environmental management. It is critical to use free-to-use modelling software to make sure that the local community can take possession of the model representation of the locality and the environmental process investigated. Proprietary software often requires significant licensing fees that makes it impossible for a local community to continue to use a model after the end of a project. Use of standard modelling software makes project outcomes transparent to experts and it also makes it possible to couple the detailed local models set up in CM projects with larger scale models used by technical consultants. One of the tasks of the natural scientist in CM is to find out which modelling approaches the technical experts in the relevant field use.

It is important to note that the goal is not to make the lay participants able to use the model in the same way as a scientific modeller would. CM aims for the lay participants to develop an understanding of how modelling works, how the environmental processes they experience are represented in models and how model outputs can be used to consider possible local mitigation options.

4.4. Connecting with decision makers

Running a CM project involves actively connecting the modelling group with local environmental decision makers. The social scientist initiates this connection, using the social science mapping of the local decision-making landscape and environmental matter of concern, undertaken before the modelling commenced. When the modelling group starts the social scientist and the modeller contact local environmental managers, technical experts and decision makers to arrange for them to meet with the local participants et the end of the project.

5. Community Modelling with Thames 21 in East London

The River Lea catchment in East London has a long-standing problem with water quality due to historical as well as ongoing pollution. The environmental charity Thames 21, with the mission to engage local communities with rivers, is addressing water quality problems by hands-on interventions, such as building new wetlands (website). When a wetland has been built the volunteers working on it continue to take water samples around it to collect evidence of its efficacy. Analysis is done of the samples to measure levels of pollutants and the values are recorded as data, the records are kept by Thames 21 and no further use is normally made of the data. This lack of use of the data collected led to a sense of lost purpose amongst the volunteers. At this point Thames 21 officers and researchers from Oxford University came up with the idea of using a computer simulation model in a Community Modelling project to consider the performance of the new wetland in a context of changing land use and climate.

In this case the recruitment of participants was delegated to the existing local charity that already worked with groups of concerned local people. This reflected the matter of concern that was tied to a local intervention that was a material expression of local people caring for the river, the aquatic ecosystem and the water quality affecting it. This existing involvement of local people was regarded as a strength and being ‘strategic’ the CM recruitment process is flexible, aiming for the best possible outcome in terms of future participation.

The customisation of the recruitment process to fit the circumstances was reflected in the organisation of the participatory modelling sessions. In the first session a natural science (hydrologist) introduced a small group of Thames 21 staff to the Integrated Catchment (INCA) model that can run on laptops and that is used to analyse water quality all over the world [5, 6]. In discussing model capacity the participants could articulate their matters of concern and the group decided on which questions it was most interesting to address with INCA. After this session the modeller set up INCA to represent the dynamics of Salmon’s Brook, a tributary to the Lea where a new wetland had been installed by

Thames 21 volunteers. The modeller used publicly available data and monitoring data collected by the volunteers.

To the second session Thames 21 officers invited the local volunteers who had been involved with the construction of the wetland in Salmon's Brook. About 15 local people took part in a three-hour modelling session organised one evening in a local community centre, organised by the social scientist. Using laptops all participants could engage with the model, inputting data (including the data they had collected) and analysing the visualisations of outcomes.

The third session involved a smaller group of Thames 21 staff and a few particularly interested volunteers. The focus this time was to repeat the hands-on modelling exercises and make a record of how this was done to have as guidance for using the model again without the Oxford University academics being present. The social scientist created a video record of the core part of the modelling process that were made available to all interested participants who wanted to try out the model by themselves and needed some support for memory.

In this case there was no need for the academics to connect the modelling groups with decision making. Already involved with decision making bodies through Catchment Partnerships Thames 21 had a very clear sense of how modelling was used in the process. The previous experience had been of modelling being an expert tool that they had no access to and limited understanding of the INCA CM activity empowered Thames 21 in relation to expert actors like the Environment Agency and corporate actors like Thames Water. The understanding of how the local wetland had performed according to measurements and could be expected to perform in the future provided Thames 21 with a new confidence regarding the value of and justification for local interventions.

An important effect of the CM project was a new sense of purpose amongst the local volunteers. Being able to use the monitoring data in the INCA model made the local volunteers interested in collecting samples and to record more exact meta data. The success of the CM project in East London prompted Thames 21 to apply for a grant to create their own version of Community Modelling, with a project officer working with volunteers using the INCA model set up for other rivers in the London Thames and linking with a citizen science monitoring project they involved with independently. Thames 21 seized the opportunity offered by the CM technique to use monitoring data for their own purposes of connecting local communities to the rives and improving the status of the Thames London ecosystem.

6. Concluding discussion

The Community Modelling technique aims to make scientific environmental computer models useable and useful to local communities. The approach centres on transdisciplinary co-production of a model set up able to address local issues that can be used by local communities after the end of the project. This aim is supported by the four core elements: resource minimalism, strategic recruitment, established software and connection with decision makers. The example case of water quality in East London demonstrated both the flexibility of the technique in relation to local circumstances and its ability to add value to the work of existing initiatives. In this case CM provided a new sense of purpose for local volunteers and it enabled local use of monitoring data in support of Thames 21's agency in decision making in the Catchment Partnership previously dominated by institutions drawing on model-based expertise.

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Strategic Monitoring – a proposal for the institutional surveillance of complex and long-term disposal programmes

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1. Summary

Deep geological repositories objectively are a long-term issue (regarding long-term safety) and require long-term institutional involvement of the techno-scientific community, the waste producers, the public administration, non-governmental organisations and the general public. The demonstration of long-term safety is very challenging and monitoring techniques may contribute to substantiate evidence, support decision making [1] and legitimate the programme. What, where and when to monitor is determined by its goal setting. Therefore monitoring may be operational, confirmatory (in the near field) or environmental (in the far field). Strategic Monitoring, as proposed in this paper, may contribute to process, implementation or policy and institutional surveillance. The "preservation of records, knowledge and memory across generations" as labelled by the corresponding NEA initiative [2] should encompass the tailored transfer of knowledge, concept and system understanding, insights, experience and documentation to specific audiences such as above. Strategic Monitoring is devised to be an integrative tool thereof.

2. Setting the problem(s)

Dealing with a complex sociotechnical system such as the disposal of radioactive waste needs an integrated perspective. Much of the widespread blockage faced in this sensitive policy area may be ascribed to the neglect of looking at the various dimensions involved. This multidimensionality requires an appropriate reference system. Normatively, the principle of sustainability (incorporating protection as well as control [3]) seems to suggest itself, for two reasons. Firstly, it facilitates a stepwise analysis according to the following dimensions: not only the triad of ecological, economical, and social but also temporal, spatial, technical, political, and ethical [4]. Secondly, it forces upon stakeholders, including decision makers, an examination of these dimensions and, consequently, it is apt to incorporate all/most parties' perspectives, needs, targets/goals, and knowledge systems [5].

The long-term objective (ecological) dimension of highly toxic waste is of outstanding ethical relevance: The ones who make the profit (e. g., of energy of which waste is a result) most likely do not bear – possible – risks from the waste (Fig. 1). The decisional situation is such that the current generations (we!) have to decide (postponement is also a decision), and: Apart of winners (this waste producing society) there will be losers (locals and future generations). This is a formidable risk-benefit asymmetry. To be able and competent to handle such complex issues needs an adequate tool – we propose to introduce a Strategic Monitoring for this purpose.

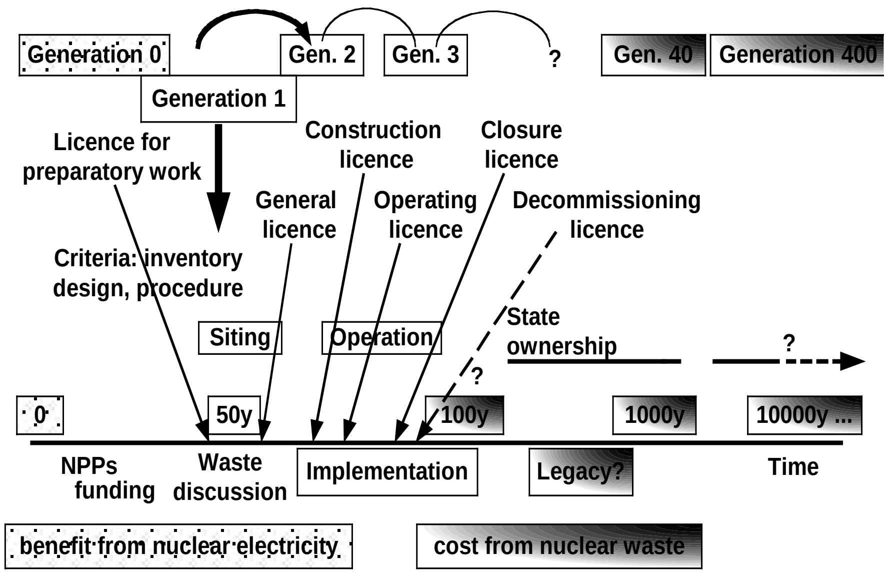

Figure 35: Radioactive waste governance has a long-term safety and a long-term project character. It must be backed up by the technical community, the political decision makers and the general public over decades. While still benefiting from nuclear electricity we, at present, are "Generation 1" having to start implementing the respective programmes. Some duties – of monitoring, etc. – must be handed over to "Generation 2" (explored in [6]). Information procedures and knowledge management play a pivotal role in success or failure of the undertaking (Source: [7]).

3. On the evolution of concepts

Sixty years ago, it was proposed to bury radioactive waste in deep geological formations [8][9] – a pioneering idea, bearing in mind that industrial waste, at that time, was usually dispersed and diluted. Forty years ago, final disposal, without the intention of retrieval, was favoured – consistent with the insight to rely on natural and passive barriers, instead of institutional barriers, due to the long toxic potential of radionuclides [10][11][12]. Thirty years ago, as to knowledge management, the sole issue remained to preserve adequate information for future generations to keep them from inadvertently boring into the underground facility [13][14][15].

During the 1990s the technical community gradually realised that a "repository is, by definition, a long term project, extending over centuries … or even much longer periods for repositories in deep geological formations, receiving [high-level waste, HLW] with long lived radionuclides. A repository project involves a relatively long lead time (possibly more than 20 years for HLW or spent fuel) and is then anticipated to receive waste during several decades. After closing the repository, a surveillance and monitoring period will almost certainly be carried out even [*sic!*] for shallow land burial type repositories with [low- and intermediate-level waste]. This underlines once again the importance of the continuity factor not only from a contractual but also from a technical point of view (possibility/obligation to transfer/receive waste, waste acceptance criteria and quality of waste, control and monitoring, etc.). On the other hand, continuity is of equal importance for the proper functioning of the cost sharing arrangements and the respective payments" [16]. Still valid today, the "official" philosophy holds "… the disposal concept requires that the presence of waste may safely be forgotten, after a period of institutional control to prevent early inadvertent intrusion" [17].

Having said this, it, nevertheless, is by no means an advocacy of perpetual surveillance. For recent analyses of institutional monitoring of radioactive legacies in the USA demonstrate in frustrating openness: "It is now becoming clear that relatively few … [Department of Energy, DOE] waste sites will be cleaned up to the point where they can be released for unrestricted use. 'Long-term stewardship' (activities to protect human health and the environment from hazards that may remain at its sites after cessation of the remediation) will be required for over 100 of the 144 waste sites under DOE control …. The details of long-term stewardship planning are yet to be specified, the adequacy of funding is not assured, and there is no convincing evidence that institutional controls and other stewardship measures are reliable over the long term" [18]. Strohl was of the opinion in 1995 already: "… institutional instruments, although indispensable with regard to long-term safety, should only be considered as making a contribution of relative importance and of limited duration, and this must be made clear" [19]. This perspective has been maintained ever since [20].

The predicament is to find an adequate tradeoff between long-term passive safety with respective confidence in performance assessments and active control based on a suitable institutional constancy, both to be decided by the present society, with due respect for the environment and societies to come. The societal aspects go far beyond considering local interests (unlike asserted in [20]). To create – at least attempt – such robust bonds over many, many years, is the aim of this contribution, a proposal for Strategic Monitoring.

4. Basic rules and procedure to follow in sustainable long-term governance

The nuclear community recognises that the long-term safety of repositories "is not … a rigorous proof of safety ... but rather a convincing set of arguments" [21]. It has, however, been difficult to "live" its socio-technical nature [22]. Albeit the waste problem is driven by technology and, indeed, a technological constraint, in the end, it has to be solved by society. Building upon the defence-in-depth principle, the concept of integral, technical and societal, robustness was developed [23][24]. A system is "socially robust" if most arguments, evidence, social alignments, interests, and cultural values lead to a consistent option [25]. The governance concept attempts to consider technical and social issues in parallel, as to force players (both from the technical community and society) to keep in mind (and strive at) an integrative "solution", satisfying technical (passive safety) and societal needs at the same time. This combination sets it apart from other approaches, either purely technocratic along the conventional decide-announce-defend line or the voluntaristic policy some national programmes have reverted to in the face of the failed technocratic approach (e.g., Sweden, Japan, UK, USA) or any unsystematic negotiated mixed versions [26][27]. Based on international experience [6][24][28], we proposed a 3-step approach for a site-selection procedure, followed by a proposal for an integrative assessment framework (cf. [29]):

Step 1: Discuss – comprehensive societal discourse
Step 2: Decide – "common ground" in goals and stepwise strategy
Step 3: Implement – start programme and prepare long-term knowledge basis

The rules and criteria of site-selection procedures have to be consented to before the start and adhered to during the process. Revisions should undergo a careful review and be consented to. A clear distinction between implementer and regulatory bodies is vital. The regulators must establish a platform for inclusive knowledge generation, based on a (pre)defined set of criteria. This necessity to integrate different requirements, the step-by-step approach, the chance of "institutional constancy", and the in most countries perceived "national" task of the issue call special attention to the role of the authorities [30]. Issues like regulatory capture, expert blocking, or technological lock-ins have to be duly considered (Tab. 8).

In view of a successful transfer of knowledge, it is vital to explore contextual issues and tacit/implicit knowledge – they determine the degree of societal understanding of the eventual disposition system. Unless the rationale of conceptual reasoning is appropriately handed over to next – technical, political and societal – generations, the entire undertaking is bound to fail [31].

The long-time process has to be overseen, e. g., with the instrument of Strategic Monitoring and by a widely credible and trustworthy body. In 2002, Flüeler suggested a "National Council for the Safe [and Secure] Governance of Radioactive Waste" as the guardian of the process [23], the Swiss expert committee EKRA foresaw a "Disposal Council" [32]. It should be pluralistically composed, independent of the industry yet knowledgeable and not driven by daily politics. A periodic policy evaluation is vital to assess whether a programme is on track (see e. g., [33]). Some respective issues and criteria to develop a Strategic Monitoring are suggested in Tab. 1 and are expatiated in the oral presentation.

Table 1: Issues (normal) *and respective criteria (Italics) to monitor and evaluate institutions for an appraisal of governance and other theoretical concepts* **(bold)** *in order to develop Strategic Monitoring (own tabulation, work in progress).*

Area	**Approach/concept**			
	"Good" governance	**Regulatory (and other) capture**	**Safety culture**	**Path dependence, lock-ins**
References	[34][35][36]	[37][38][39]	[40][41][42][43]	[44][45][46]
A. Formal (system) structure	Legitimation	Asymmetry	Continuous system learning	Persistence
	Legislation: goal, time frame, players, boundary conditions, etc.	*Research & development plan*	*Code of conduct, guidelines, etc.*	
	Degrees of participation by players/stakeholders	*Resources (staff, financial)*	*Feedback from staff and stakeholders*	*Research financing*
	Goal orientation, effectiveness/efficiency	*Competence(s) and experience*	*Education, permanent training; team learning*	*Review organisation*
	Degree of consensus, inclusiveness, capacity building	*Expert blocking*	*Organisational learning*	
	Rule of law			
B. Understanding of roles	Division of roles	Institutional analysis	(Senior management) commitment	Openness of decision making
	Programme tasks	*Interrelations with other players*	*Leadership*	*Comparison of options*
	Strategic planning	*Structure analysis*	*Employee involvement*	
	Responsibility			
C. Internal (organisational/personnel) structures	Transparency/ accountability/ equity	Mental models	Failure culture	Resistance vs. innovation
	Justification of decisions	*Recurrent key statements*	*Openness of communication, culture*	*Mechanism of selection*
	Framework and respective guidelines	*Terms of reference, code of conduct*	*Trust*	*Components of self-reinforcement*
	Controlling: target analysis	*Performance analysis*	*Compliance analysis*	
	Responsiveness	*Agenda analysis*	*Incident reporting*	
	Quality management		*Complacency*	
	Reviewing		*Norms, values and basic assumptions*	

5. Conclusion

To consider both technical and social issues needs an inclusive, systematic and participatory approach to single out goal priorities (presumably with safety first). Setting up a respective process is a prerequisite to proceed in site selection (and further programme steps). It is essential to have a (national) lead agency in conjunction with a clear division of roles among the players, rules of the "game" and criteria to judge. The proposed oversight body surveils the programme and its focused implementation. The complex and long-lasting procedure necessitates extensive resources on all sides and of all types over time.

Our society's success in credibly addressing *intra*generational issues might convince future generations to be willing to carry on the programmes when needed. According to the concept of social robustness, the concerned and deciding stakeholders must achieve consent on some common interests, at least on three levels: the problem recognition, consensus on the main goals, and the procedural strategy ("rules of the game") [6]. As to knowledge transfer, the challenge is to ensure a continual process so that the broadly consented goals can be understood, agreed to and followed by generations to come.

It has become clear that the institutional aspects are more and more getting to be the linchpin of the issue – and maybe of the solution:
- The long-lasting and entwined project character rests on the constancy of competent and trusted institutions;
- Society may only exert indirect control on such complex technological projects as the one at hand, via institutional paths [47][14][15]; the main quality check in science, at that, is institutional peer reviewing [48][49][50][51][52];
- The public appraises technologies, thus nuclear, as a whole, including the respective institutions [53] and their achieved "degree of safety" as Vlek & Stallén [54] put it;
- The debate on risks is also a debate on democracy and progress, it is sparked off by the "controversy over the institutionalisation and regulation of the progress of technological knowledge" [55]; Kasperson and colleagues went so far as to coin the "risk crisis" to be truly an "institutional crisis" [56].

The broader the societal agreement on key issues is (e. g., what is the main goal of a programme, what are complementary goals? Where is consensus, where dissent, where compromise? How safe is safe enough? When shall monitoring be terminated, on what grounds?) the more valuable – "robust" – and useful is the social-pool, and, at that, also the technological, resource the future generations can draw from. Strategic Monitoring may serve to cover the mentioned aspects.

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C.g – Closing Session

Regulatory perspective about monitoring dedicated to geological disposal facilities for radioactive waste

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1. Summary

This paper provides a regulatory perspective on the role of monitoring of deep geologic repositories in Finland.
The Finnish regulation specifies how monitoring shall be used to gather information and to follow the facility safety, and the 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. During the operational period of a geologic repository, the Finnish regulation requires monitoring of safety relevant bedrock properties and disturbances, and also monitoring of the engineered barrier system (EBS) . The Radiation and Nuclear Safety Authority (STUK) will ensure that the proposed monitoring programme is adequate, and carries out the necessary regulatory oversight.
In Finland, Posiva and STUK have thorough and long-term experience on the site characterization and monitoring of the effects of construction of the ONKALO Underground rock characterization facility (URCF), and during the construction activities of the actual spent nuclear fuel (SNF) repository. STUK has reviewed, assessed and inspected the implemented monitoring programme.
In addition to the regulatory oversight on the monitoring of the SNF repository under its current contruction phase, STUK's oversight has included also the two operational low and intermediate level waste (LILW) repositories, since 1992 and 1998.
One of the key elements regarding monitoring, is the development of monitoring strategy, and understanding what is necessary, and what can be achieved by monitoring during the operational period in relation to the long lasting evolution of the barriers.

2. Introduction – Nuclear waste disposal in Finland

In 1983, the Finnish Government made a strategy decision on the objectives and target schedule for the research, development and technical planning of nuclear waste management. At the end of 1999, Posiva Ltd, the current implementer of the disposal programme, submitted the application for a DiP [1] for a SNF 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 the construction of an URCF, to the depth of the actual planned disposal, as required by regulation.

The Government granted Construction License for the Olkiluoto SNF disposal facility in 2015 and the facility is expected to start operation around 2024.

The URCF, ONKALO, has been excavated, and is integrated to the spent nuclear repository, now under construction. Since ONKALO was constructed at the actual repository site, the construction and operation of this facility should not cause major disturbances to the bedrock properties important for the post-closure safety. As ONKALO was foreseen to become a part of the disposal facility, it was constructed under STUK's regulatory oversight .

There are also two operating LILW disposal facilities in Finland, at the depth of approximately 100 meters. The LILW disposal facility operated by Fortum Power and Heat Ltd since 1992 is in Loviisa. The other one is operated by Teollisuuden Voima Ltd since 1998, and is situated in Olkiluoto.

3. General aspects of the role of monitoring

The roles of monitoring are related to specific phases of the 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 the pre-construction period monitoring establishes knowledge of the site baseline and natural evolution. During the construction phase, monitoring follows the effects of the construction, compared to baseline or expected disturbance. If construction continues during the operational phase, monitoring of disturbances goes on. These different roles of monitoring are related to site, and are agreed among different parties.

During the operational phase, some kind of monitoring of the barrier system evolution is required. The strategy and implementation are 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, the implementer may choose from the following alternatives of monitoring: near field site properties, in-active demonstrations of engineered barrier performance, defined active waste packages, or to use future wireless technology for monitoring all canister locations.

For every selected route, it would be important to develop a 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. The key question is to address the level of confidence that can be achieved through monitoring and reliability of information that can be gained with long-term monitoring.

4. 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 confirmation of the performance of the safety barriers.

STUK has imposed requirements for monitoring in nuclear facilities, especially for radiation and environmental monitoring, for all phases of the life span on a facility; licensing, design, operation and decommissioning. The STUK Regulation STUK Y/4/2018 [2] for the disposal of nuclear waste imposes requirements how to performmonitoring. These requirements are also given in more detail in STUK's YVL Guides.

The STUK Regulation identifies the need of using investigations and monitoring for ensuring post-closure safety. The Regulation also has requirements concerning favourable site properties that shall be observed using a research and monitoring programme. Concerning barrier performance, it is required that ”In order to ensure the performance of the barriers, a research and monitoring programme shall be established and implemented for the operating phase of the disposal facility.”

STUK YVL Guide D.5 [3] part “Construction, operation and closure of the disposal facility” gives more detailed requirements for monitoring:

“During the construction and operation of the disposal facility, a research and monitoring programme shall be executed to ensure that the site and the rock to be excavated are suitable for disposal and to collect supplementary information about the safety-relevant characteristics of the host rock and the performance of the barriers. This programme shall at least include

- characterization of the rock volumes intended to be excavated
- monitoring of rock stresses, movements and deformations in rock surrounding the emplacement rooms
- hydrogeological monitoring of rock surrounding the waste emplacement rooms
- monitoring of groundwater chemistry
- monitoring of the performance of engineered barriers; and
- monitoring of the surface environment.”

Monitoring is also related to the basic principle of continuous improvement of safety. STUK guide YVL D.5 requires the licensee to have a programme for operating experience feedback, with a monitoring programme as one of the information sources. Based on these programmes, possibilities for safety enhancement shall be considered and any improvements found justified, shall be implemented.

5. Monitoring in the different phases of repository lifecycle

The Finnish regulations require the implementer to develop a safety concept including the safety functions and performance targets for the different barriers. The regulation also includes general requirements for monitoring. The requirements have evolved during the development of the deep geologic repositories. It is the implementer’s responsibility to identify which geological or other parameters the monitoring programme should include. As a regulator STUK ensures that the proposed monitoring programme has adequate content, it is carried out and information is collected, evaluated and recorded. STUK reviews all monitoring results dealing with the facilities under construction, and regularly during the operational period. 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 into the following phases: site selection, construction, operational, closure and post-closure. The monitoring may be related to these phases for example by the following tasks:

- Monitoring before the site selection (for the Environmental Impact Assessment, EIA)
- Baseline or basic monitoring of site properties (bedrock, environment, 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 the first part of the disposal)
- Monitoring related to demonstrations for technical feasibility of the concept (research phase dealing with EBS-components) , and the performance confirmation of barriers

- Monitoring the effects 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.

5.1. Monitoring before construction

The safety of the disposal facility is based on ensuring the long-term engineered containment and isolation 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 the barrier system, and to 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 the undisturbed conditions. This process can be part of identification of undisturbed host rock properties that form the baseline for monitoring during the construction phase.

After the site selection and the finalization of the DiPby the Finnish Parliament in 2001, STUK informed Posiva about the future regulatory oversight, and about the content of information to be submitted before construction work could start. According to STUK’s request, a set of URCF documentation was prepared that focused on the construction of the facility and on post-closure safety issues. The documentation consisted of baseline conditions, main drawings, assessment of disturbances caused by construction and operation of URCF, monitoring program during construction and operation of the URCF and the programme for underground characterisation and research.

The monitoring plan was is in principle adequate for the URCF phase, but when entering to construction of actual disposal rooms or to disposal operations, the coverage of monitoring programme should be re-evaluated. The monitoring programme comprehensively covered the monitoring of disturbances in surrounding bedrock, surface water and groundwaters and in the surface environment. STUK noticed that a seismic monitoring network should be established to Olkiluoto and the 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.

The monitoring programme was based on assessment of post-closure safety relevant site properties and possible disturbances affected by construction. The effects were classified 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’s oversight are described later in this paper.

5.2. Regulatory oversight of construction monitoring

In Finland the construction of the URCF, ONKALO, has been finalized and it is integrated as a part to the disposal facility. During the construction of the URCF, an extensive monitoring programme was carried out to follow for construction effects. This programme included several monitoring areas, such as the surface environment, hydrology, hydrogeochemistry, rock mechanics and foreign materials. STUK followed Posiva's monitoring activities, inspected specific parts of Posiva's Olkiluoto Monitoring Programme, and reviewed the documentation. The information that the programme provided was utilized in the construction license application review process. STUK expected that a similar and extended monitoring programme will be used later during the construction and operating periods of the disposal facility.

In connection with the construction licence application, the updated monitoring programme was based on the monitoring program implemented during the construction of an URCF. It described the general principles for monitoring during the operation of the of the disposal facility. The monitoring program also describes the plans for monitoring the behavior of the EBS as a new field, discussed later in this paper.

The long-term effects of construction are the key aspect observed in the periodically updated monitoring programme . The programme includes monitoring of bed rock mechanics, hydrology, hydrogeochemistry and surface environment in the vicinity of the disposal facility. 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 results from the monitoring of the bedrock and groundwater are primarily used to verify the models that describe the evolution of the site. In addition, construction activities disturb the geological environment and conditions in many ways. The purpose of STUK's regulatory control of disposal facility construction is primarily to ensure that the design, adaption and construction are carried out in such a manner that the geological 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 disposal facility tunnels and shafts, and
- Introduction of foreign, potentially harmful substances to disposal facility during construction (cement and other grouting materials, reinforcement materials, explosives, hydraulic oils etc.).
- Hydrological flow routes from surface to disposal rooms

STUK has had a comprehensive regulatory approach for review and assessment and inspection of construction activities. STUK has reviewed the updates of the monitoring programme during construction, and also the annual reports of the different fields of monitoring.

During the construction STUK has reviewed procedures for excavation, injection grouting and rock reinforcement where also the aspects of disturbance and monitoring are assessed. STUK has made inspections to management of the 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.

5.3. Monitoring of operational safety

The monitoring programme for the effects of construction is continued during the operational phase since the continuous construction and keeping the facility open may have effects 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.

5.4. EBS monitoring

Regulatory guide (YVL D.5) includes the requirement of EBS monitoring also during the operational period. The EBS monitoring 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 the 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 (STUK Y/4/2018) contain the requirements to carry out research to follow up and develop the disposal process (concept, process, technology) during the 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 activity can also include the 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 EBS monitoring is carried out to follow the evolution of different engineered barriers in contact with the bedrock and the groundwaters. 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 not 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 the planned operational period of the disposal facility and barrier evolution. 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 for managing and minimizing uncertainties in the information used in the safety analyses for periodically updated safety cases.

5.5. Monitoring during the institutional control phase

According to Nuclear Energy Act ("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.

In case the State considers it necessary, a monitoring system may be used and the estimated life time cost will be charged in advance from the implementer, before the approval of the closure.

This monitoring is mainly used for confidence building for 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 the 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.

6. 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-made instrumentation is high. Also experience of successful long term instrumentation and monitoring test or demonstrations is sparse. The necessary technology may still be available in the future during the operational period, up to and over hundred years, from the 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.

7. Conclusions

In Finland STUK has experience in regulating the monitoring of the first phases of the repository lifecycle. Posiva has developed a monitoring programme for site characteristics, baseline, and construction effect monitoring. FPH and TVO have implemented monitoring programs successfully for the operational period of the LILW disposal facilities. STUK has reviewed, assessed and inspected the implemented programmes. A monitoring programme should be comprehensive and support the maintenance of the favourable site properties. Based on STUK’s regulatory experiences, it is important that the implementer addresses carefully the safety relevant properties, the parameters selected for monitoring and the management system to take actions based on monitoring findings.
The more detail requirements for EBS monitoring is under discussion. However, the regulation is seen to be sufficient for the construction phase. The need for an update is evaluated before the operational phase.
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 the 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.

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Regulatory Perspective about Monitoring dedicated to Geological Disposal Facilities for Radioactive Waste in Switzerland

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1. Summary

The Swiss disposal project (deep geological disposal for L/ILW and HLW) is currently in a site selection process. This process, called "Sectoral Plan for Deep Geological Repositories", has reached its third and final stage. Major milestones of this plan include the publication of the implementer's decision on the site(s) in 2022, the application for the general license in 2024, the regulatory review by 2026, the decision of the federal council in 2029 and a facultative national referendum afterwards. This abstract provides an overview on the current regulatory framework regarding monitoring and monitoring-related regulatory activities by the Swiss regulator ENSI (Swiss Federal Nuclear Safety Inspectorate). With regard to the last stage of the sectoral plan and the upcoming general license application, ENSI has updated its requirements and is currently updating its guideline. This document provides an overview on the requirements in force and the approach on monitoring activities by ENSI.

2. Introduction

The passively safe geological disposal is widely accepted 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). This principle is anchored in the Nuclear Energy Act (NEA) [1]. The legislation thus calls for deep geological disposal of all categories of waste arising in Switzerland. The required disposal concept was expected to be based on a combination of natural and engineered 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, the concept of monitored long-term geological disposal has been developed. This 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.

The "Sectoral Plan for Deep Geological Repositories" [2] specifies how sites for deep geological repositories for radioactive waste are to be selected in Switzerland. The concept for the sectoral plan for deep geological repositories was developed by the Swiss Federal Office of Energy (SFOE) together with other agencies and organisations, and was approved by the Swiss Government in 2008. The sectoral plan allows a transparent and fair choice of locations, in three stages. The third and final stage of the sectoral plan started in November 2018 and is planned to be completed around 2030.

ENSI is responsible for reviewing and assessing the proposals for sites in terms of safety and technological feasibility. For this purpose, ENSI issues requirements and guidelines to formalise the implementation of the Nuclear Energy Act (NEA) and Nuclear energy Ordinance (NEO) [3]. Furthermore, ENSI releases safety-related specifications for different stages of the sectoral plan.

The purposes of this document are to illustrate ENSI's approach in defining its current expectations regarding the monitoring of a deep geological repository and to provide a more detailed view on the monitoring perspectives of ENSI. Regarding a detailed overview on the entire waste management plan in Switzerland the author refers to the latest joint convention country report [4], ENSI's latest annual oversight report [5] or the Waste management plan by Nagra [6]. Nagra (National Cooperative for the Disposal of Radioactive Waste) is the Swiss implementer, which is responsible to prepare and implement solutions for the disposal of all radioactive waste categories. This document focuses on the perspectives and activities by ENSI and does not include monitoring-related activities by Nagra.

3. Repository concept and regulations

According to the Swiss framework for monitoring (NEA and NEO), a deep geological repository system comprises the following three elements (Fig. 1): a) a main facility for the emplacement of the radioactive waste, b) a pilot facility for monitoring repository system behaviour and for demonstrating compliance with safety requirements, c) test areas (underground rock laboratory with several test areas).

The Swiss NEA, the NEO and the guideline (ENSI-G03) [7] specify in more detail the requirements for monitored geological disposal. According to the NEO, any measures that would facilitate monitoring and maintenance of a geological repository or retrieval of the waste may not compromise the functioning of the passive safety barriers (§ 11, NEO).

After closure of the repository, the Federal Council can (§ 39, NEA) order a further limited monitoring phase. Following final closure, or after expiry of the monitoring period, a geological repository is released from the provisions of the nuclear energy legislation by an appropriate order (§ 39, NEA).

According to the regulatory framework the test areas are self-contained parts of the geological repository without emplaced waste, 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 (monitoring) 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 program 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 evolution. For this purpose, the pilot facility has to be built in the same design as the main facility.

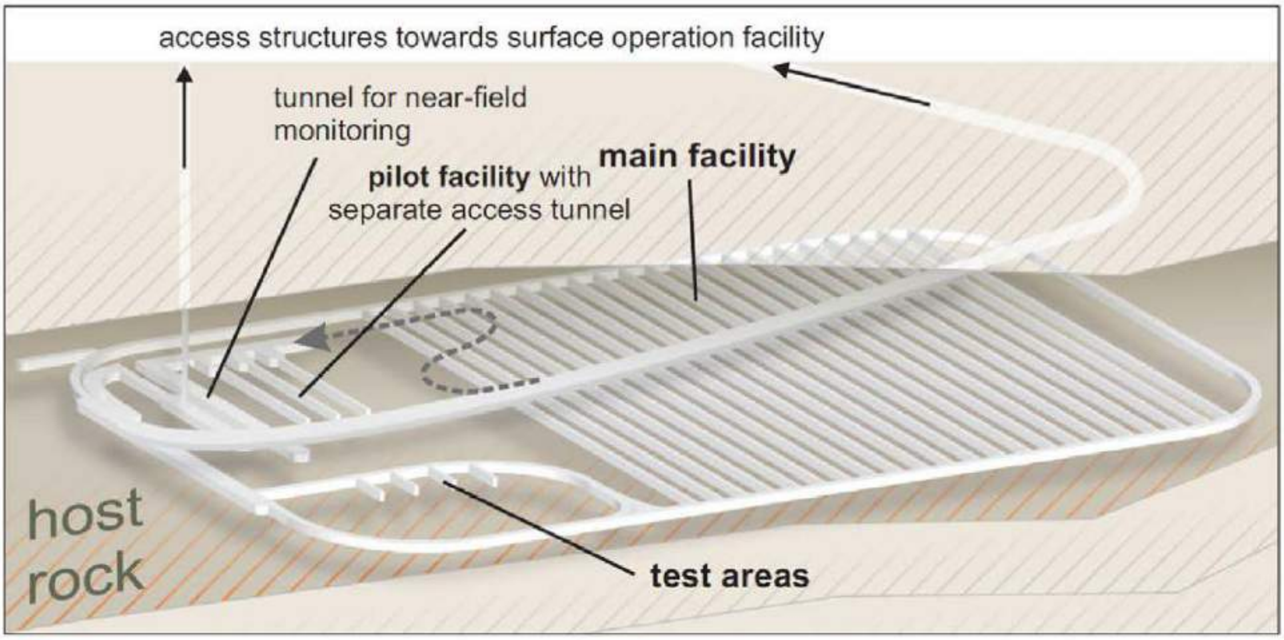

Figure 1: System elements of a monitored geological repository: main facility, test areas and pilot facility.

4. Phases of repository implementation

Following the requirements of NEA/NEO, implementation of a geological disposal facility is a stepwise process over several decades which include the following key phases (estimated time needed for each phase of the implementation of a deep geological repository for high-level waste (HLW) is indicated in parentheses):

1) Site selection process based on the sectoral plan for deep geological repositories [2] and general licence application for the selected site (appr. 20 years)
2) Pre-construction environmental monitoring phase (set-up of baseline conditions) (depending on parameter)
3) Underground exploration phase (rock laboratory for site characterisation) including test areas (20 years)
4) Repository construction including pilot facility (10 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 (6) 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 program, 50 years have been assumed.

5. Current requirements for monitoring

The guideline ENSI-G03 specifies the applicable protection objective and protection criteria and the requirements applying to a deep geological repository. In preparation for stage 3 of the sectoral plan, ENSI is currently revising the current version of the guideline from 2009. For this revisions, compliance with the IAEA safety standards (e.g. SSG-31 [8]) shall, if applicable, be achieved. Following the same procedure, ENSI has already specified its requirements for stage 3 of the sectoral plan and the general licence application for a DGR [9].

According to ENSI-G03, the environmental monitoring of a geological repository must be initiated prior to the start of any underground construction to allow reliable data to be collected 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 until repository closure. The monitoring shall include at least

- monitoring of the geological environment,
- radiological environmental monitoring,
- radiological monitoring during operation,
- monitoring of the pilot facility, and
- geotechnical monitoring during construction and operation of the facility.

Monitoring must continue until the facility is released from the provisions of the nuclear energy legislation. Monitoring may not compromise the passive safety barriers. The monitoring program might be divided in subprograms according to their objectives and aspects. The suitability of the monitoring program has to be checked periodically. In this framework, the monitoring program(s) and its (their) results are to be submitted periodically to ENSI for review.

In preparation for stage 3 of the sectoral plan, ENSI has specified the requirements regarding monitoring. Thereby ENSI has defined its expectation regarding the scope of the monitoring and the related documentation to be submitted for this pre-licensing phase. Based on its regulatory project, which will be described in further detail below, ENSI has formulated the following requirements [9]:

- For the general license, the implementer has to submit an integral concept for monitoring for all phases and aspects of a deep geological disposal. The integral concept for monitoring has to take into account the design requirements specified in guideline ENSI-G03.
- For each phase in the realisation of a deep geological repository, the relevant processes and parameters have to be discussed and an integral concept for the accompanying monitoring proposed.
- The integral concept for monitoring has to cover the handling and archiving of gathered samples and data.
- To provide sufficient and conclusive data, baseline monitoring has to begin early enough before the construction phase. Therefore, for each parameter the measurement methodology, the spatial and temporal resolution, the required time series and, consequently, the start of the measurement have to be discussed.

- The implementer has to show how previous information and data (e.g. from previous site investigations) will be included in the long-term- and baseline monitoring program.

According to the decision of the Federal Council [10] regarding the waste management plan 2016 [6], the implementer has to document preparatory activities regarding the baseline monitoring within the next waste management plan in 2021. Thereby, it has to substantiate the relevancy of processes and parameters for the environmental monitoring and the baseline monitoring and how they are to be measured.

6. Regulatory research project

To clarifying outstanding issues, establishing fundamentals and developing tools to perform its supervision of nuclear safety of Swiss nuclear facilities ENSI is performing regulatory research projects. In recent years, ENSI has executed several projects with relevance to monitoring under this framework. The scope and the results of the projects “Pilot facility” and “Monitoring” have been presented at the “Proceedings for the international conference on repository monitoring” in Luxembourg in 2013 [11]. In 2018 ENSI has launched a follow-up project on “Concepts for Monitoring and Monitoring installations 2”. The primary goals of this project are

- providing the fundamentals for the revision of the regulatory document ENSI-G03 and the specific requirements for stage 3 of the sectoral plan, and
- developing regulatory expectations regarding a concept for monitoring.

This involves the discussion of regulatory requirements and the interfaces of different areas and aspects of monitoring such as the pilot facility, the test area, the environment, as well as monitoring during construction and operation of the facility, the verification of site specific scientific data, and the framework of a suitable baseline monitoring.

To achieve the project goals, ENSI is following the activities in national and international projects (e.g. Modern2020, Mont Terri Rock Laboratory), holding workshop with internal and external expert and with other regulatory bodies in Switzerland, performing scientific experiments (e.g. at Mont Terri Rock Laboratory), studying monitoring approaches for international disposal projects, reaching out to other industries, and visiting disposal sites. The project shall terminate in 2020.

Preliminary results indicate the complexity in monitoring a disposal facility. Figure 2 shows the schematic interaction of different monitoring subprograms over different phases of the implementation of a deep geological repository. The monitoring of a deep geological repository usually comprises many different fields covering all phases of the disposal project. Depending on the regulatory framework multiple authorities (for Switzerland e.g. Federal office for the Environment, Federal office of Public Health, regional authorities) are involved the regulation and oversight of various aspects and phases of a deep geological repository. Therefore, it is to be considered that different monitoring programs might overlap and interfaces between these might exist. It has been identified, that due to the future evolving state-of-the-art technology, knowledge and experience, the monitoring program should stay flexible enough to meet any changing needs during the different phases of implementation of a disposal facility, in connection with the associated milestones and for the support of the safety case.

Each monitoring subprogram has its own objectives, covers different phases of implementation (Fig. 2) and has specific baseline monitoring requirements. Several subprograms will provide valuable information for decisions points. ENSI therefore requires that the implementer will submit for the general licence application an integral concept for monitoring that covers all aspects of the overall monitoring program and its internal interaction.

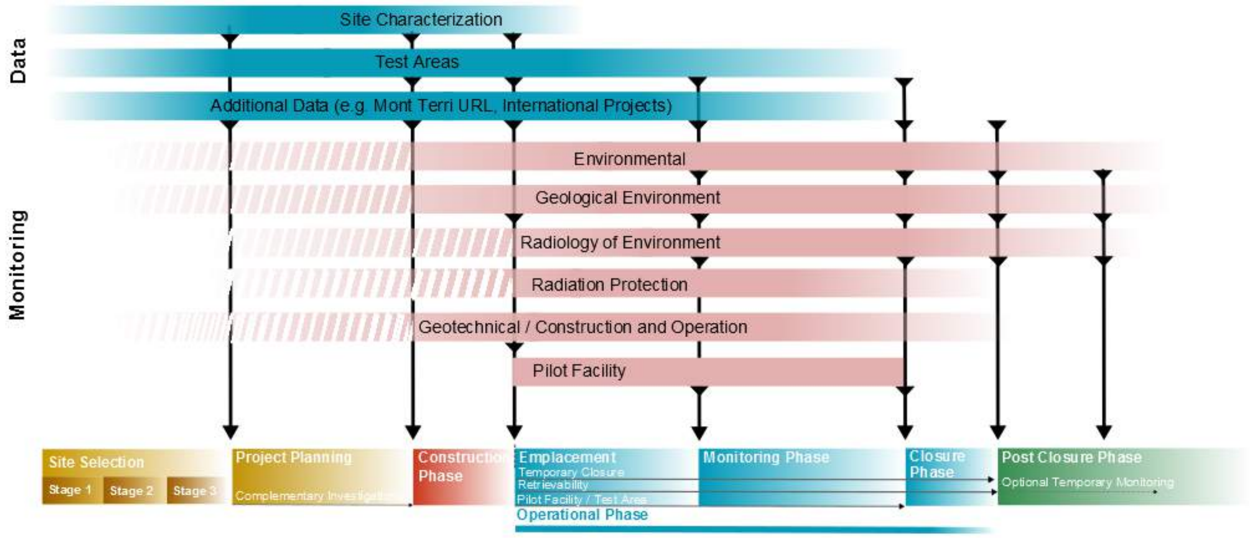

Figure 2: Schematic overview of different monitoring activities and data gathering to support decision making processes during the development and implementation of a deep geological facility (see phases below). The vertical arrows represent decision points. The shaded parts of the monitoring subprograms indicate baseline monitoring phases.

One of the key elements in the decision for closure of the facilities is the pilot facility. In the framework of an ENSI-internal project "Pilot facility", safety relevant processes and parameters were discussed, which now are used to develop an independent view on the extent of the related monitoring program.

7. Requirements for the pilot facility

In the pilot facility, the behaviour of waste, backfill material and host rock shall be monitored up to the end of the monitoring phase. During monitoring, data for the performance of the main facility are to be collected to evaluate the validity of 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 monitoring program for the pilot facility has to aim at investigating 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 evaluate the validity of the safety assessment.

8. Outlook

The revised version of the specific design principles for deep geological repositories and requirements for the safety case (ENSI-G03) will be subject of a public consultation in 2019 before it becomes effective in 2020. This revised version will also take into account first results from the ENSI-project on "Concepts for Monitoring and Monitoring Installations 2".

An integral monitoring concept/program has to consider all phases, the current state-of-the-art knowledge and technology, flexibility for any evolving needs over time. It has to provide evidence on the validity of the safety case for all stages in the implementation of a deep geological repository.

The project "Concepts for Monitoring and Monitoring Installations 2" will provide an important basis for the future ENSI review of the next waste management program of Nagra in 2021. It will allow to evaluate Nagra's activities regarding baseline monitoring. ENSI will periodically discuss the regulatory expectations regarding monitoring and adapt it to the state-of-the-art in science and technology.

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Appendix D. Full Conference Papers – Poster Presentations

D.a – Session on Monitoring Technologies

Development of thermocouple psychrometers for water content measurement

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Problem and motivation

The use of bentonite-based materials is considered in almost all programs as an engineering barrier for the geological disposal of HLW. Bentonite based materials are used as a buffer that surrounds waste packages and/or as tunnel seal. These materials are selected mainly because of their low hydraulic permeability when saturated and because of its swelling pressure, which improves its sealing capacity. Bentonite buffers do not reach saturation until a certain time after its installation. During that period, bentonite water potential domains groundwater flow, along with radionuclides through the EBS. Therefore, water potential monitoring is important to evaluate the performance of the buffer.

Thermocouple psychrometers have already been used to measure the total water potential in bentonite-based materials with high water contents (suctions below 6200kPa). While other types of sensors, such as capacitive ones, have a limited performance in high relative humidity environments, thermocouple psychrometers can cover the range between 95% up to 100%.

This good performance in high humidity ranges is due to the measurement principle: A fine-wire Peltier junction (thermocouple) can be warmed or cooled passing an electric current through it. When this process is done under high relative humidity conditions, water evaporates or condenses on the junction, generating an electromotive force in the thermocouple. In thermal equilibrium, this electromotive force is dependent on the water potential. Thermocouple psychrometer transductors can be interrogated using two methods: the psychrometric method and the dew point method:

- The psychrometric method consists in cooling the thermocouple to a temperature below the dew point to allow water droplets to create on the junction. After that, the current injection is stopped, and the junction is let to reach thermal equilibrium again, but before that, condensed water must evaporate. This produces a slope on the temperature graph that can be interpreted as the equilibrium point. However, it is difficult to determine the exact moment when equilibrium is reached because it is a transitory effect. In addition, different mathematical criteria can be applied to detect the equilibrium, so the accuracy is limited.
- The dew point method can provide a continuous measurement, allowing greater precision in measurements. After the cooling process, this method modulates the cooling current just to compensate the evaporation process, reaching a permanent state of equilibrium, which is more reliable.

Nowadays, only the psychrometric method is being used for tracking water on EBS. Moreover, the available measuring electronics for long-term monitoring only operates using the psychrometric method.

Besides, commercially available dew point measuring devices are scarce, complex, voluminous, expensive and they are usually based on old fashioned electronics.

Hypothesis

This work is focused on developing a new, cost-effective solution to handle the dew point method for long term water potential measurements in the bentonite barriers when close to saturation state. Two main tasks can be distinguished:

1. The research on new electronics and software to carry out the measurements.
2. The integration of the new electronics with a commercial thermocouple psychrometer in a robust solution to operate under the repository conditions.

Method

After a state-of-the-art compilation on available measuring devices and related technical documentation, **it was decided to use** a Wescor HR33T microvoltmeter **as a reference during the first steps of the design**.

The HR33T is a device developed in the 1980s based on analog electronics. It is conceived for measuring water potential with thermocouple psychrometers. The device is built on a small suitcase (310mm x 250mm x 130mm), needs a symmetrical power supply of ±18V and weights around 3kg with 10-hour operation batteries. It has been chosen because it can operate not only using the psychrometric method but also the dew point one, being the only one known by Arquimea to perform such measurements.

Commercial Wescor PST-55 psychrometers, which are compatible with the HR33T, have been selected as transductors for the sensing system.

A deep research was also made on the physics involved in the dew point measurement process which must be performed following a sequence of defined steps:

- Zeroing sensor lectures.
- Sensing temperature of the sensor in thermal equilibrium with environment.
- Cooling a fine-wire thermocouple with a pulsed current (Peltier effect) to condensate water on it.
- Modulating the cooling current pulse width as condensed water evaporates until no evaporation nor condensation is produced, matching dew point temperature.

While the HR33T is conceived as a device to be operated manually, for long term monitoring of EBS not only an autonomous solution is mandatory, but also a small size and low power features are a concern, so it was decided to develop a completely new electronic system for this purpose.

The new system has been developed around an ARM Cortex-M4 microprocessor. It has been designed not only to be operated as a standalone measuring device but also to be easily integrated on more complex applications.

Flexibility has been a key design driver, so the new system presents both USB and UART connectivity to be operated and read. It can be powered directly from the USB or through a dedicated 5V interface. A universal connector is provided to easily switch measuring between different psychrometer sensors with a single device. A programmable current source is used to stimulate the psychrometer, and two instrumentation amplifiers and filtering electronics are provided to conditionate the readout of the thermocouples. Finally, some transistor switches are used to control the circuit depending on the stage of the measurement process. The proposed system is very compact with dimensions of 63mm x 20mm x 20mm and 20g weight.

For its use at LTRBM demonstrator, the psychrometer sensor head has been placed inside a porous cap made of sintered stainless steel while the rest of the sensor body has been sealed with epoxy-resin in a stainless-steel cylinder.

Main findings

The accuracy and sensitivity of the new system have been tested using three different calibrated water potential standards. Provided samples are made up of a saline dissolution (NaCl) with a known molality that gives a known constant water potential, in this case the standards were -0.25 MPa, -0.725 MPa and -2.5 MPa.
To conduct the measurements, the transductor and the sample were introduced into a gastight metallic sample chamber using the procedures detailed in [1]. To reduce ambient temperature influence during the experiments, the chamber was enclosed inside an adiabatic case. This setup was validated with the HR33T using each of the samples.
First tests with prototype demonstrated that the designed system was sensible to water potential variations, although not completely accurate. Results are detailed on Table 1**.**

Table 9: First measures of the prototype electronics using standard potentials.

Water Potential of the sample	Date	Hour	Tpsy (°C)	Water Potential (bar)
-25 bar	21/05/2018	15:51	23.85	-23.99 ±0.152 bar
-25 bar	21/05/2018	16:02	24.09	-24.063 ±0.122 bar
-25 bar	21/05/2018	16:05	24.04	24.128 ±0.122 bar
-25 bar	21/05/2018	16:08	23.96	24.135 ±0.183 bar
-7.25 bar	22/05/2018	17:20	20.57	-4.156±0.122 bar
-7.25 bar	22/05/2018	17:29	20.62	-4.216±0.122 bar
-7.25 bar	22/05/2018	17:39	20.96	-4.487±0.182 bar
-7.25 bar	22/05/2018	17:51	21.12	-4.421±0.158 bar

During the prototype testing, some noise problems were found, mainly related to parasitic effects on the acquisition chain during excitation (cooling cycles) and readout processes. Therefore, PCB design and layout efforts made to improve measurements quality on the final design. Five units (5) with the final design were manufactured for LTRBM test. Extensive testing was performed with them, showing good results, and much better noise performance. Finally, these units were verified by an external laboratory using a controlled humidity generator chamber instead of the calibrated water potentials.
Obtaining a very controlled high relative humidity is technologically quite a challenge. Due to this reason, only it was possible to measure one point in the upper part of the scale (around the 98%RH). Results are condensed in the following table (Table 2) showing a good correlation between the measured pattern and the measurements taken by the psychrometers.

Table 10: Measures of the final systems using a controlled humidity generator chamber.

PSY#0	RH reference (%)	Specimen RH measurement (%)
	98.10	98.60
	98.61	98.80
	98.60	98.83
	98.38	98.85
PSY#1	**RH reference (%)**	**Specimen RH measurement (%)**
	98.06	98.63
	98.09	98.62
	97.87	98.62
	98.65	98.96
	98.58	99.03
	98.57	99.05
PSY#2	**RH reference (%)**	**Specimen RH measurement (%)**
	98.4	97.16
	98.3	97.34
PSY#3	**RH reference (%)**	**Specimen RH measurement (%)**
	98.44	98.75
	98.36	98.75
PSY#4	**RH reference (%)**	**Specimen RH measurement (%)**
	98.18	98.17
	98.35	98.33

Conclusion

A new system to measure relative humidity through dew point method using psychrometer sensors have been developed and tested. Relative humidity sensitivity has been demonstrated using calibrated samples. Moreover, it has been validated by an external laboratory to confirm its precision showing good results.

The resulting system is autonomous, has a low size and it is versatile enough to be adapted to different cases of use, providing different working modes and control interfaces.

Four units have been installed on LTBRM demonstrator.

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Techniques for non-contact displacement measurement

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1. Summary

In the framework of the H2020 Project Modern2020, this work reports on the final results for the activity in the context of WP3: Research and development of relevant monitoring technologies - SubTask 3.4.5: Techniques for non-contact displacement measurement. Some of the more promising non-contact techniques (ultrasonic, time to flight, radio...) have been investigated to develop new short-range displacement sensors to be buried into the engineered barriers system. This kind of sensors could solve the problem of having preferential paths in the EBS found when using standard extensometers. The starting point of the activity has been the results coming from the MoDeRn Project, which represented an important step toward the definition of monitoring requirements and needs. In this work the electromagnetic non-contact techniques for monitoring displacements are presented in detail.

2. Introduction

Under the MoDeRn Project, impressive progress has been made in developing and analysing the capabilities of monitoring technologies in the fields of measurement probes and methods, data transmission, and energy supply. Many problems remained to be investigated, for example the possibility of measuring specific physical parameters by using non-contact techniques. This study should be preliminary to the design of new sensors able to overcome all the issues reported in past studies [1].

A nuclear waste repository is a harsh environment. This feature is a major issue for the design of reliable, long-life equipment. Expected environmental conditions in each of the identified potential monitoring areas are mainly defined by seven parameters: temperature, mechanical pressure, hydraulic pressure, water saturation, salinity, radiation and displacement.

Harsh conditions suggest the possibility to study alternative method for measurements, for example methods not using cables or buses for detecting relevant data, which can affect the behaviour of the engineered barriers [2].

A possible approach is substituting cables with wireless sensors. But if cables can not be used and the use of wireless techniques is required, new sensors must assure reliable transmission through the isolated areas of a repository without affecting the engineered barriers performance and reliable use of energy supply for the measuring equipment over long periods.

More in general, it is better to enlarge the investigation range to include not only wireless technologies (i.e. EM waves) as data transmission carrier but also considering these frequencies as a form of measurement in itself, together with other physical techniques coming from non-EM physical principles, provided that the connection between the monitored parameters and the detection system is contactless.

The objective of this work is to better understand whether *non-contact techniques* could be a promising solution for measurements in a harsh environment, in particular for *monitoring displacements*. The evolution of repository structures along time is one of the critical issues to be continuously monitored. The evolution could give rise to several deformations, e.g. deformation of openings (orientations and apertures, propagation rates) or canister movements due to the buffer maduration. Detecting displacements is the typical measurement method for the monitoring of repository structures and structural stability of openings.
Therefore, the aim of this work is to find alternative measuring methods with respect to the *contact* type sensors to track the position of the future canisters in the repository, in order to avoid the lack of reliability and to better follow the movements, or to better ascertain the potential retriviability of the canister by checking the gap between canister and metallic liner or a concrete lining or the rock itself. Three different non-contact techniques for monitoring displacements have been investigated during the Modern2020 Project. It should be observed that the presented approaches do not represent all possible solutions. They are only the methods that, to the authors' knowledge and expertise, give some potentialities for the design of realistic sensors for the considered problem. The three possible approaches have been here taken under investigation are the following:

1) Ultrasonic techniques,
2) Gradiometric techniques,
3) Electromagnetic techniques.

In this paper, for the sake of brevity, a particular attention will be given only to the third one, whose results are here proposed with a higher detail.

3. Reference scenario

In order to focus the problem, a standard test case has been considered as a reference scenario although other geometries are possible depending on the repository concept and hosting rock. The ideal repository here considered consists of an underground arrangement of horizontal galleries where the canisters confining the nuclear waste are disposed-off. The additional isolation method (engineered barrier) is based on the combined use of a lower bed made of highly compacted bentonite blocks, and an upper backfill made with a bentonite pellets based material, that can be projected from some distance.
The desired measuring device should be capable of tracking the changes in locations of the canister with no contact. The device could be located at the rock walls or in the surrounding buffer material. The accuracy of such measurements should be better than 1cm. They should not be affected by the expected changes in the buffer (increase of water contents, salinity changes, increase of temperature, increase of mechanical pressure due to the swelling of the bentonite and the elevation of the pore pressures) and by the presence of the radioactive source (the waste), the corrosion induced by the media or the potential release of gases. The duration of the measuring solution is expected to be of decades.
The approach is here very general and implementation-independent, as technical or operational requirements imposed on monitoring equipment may be attributed to several aspects, like individual national monitoring concepts and scopes, safety issues, cross-sensitivity to other environmental variables, interference with other concurrent devices and techniques, and so on. Finally, the sensor could be subjected to requirements due to an obligatory positioning of the sensor itself.
It should be observed that, in this work, no specific assumptions have been made on operational parameters, such as lifetime of the system, measuring range or measurement accuracy of the device.
All the operational requirements are then here neglected, as they will be considered in the implementation phase of the sensor, not considered here.
A general reference scenario can be considered as in Figure 1.
To fix the ideas, a sensor network (wired or wireless) is installed inside the disposal tunnel. Sensors are buried into the Engineering Barrier Systems (EBS), located in noncontact, close proximity with

the measured surfaces. Data are transmitted to an Acquisition Data System located in the access tunnel by means of a wired or wireless data transmission technique (Figure 1).

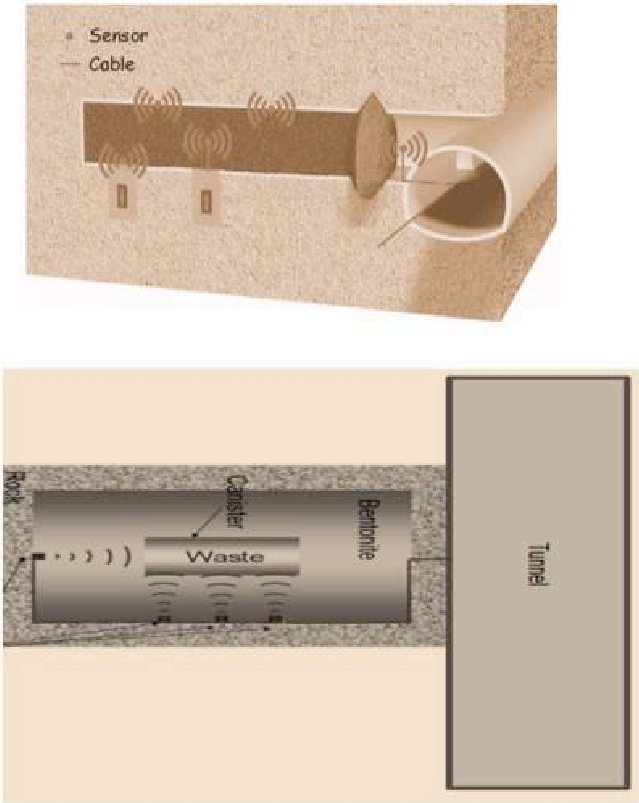

Figure 1: Schematic of potential implementation of the sensor.

4. Displacement measurement techniques

In literature there is a wide variety of works giving results potentially useful for tackling the problem. To the best authors' knowledge, no specific studies are available for the considered investigation. All papers found in the literature refer to situations that only vaguely could be associated to the current case study, so that only general considerations can be applicable to it. A comprehensive review of literature is out of the scope of this work. Here, we just refer on three different possible approaches, without exhausting the variety of potential techniques that could be applied to the considered problem. The three possible approaches have been extensively taken under investigation by the authors are ultrasonic, gradiometric, and electromagnetics (EM) techniques, based on three different physical principles, namely: ultrasound waves, gravity, EM waves.
In principle, all approaches could be suitable to solve the studied problem, yet several technical issues are to be faced before defining the best solution, which will be the result of a trade-off among accuracy, depth of penetration and complexity of the detection system.
A direct comparison among them in terms of pros and cons have not been considered being well beyond the scope and the objectives of this work, as it should involve not only physical considerations but also a direct evaluation of the maturity level of the correspondent technology.
Though, the objective of this activity has been to understand potential approaches to the individuation of alternatives to cable or contact existing technologies.
The *ultrasound waves technique* can be considered a mature technique already used in several applications for similar purposes [3-6]. But in order to arrive to a real study of feasibility on the

realization of a contactless sensor to be used for displacements measurement, more effort is required in order to design and test a prototype in a realistic application.

The so-called *gradiometric technique* is a novel technique, originally proposed by the authors for the first time in the context of the Project Modern2020, but it should be considered at this stage as a pure conceptual proposal, yet a very promising one.

More attention is paid here to the third approach, i.e. the *EM waves technique*. This possibility has been widely considered both on the theoretical and the simulation point of view.

The EM approach proposed here is based on a combination of Ground Penetrating Radar (GPR) and Nuclear Magnetic Resonance (NMR) methods widely known in the literature [7]. An EM method requires a specific characterization of the dielectric parameters the signal passes through. Several works proposed validated models that have been used in the simulations [8-18].

It should be underlined that the diagnostic systems based on the propagation of RF waves are limited from the maximum depth of penetration. This in turn is inversely proportional to the alternating current (AC) conductivity of the medium penetrated by the radiofrequency (RF) wave and therefore inversely proportional to the water concentration of the medium. In the presence of non-negligible water concentrations, it is therefore necessary to reduce the frequency of the RF wave so that it penetrates in the medium and can be detected with sufficient signal-to-noise ratio. In this way, however, the spatial resolution (limited by diffractive phenomena) tends to decrease overall, despite of a reduction in the length of the RF wave in the presence of media with a higher water content. The criterion to be adopted in order to operate in a dissipative medium consists in confining the electromagnetic field as much as possible using shields and/or conductive surfaces, and favoring the occurrence of resonant electromagnetic phenomena.

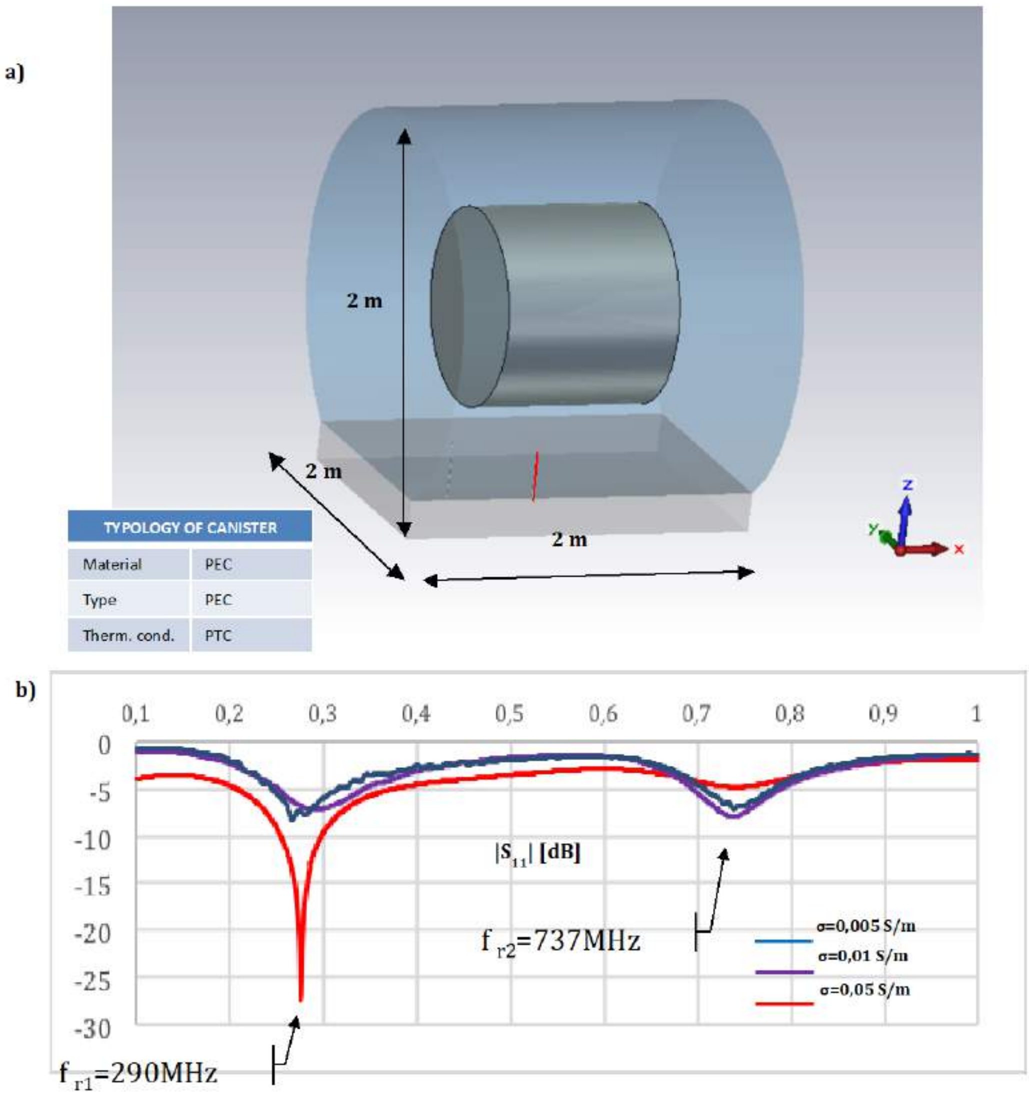

Figure 2: a) Example of a simulated scenario (in red the peakup antenna); b) trend of the scattering parameter S11 as a function of the frequency of the RF signal and of the conductivity of the medium σ or of the aqueous concentration. The graph also shows the resonant frequencies where the measurement system has its best performance.

The first point allows limiting the power of the RF source that must guarantee, during the design phase, the exceeding of the minimum threshold of the signal-to-noise ratio allowed by the measurement system.
The second point allows to intrinsically improving the resolution of the measurement method but limits its measurement dynamics in which the system's response is linear.
It is therefore clear that the resolution depends here on the quality factor of the analysed resonant mode, which in turn is inversely proportional to the water concentration of the medium. Both points can be guaranteed by selecting the range of wavelengths on which the measurement system will operate and the size and configuration of the measurement scenario (Fig. 2.a).
The diagnostic method that will be examined evaluates the frequency response of the scattering parameters in reflection (Fig. 2b, where the trend of the scattering parameter S_{11} is shown at the two resonance frequencies as a function of the conductivity of the medium). The measuring system employs two or more electromagnetic peakups through which the resonance frequencies depend exclusively on the geometric conformation of the conductive surfaces will be preliminarily

identified. These resonance frequencies are the only ones able to propagate in the dissipative medium and be detected with sufficient confidence by the measurement method used. Figure 3 shows, for example, the distribution of the EM field relative to the scenario of Figure 2.a corresponding to two resonance frequencies for which it is possible to detect from the peakup antenna a signal with the best signal-to-noise ratio.

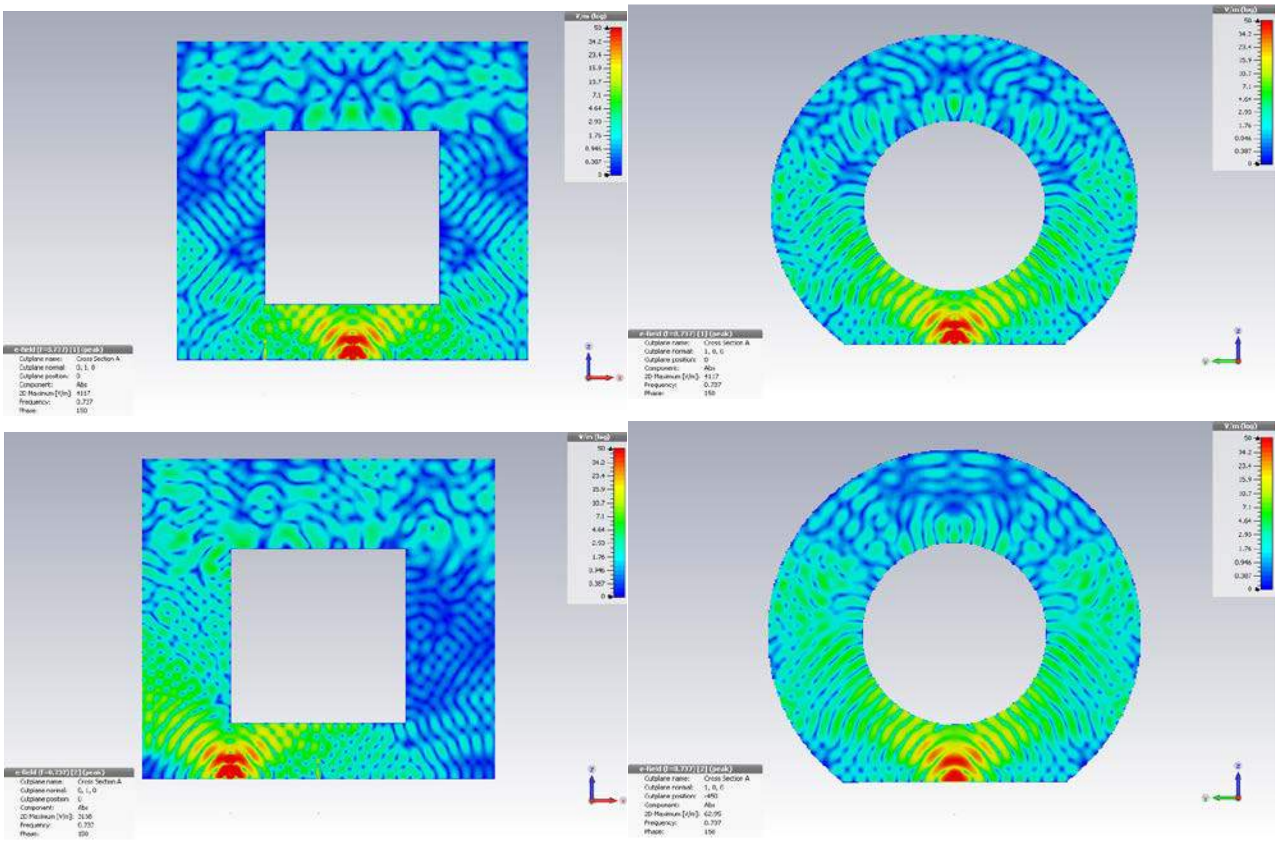

Figure 3: Distribution of the electromagnetic field produced by a peakup antenna in corrispondence of the frequency f1 (top) and frequency f2 (bottom) related to Figure 2b.

An elementary system of detection of the scattering parameters can be implemented by means of a bidirectional coupler that allows to evaluate the ratio between the signal obtained in the reflection and the excitation signal.
Thanks to this measuring system it is possible to detect any variation in the geometry of the conductive surfaces: in fact, these correspond to a variation of the phase and the amplitude of the resonance frequencies.
The linearity of the phase and amplitude shift with the displacement of the analysed object and the corresponding sensitivity require a preliminary analytical and numerical study of the scenario.

5. Conclusion

In this work possible approaches to the contactless displacement measurement problem based on different physical principles have been considered: ultrasound waves, EM waves, gravity. It is not possible here to give a direct comparison among them in terms of pros and cons, because the maturity level of the correspondent technology has not here considered, being well beyond the scope and the objectives of this work.

More attention has been paid here to the third approach, i.e. *EM waves*. This possibility has been widely considered both on the theoretical and the simulation point of view. Each method must be evaluated in terms of *depth of penetration* and *accuracy* of the detected signal. This requires to perfectly knowing the dielectric medium the signal passes through.

In the presence of non-negligible water concentrations, it is therefore necessary to reduce the frequency of the RF wave. However, the spatial resolution tends to complessively decrease.

By effectively confining the electromagnetic field using conductive surfaces and appropriately choosing the wavelength range it is possible to favor the propagation of stationary electromagnetic waves which improve the overall signal-to-noise ratio of the device. However, the quality factor of the aforementioned modes is strongly influenced by the aqueous concentration of the dielectric medium. Vice versa, the frequency and the phase of the main resonant modes will be influenced by the position of the conductive objects and / or surfaces. Therefore, the analysis of the scattering parameters in reflection in correspondence to the resonant modes can be used to evaluate the variation of position of the conductive objects.

The linearity of the frequency/phase shift with the displacement of the analyzed object and the corresponding sensitivity require a preliminary analytical and numerical study of the scenario. Preliminary simulation results confirm that as the frequency increases, the depth of penetration tends to dramatically reduce. But decreasing the frequency means that a higher antenna should be used. As a consequence, the design of the sensor should be done by a trade off between accuracy and geometrical dimension of the sensor (that should be designed so as to be easily included in the proposed environment). A detailed design could be done only after a thorough experimental campaign. The presented results could be used as a basic reference guide to start with.

Acknowledgements

This work has been partially funded from the Euratom research and training programme 2014-2018 under grant agreement n° 662177 (Modern2020 Project).

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Range-resolved optical remote sensing of hydrogen gas by Raman Lidar

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Abstract

In the frame of Cigéo project, nuclear waste packages are to be buried 500 meters below the ground inside horizontal galleries of a few hundred meters long (disposal cells). Some waste packages generate hydrogen gas (H2) by radiolysis. The release rate is expected to be slow (1.6 mol/package/year) but may occur during a long time. To ensure that H_2 concentration remains well below the lower explosive limit (4% in air), it is important to develop means for profiling H2 concentration within disposal cells' atmosphere. Performed at high spatial resolution, such monitoring could also highlight potential deterioration of waste packages by detecting unexpected local release rates of H2. The LIDAR technique (Light Detection and Ranging) has the potential to perform remote and non-intrusive measurement. In a radioactive environment, this could prove very useful compared to point sensors or distributed in situ technologies [Hübert 2011].

A multi-channel Raman Lidar has therefore been developed during a research program called CALISTO, conducted in partnership between Andra, Onera, and Latmos. The CALISTO lidar has the unique capability of allowing high-resolution range profiling of hydrogen gas, at a remote distance of several hundred meters. The range resolution along the laser line of sight is as low as 1 meter. The water vapor profile is measured simultaneously, since water vapor was shown to be optically interferent with hydrogen [Limery 2017]. A picture of the CALISTO lidar is shown on fig 1.

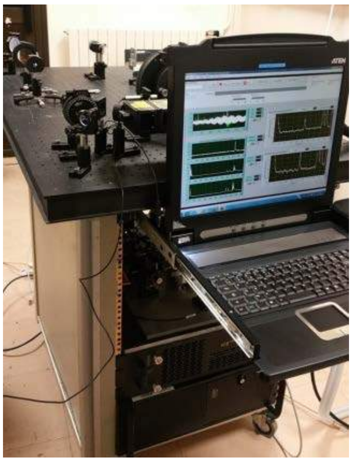

Figure 1: CALISTO Raman lidar for range-resolved remote detection of hydrogen. The current lidar size is approximately 100 L (and could be reduced). It can be moved easily.

Scattering of light in the disposal cells will include strong elastic scattering from aerosols and dust, elastic Rayleigh scattering from molecules, and inelastic (i.e. frequency-shifted) Raman scattering from molecules with species-dependent spectral signatures. The Raman Lidar exploits the different frequency signature of vibrational–rotational molecular transitions of hydrogen H_2, nitrogen N_2, and water vapor H_2O. Fig. 2 shows the computed backscattering spectra for O_2, N_2, H_2O and H_2 for a case study gas mixture, and for a laser excitation at 355 nm. The Raman signatures of O2, N2, H2,

and H2O extend from 370 nm to 420 nm (fig.2 left). An interference between H2 and H2O spectra can be noticed. Both must be measured simultaneously to avoid any quantification bias. We use two different spectral filters (fig.2 right) for that purpose. A third filter is used to measure nitrogen, which serves as a reference to compute H2 and H2O mixing ratio.

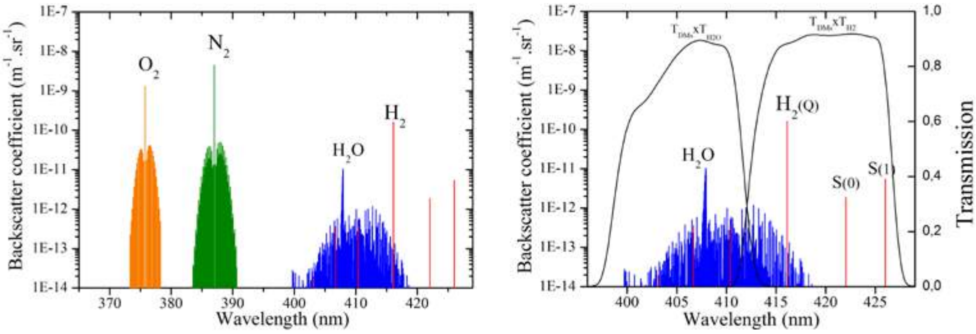

Figure 2 : (left) Vibrational-rotational Raman spectra (left) for an air composition of 78% N2, 20% O2, 1% H2O and 1% H2 at 300K for a 355 nm laser excitation. (right) Zoom on H2O and H2 vibrationnal spectra along with optical transmissions on each channel (transmission product of dichroic mirrors and band pass filters)

Long-range measurements of H_2 and water vapor profiles have been performed for system concept demonstration. A 5-meter-long open gas cell of 10 cm diameter has been developed to simulate H_2 releases. In order to redirect laser beam in a more convenient area, a mirror has been placed at 50 m as shown in Fig. 3. The effective distance to the gas cell reached 85 m. Bottles of pure dry air and of H_2 at 2% in dry air were available for gas-release experiments (through the center of the tube). Mixing ratio calculations and displays were performed in real time by a computer. In these experiments, the laser energy was reduced to 5 mJ to avoid signal saturation, and the optical system (laser focus and telescope field of view) was optimized at the center of the tube.

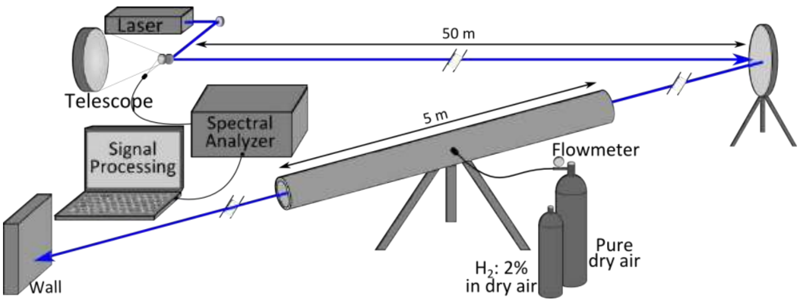

Figure 3: Experimental configuration for H2 and H2O measurements into a gas generation cell.

Three successive experiments have been conducted on a winter night (T=4°C, RH=84%) and the calculated mixing ratio profiles for H_2 and H_2O are shown in Fig. 4. The first experiment (blue line) was made with the natural humid atmosphere (no gas released). The second experiment (green line) was made with pure dry air released inside the tube, and the third one (red line) with hydrogen gas at 2% in dry air. For water vapor profiles, a first-order calibration has been performed using an in-situ hygrometer. H_2 profiles are given in arbitrary unit because no calibration sensor was available (currently under development). All profiles are shown for 1 m resolution and 1 min accumulation time. Drawn error bars show the expected 1□ standard deviation of H_2 mixing ratio given by signal modeling. At the center of the tube (84 m), the expected relative random error is evaluated to 7%.

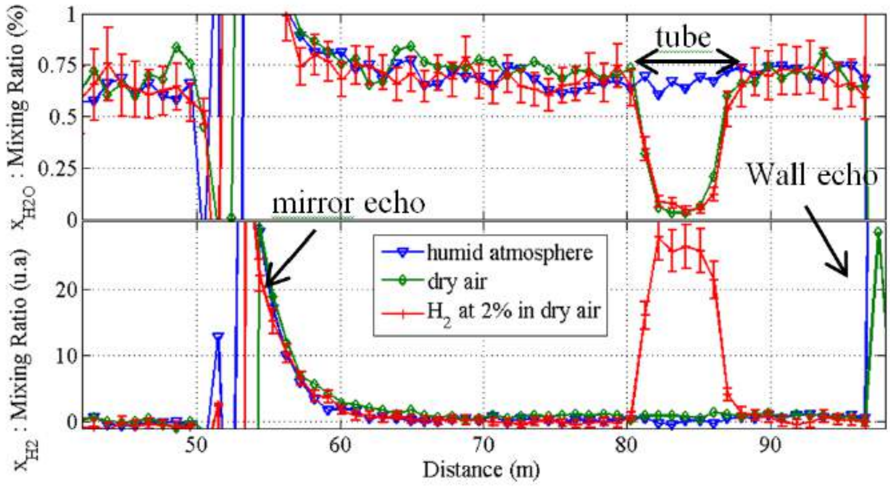

*Figure 4: Profiles comparison for water vapor and hydrogen gas mixing ratio (top and bottom resp.) with 3 different gases in the tube: i) natural atmosphere, no added gas (blue); ii) dry air (green) and iii) 2% of H2 in dry air with its ±**1σ** estimated error bars (red).*

From these results, and from system modeling, it is possible to infer the performance of the lidar system for an extended range of 500 m (length of a disposal cell). Assuming 3m range-resolution (average size of a waste package), full laser power (25 mJ/pulse), and stable system operation (noise stationarity) it should be feasible to reach a 500 ppm (0.05%) limit of detection for H2 within an accumulation time less than half an hour. Such experiments could be conducted in the future.

Conclusion

The CALISTO Raman Lidar has the unique capability to perform remote, non-intrusive, and range-resolved hydrogen gas measurements with meters range-resolution at several hundred meters of distance, with expected time resolution below half an hour. First experimental demonstration has been made, showing good performance for the lidar prototype. Future works could include more tests at longer distance including within the CMHM underground galleries, as well as further developments like additional oxygen detection.

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Development of a wireless relay system for monitoring of geological disposal using low- frequency electromagnetic waves

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1. Summary

A wireless relay system has been developed for the transmission of the monitoring data on a long-distance through geological rocks. The developed system is based on the concept of multi-stage relay transmission to reduce the power-consumption of each relay device, and on the concept of multi-route relay transmission to increase the reliability of the system. Transmission test of a relay device and operation tests for multi-stage relay transmission and for multi-route relay transmission have been performed. Durability of relay devices has been tested through a series of transmission of more than 4,000 times within 6 months.

2. Introduction

The monitoring to help the confirmation of the evolutions in the geological disposal facility of radioactive waste may be continued from the construction phase to the backfilling/sealing phase. In developing a monitoring system to meet the purpose above, the benefits from gaining data on the behavior of the system components need to be balanced against any detriments resulting from the process of monitoring. This is the why RWMC has been developed wireless data transmission systems as part of their monitoring system to avoid detrimental effects of the monitoring system on the quality and performance of the seals in a geological repository.

In order to enable monitoring in a limited space such as inside buffer materials or the near-field environment, a miniaturized transmitter and a series of adapters to connect different types of sensors such as vibrating wire and linear variable differential transformer have been developed [1]. Also, to enable receiving the monitoring data on the surface, middle-range and long-range transmission antennas have been developed [2]. These developments include a collaborative study with Andra. The developed underground wireless transmission technology uses electromagnetic waves with frequencies of several kHz to minimize attenuation in the ground and in water.

To enable receiving the monitoring data from miniaturized transmitter in the near-field environment at a distance of hundreds of meters, RWMC has considered a wireless relay system as one of the solutions. A prototype of wireless relay system using the long-range transmission antenna has been developed, and a transmission test for a distance of 250 m has been successfully carried out at the Horonobe URL using an external power source. This development has revealed a series of technical challenges for the development of the wireless relay system for a longer distance and for a long-period of monitoring.

3. Technical challenges for the wireless relay system

A large power supply is necessary for long distance transmission by underground wireless transmitters and relay devices, based on the relation between magnetic field strength and transmission distance. But the supply of power is a limiting factor. To reduce power consumption, we have proposed a multi-stage relay system to shorten the transmission distance between devices.

A multi-stage wireless relay system is thought to have a probability of failure larger than single-stage transmission system, because the probability of the failure of the system will increase with increasing number of relay devices. We have worked to improve redundancy by introducing a multi-route relay system to secure transmission routes in case of malfunction.

A multi-stage/multi-route wireless monitoring system may need many devices in different environment of temperature. The schedules for data communications between devices are controlled by the internal clock of each device which will be affected by the temperature of the environment. Thus, we have worked for the development of temperature-compensated crystal oscillator and for the synchronization of clocks using wireless communication.

These technical challenges and solutions are summarized in Table 1 and detailed in the following sections.

Table 11: Technical challenges and solutions for the wireless relay system

Technical challenges		Solutions
Power-consumption	・A large power supply is necessary for long-distance transmission. ・Relay device must be kept waking up during waiting, receiving and sending data. ・Long-term monitoring may be required.	・Multi-stage relay system with a number of relay devices and shorter distance between devices ・Development of a new program for saving energy
Accurate time-keeping	・The schedules for data communications between devices are controlled by the internal clock of each device. ・Quartz-crystal oscillator of clock is affected by the temperature of the environment.	・Temperature-compensated crystal oscillator ・Synchronization of clocks using wireless communication
Improving redundancy	・Improving the redundancy of the relay system is needed for the case of malfunction.	・Multi-route wireless relay system

4. Power saving by introducing multi-stage wireless relay system with a new code

The power consumption of a relay system can increase when the relay device manages several transmitters due to the increase of the time for the ‘reception standby’ mode, i.e. when the relay waits to receive a complete set of data from all transmitter nodes. Analyzing the power consumption status for each mode of the relay device, it was found that the power consumption during the reception standby mode is significant: about 70 % of the overall power consumptions. To reduce the power consumption of this mode, a low consumption activation code [3] was introduced that optimizes the receiving circuit usage state. A software was implemented that successfully reduced the power consumption of this mode from the 123 mA to 4 mA, allowing the relay system to be connected to the intended number of transmitters with only 4% of the power.

5. Accurate time-keeping

The schedules for data communications between devices are controlled by the internal clock of each device, but the frequency of a crystal oscillator in the internal clock of each device is affected by the temperature of the environment. To keep an accurate-time, temperature-compensate program has been installed in the electronic circuit of relay device. In addition to the temperature-compensate program, the program for synchronization of clocks in different relay devices using a dedicated signal has been developed.

6. Reliability of multi-stage and multi-route relay system

In a multi-stage and single-route relay system, malfunction of a relay device causes the failure of transmission of monitoring data from the transmitter connected with sensors to receiver. To improve the reliability of the relay system to complete the transmission of data, the concept of a multi-stage and multi-route relay system has been introduced.

Eq. 1 shows the reliability of a multi-stage and multi-route relay system (Fig. 1) decreases with increasing number of stages of a route of transmission of data, and increases with the number of routes (number of rows in Fig. 1).

$$: \ R(N,X)=(1-(1-\alpha)^N)^X$$

R: reliability of the system
α: the reliability of a relay device for a specified period of time
N: number of rows
X: number of stages (=l/L)

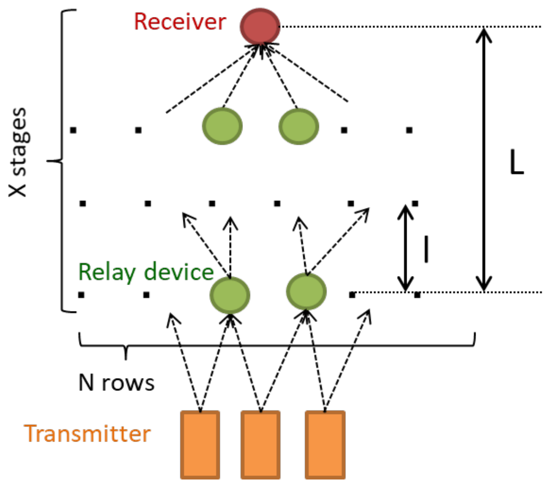

Figure 36: Schematic diagram of multi-stage and multi-route relay system

Table 2 shows an example of results of calculation of reliability of a multi-stage and multi-route relay system (R) using Eq. 1 at a value of reliability of the relay device (e.g. α=0.744) for the system. This table provides proper combinations of the number of stages (X) and the number of rows (N) to increase the reliability of multi-stage and multi-route relay system (i.e. R>α=0.744).

The example value of the reliability of a relay device (α=0.744) in table 2 is from those of wireless transmitters for the case of a ten-years monitoring.

Table 12: Example of reliability of multi-stage and multi-route relay system (R atα=0.774), Modified from[6]

		Number of stages (X)								
		1	2	3	4	5	6	7	8	9
Number of rows(N)	1	0.774	0.599	0.464	0.359	0.278	0.215	0.166	0.129	0.100
	2	0.949	0.900	0.854	0.811	0.769	0.730	0.693	0.675	0.624
	3	0.988	0.977	0.996	0.955	0.944	0.933	0.922	0.911	0.901
	4	0.997	0.995	0.992	0.990	0.987	0.984	0.982	0.979	0.977
	5	0.999	0.999	0.998	0.998	0.997	0.996	0.996	0.995	0.995

7. Design and manufacture of the relay device

In a next step, antennas, power supplies, and a container to protect the whole relay device were designed and manufactured. At this stage of development, three relay devices are manufactured for test. One of them was with container, and the others were without container. The specifications of the relay device are summarized in Table 2.

Table 2: Specifications of the relay device

Transmission interval	1 week
Transmission distance	100 m
Output power	10.1 W
Transmission speed	75 bit/s
Transmission efficiency	135 mWs/bit
Durability	About 10 years
Size (diameter x length)	Φ216mm×565mm
Frequency of electromagnetic wave	8.5 kHz
Pressure resistance	5 MPa
Number of transmitters managed	10

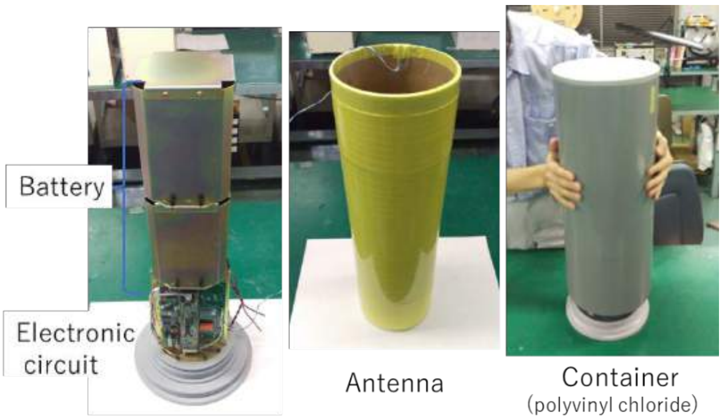

Figure 37: Relay device for the multi-stage / multi-route relay system[5]

8. Test of relay device

8.1. Transmission test for relay device

Transmission tests for a transmission distance up to about 95 m were carried out at the surface, and the received signal strength were measured. This result allows an estimation of a high possibility of the transmission with a similar distance in a rock or soil based on the results of other transmission tests using the same frequency of electromagnetic wave. All measured signal strengths were above the noise level, as well as on or above the theoretical attenuation line, confirming that the stable transmission was secured. The maximum transmission distance was constrained by the capacity of experimental facility.

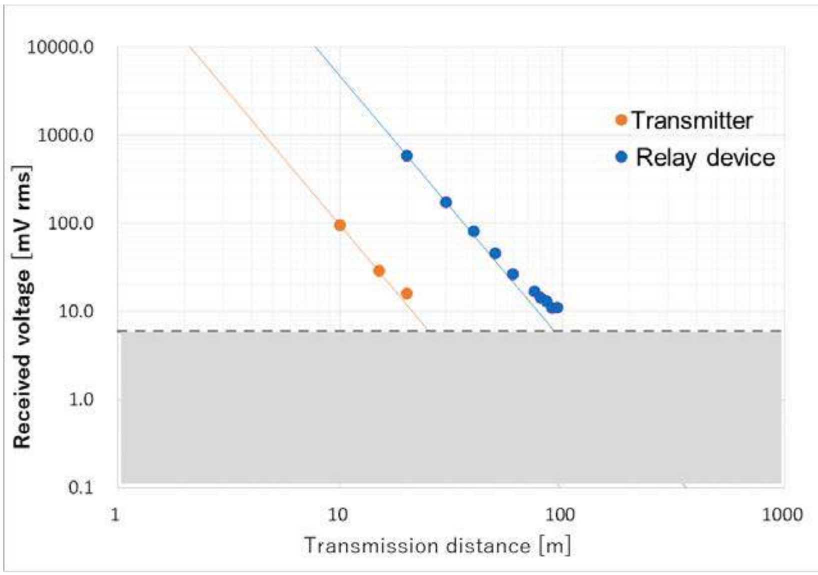

Figure 38: Received voltage from the relay device plotted against the transmission distance. The lines depict the expected signal strength of the relay device (blue) and the transmitter (orange). The shaded area denotes where transmission is not reliable as learned from past experiments when a noise level is 2 mV. Modified from[6]

8.2. Test of multi-route wireless relay system

With the aim of securing the redundancy of the relay system in the case of malfunction, RWMC carried out data rerouting tests using three relay devices with a distance of several meters in a laboratory by the following sequence (Fig. 4):

Step 1: Transmitter 1, 2 → relay device 1 → relay device2 → receiver
Step 2: Malfunction of relay device 2
Step 3: Instruction signal from receiver manually sent to relay device 3 to transmit data to the receiver
Step 4: Transmitter 1, 2 → relay device 1 → relay device 3 → receiver

As result, data from the transmitter were successfully delivered to the receiver even when the data was rerouted from the relay device 2 to 3.

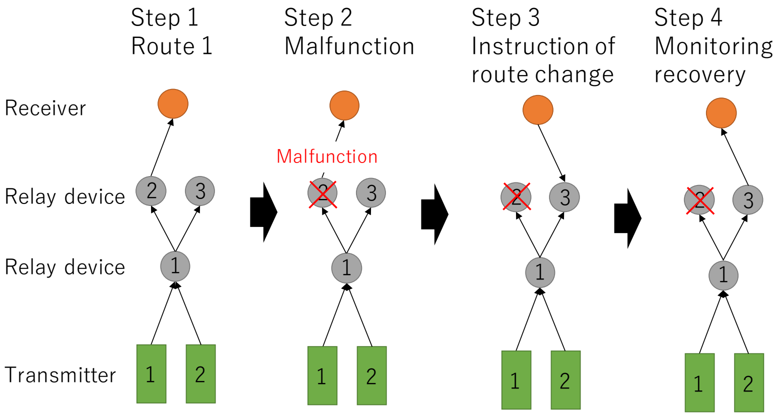

Figure 39: Conceptual diagram of route change in the case of device malfunction. Modified from [4].

8.3. Endurance test for relay device

To validate the durability of the relay system and to evaluate early infant mortality failure rates, an endurance test has been performed with several meters in a laboratory. The test has been continued for 6 months, and more than 4,000 transmissions have been executed without loss of data.

9. Discussion

The relay device for a multi-stage/multi-route relay system has been developed and tested in the laboratory and on the surface. Transmission tests for a distance up to 95 m (Fig. 3) were carried out at the surface, and the results allow an estimation of a high possibility of the transmission with a similar distance in a rock or soil based on the results of other transmission tests using the same frequency of electromagnetic wave. But, the influence of steel members in underground facilities to the transmission should be confirmed before installation to the disposal facility.

The reliability of the transmission system has been estimated with the numbers of steps and rows of transmission routes (Table 2), but the confirmation of the behavior of the transmission system with a large number of relay devices remains as a future challenge.

The developed relay device (Fig. 2) has a limited size of transmission antenna to reduce the size of the device. Small devices will ease the installation works and limit detriments of resulting from the installation of the device to backfilled tunnel, for example. But if the installation of a larger antenna is allowed, the distance of transmission of data from a relay device could be increased larger than the distance of the developed relay device (i.e. larger than 95m) with the same level of power consumption. And thus, the reliability of the system could be increased with decreased number of steps of relay for the same distance.

10. Conclusion

A wireless relay system has been developed for the transmission of the monitoring data on a long-distance through the geological rocks. The developed system is based on the concept of multi-stage relay transmission to reduce power-consumption of each device, and on the concept of multi-route relay transmission to increase the reliability of the system. The developed relay device includes programs to reduce power consumption and to synchronize the clocks of relay devices. Transmission tests for a distance up to 95 m were carried out at the surface, and operation tests for multi-stage relay transmission and data rerouting tests have been performed successfully. Durability of devices has been tested through a series of transmission of more than 4,000 times within 6 months without loss of monitored data.

Acknowledgements

The research in RWMC was a part of “Development of Advanced Technology for Engineering Components of HLW Disposal” under a funding from the Agency for Natural Resources and Energy (ANRE) of the Japanese Ministry of Economy, Trade and Industry (METI).

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Estimation of the initial dry density distribution of granulated bentonite mixtures in the Full-scale Emplacement experiment by means of active distributed temperature sensing

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1. Summary

The granular bentonite material was used as backfilling material in the Full-scale emplacement (FE) experiment. For distributed temperature sensing (DTS), fiber optic cables with heating capabilities were implemented on the tunnel wall during the implementation phase of the experiment. Since the start of the experiment heating tests (referred as *active DTS*) have been conducted periodically (every 2 – 3 months) on these fiber optic cables.

The ability of *active DTS* to estimate the physical properties of granular bentonite has been studied recently and provided very promising results especially for the calculation of the dry density under constant moisture content. After a series of feasibility and optimization experiments conducted separately, the relationship between the thermal conductivity and dry density for the granular bentonite material used in the FE experiment has been obtained. The *active DTS* data were closely evaluated in estimation of thermal properties of the granular bentonite mixture, which was then used to estimate the initial dry density at the time of the emplacement using the relationship between the thermal conductivity and dry density.

2. Introduction

Full-Scale Emplacement (FE) experiment [1] in the Mont Terri rock laboratory is implemented as a 1:1 scale repository tunnel according to the Swiss radioactive waste disposal concept. Granulated bentonite material (GBM) [6] is used for the backfilling of the radioactive waste repository tunnels as one of the engineered barriers. The dry density of the GBM at the emplacement is one of the crucial parameters, since many other important parameters (e.g. thermal conductivity, hydraulic conductivity) for thermo-hydro-mechanical (THM) processes are depended on it. Previous studies (e.g. [2], [3]) showed that, if no countermeasures are taken, the emplaced dry density of the GBM varied within the tunnel cross section leading to a differentiation in the thermal conductivity, although the required average dry density of GBM could still be achieved.

Although point measurement techniques provide reliable data, detailed monitoring of the GBM dry density distribution along the entire tunnel as a profile under in-situ conditions is challenging because of a lack of measurement techniques. Therefore, distributed temperature sensing (DTS) in combination with heatable fiber optic (FO) cables was selected as the measurement technique to investigate the dry density distribution of the GBM. DTS is a well-established technology for measuring temperature along a fiber optic cable. It provides with a continuous temperature profile along the cable for up to several kilometers. The obtained temperature information is defined by the spatial resolution (decimeter to meter scale) and the temporal resolution (seconds to hours) of the measuring device. The active heating of the FO cable combined with DTS, known as "*active DTS*" has been studied recently to estimate soil moisture (e.g., [4]) and the dry density [5]. In this work, the *active DTS* combined with FO cables is used to estimate the initial dry density along the cable in FE experiment at the time of the emplacement.

2.1. Methodology

A multi-component FO cable with a heating capability is used for temperature measurements in the GBM along the FE tunnel [6]. The heating of the cable is done by introducing electrical current on the copper wires that are embedded inside the FO cable. Temperature changes are then monitored by the DTS system, which uses the Raman backscattering to calculate the temperatures from the two different components (Stokes and Anti-Stokes) of the backscattered light.

Feasibility experiments [5] has shown that the thermal conductivity method, briefly described below, yielded consisting results with the actual thermal conductivities. The method uses the dependency between the dry density and the thermal conductivity of the material. If moisture content of the GBM remains constant, the thermal conductivity of the material only depends on the dry density. Therefore, when the FO cable surrounded by GBM is heated, the thermal response along the cable can be used to differentiate between varying dry densities along the cable.

The method assumes an infinite line heat source to calculate the thermal conductivities from the temperature changes dT plotted against ln$t$. For a certain heating period of the active heating, the slope of dT-ln$t$ reflects the effects from the surrounding GBM. The slope is then used to calculate the thermal conductivity (λ) with,

$$\lambda = Q/4\pi a \qquad \textit{Equation 1}$$

where Q is the heating power applied along the FO cable (W/m) and a is the slope of the dT-ln$t$ data.

2.2. In-situ experimental setup of the heatable fiber optic cables

A set of various types of FO cables with DTS were installed on FE tunnel wall. Amongst the standard FO DTS cables, a heatable FO cable (approximately 250 m long BRUsens LLK-BSTH 85 °C, multi-component FO cable with outer diameter = 0.004 m [5]) was installed on the top section of the lined section of the tunnel, and three loops at the interjacent sealing section (ISS) (Fig. 1-a) in the gaps 2, 4 and 6 between the steel sets.

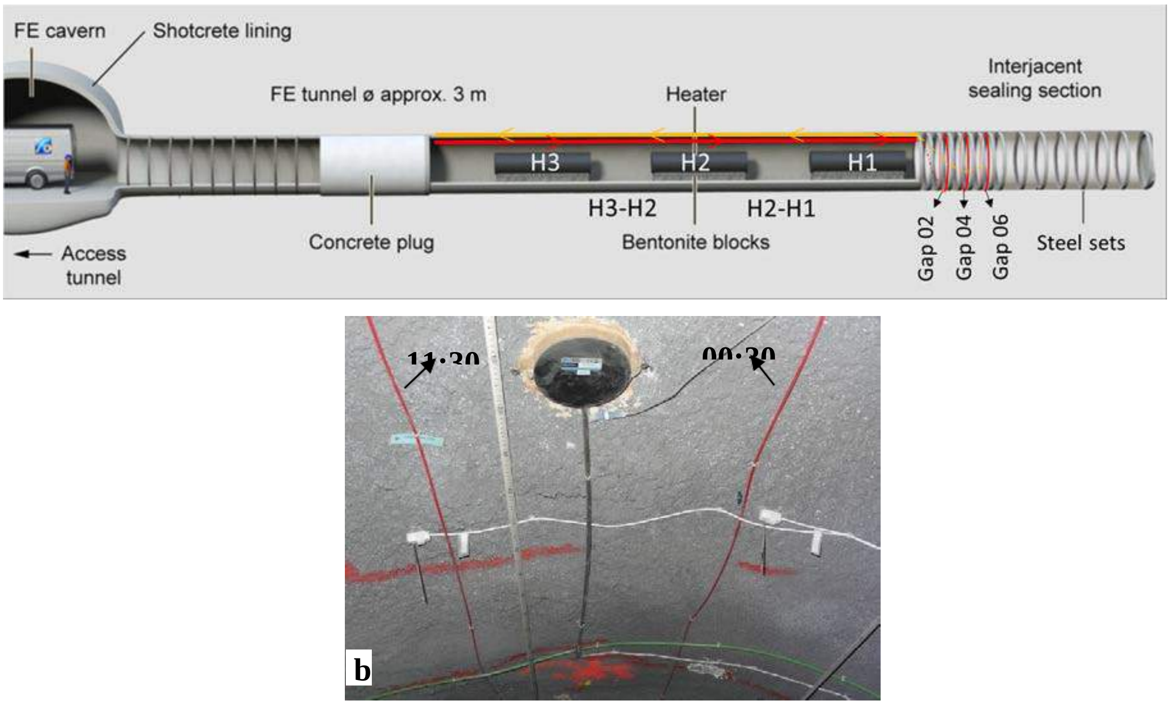

Figure 1: Representation of the heateable FO cable (red lines) installed in the FE Experiment a- side view along the heaters and ISS and representation of the cable runs; red run-in at 00:30 and 3-loops at ISS and orange; cable running out at 11:30 direction; b- installation in the tunnel with their clock positions looking from the access tunnel towards the ISS. Figure 1-a taken from and modified after [1]

In the FE experiment, the heatable FO cables were installed loosely at each 60-70 cm onto the shotcrete tunnel wall (at the positions shown in Fig. 1-b) and the tunnel was backfilled with GBM. Therefore, after the backfilling, the void space between the tunnel wall and the FO cable was filled with GBM. The effects of shotcrete on the thermal responses monitored by FO cables were further investigated before calculating the initial dry density with thermal conductivity method [7].

3. Estimation of initial dry density in the FE tunnel

Since the start of the FE experiment, active heating tests have been conducted periodically (2 – 3 months) with the heatable FO cables installed in FE tunnel. The earliest available active DTS test case after the completion of the backfilling dates back to 30 April 2015 (4-month after the switch on of heater 1 and 2-month after the switch on of heater 2 and 3). Since the hydraulic conductivity of the Opalinus Clay is very low, the GBM was regarded to have kept the initial water content at the time of the heating test. Therefore, the calculated thermal conductivities with *active DTS* with FO cables would reflect the initial dry density at the time of the emplacement. Any further changes that take place in the thermal conductivity is then regarded to be due to the changes in the humidity.

For the measurements, the DTS unit (DiTemp SR Unit) with a spatial resolution of 1.02 m (within which 90% of a step temperature change can be detected) was used. The sampling resolution at which temperature data were recorded was also 1.02 m.

For estimating the initial dry density of the GBM at the time of the emplacement, the following test was selected:

- Test date: 30 April, 2015
- Heating power (*Q*) = 0.41 W/m
- Heating duration = 60 min
- Sampling time (*dt*) = 150 s
- Sampling resolution = 1.02 m
- Data duration = 3-60 (data between 3- to 60-min heating have been used for calculations)
- DTS unit = DiTemp SR Unit
- Heat generator = Heating Relay Module (HRM)

In Fig. 2, the temperature profiles before the heating of the FO cable started (0_min) at 60 min heating are shown.

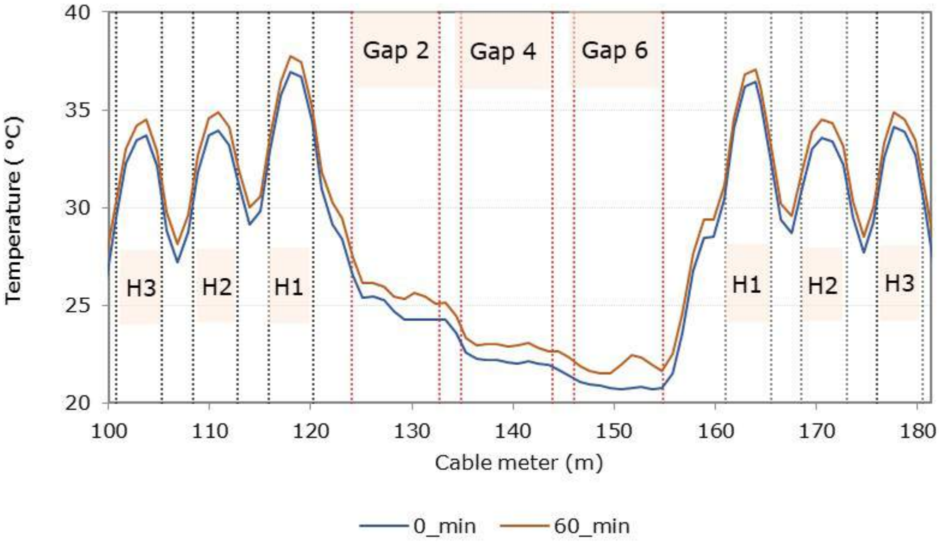

Figure 2: Temperature profiles before and after the FO cable heating test on April 30, 2015.

Note: The cable runs into the tunnel at 00:30 direction along the heaters and makes 3-loops at the ISS section at G2, G4 and G6 and runs back along the heater section and leaves the FE tunnel (See Fig.1).

Using *equation 1*, thermal conductivities along the FO cable were calculated and plotted in Fig. 3. The first 3 min data was excluded from the slope calculation due to a non-linear behavior [5]. With the low heating power of 0.41 W/m, it was found that use of d*T*-ln*t* data up to 60 min after the heating started yielded reasonable slopes in the d*T*-ln*t* data with less noise.

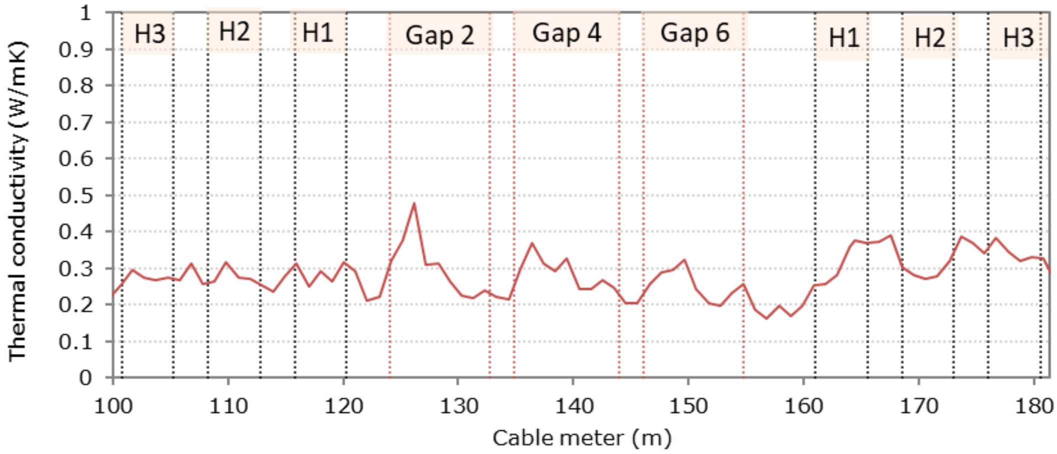

Figure 3: Thermal conductivity profile along the FO cable.

Note: The profile is calculated by using equation 1 around the FO cable at the crown of the FE tunnel

The thermal conductivity profile shown in Fig. 3 will be used to show the estimated the initial dry density of the GBM around the FO cable running at the top section of the tunnel by using the calibrated function for the GBM used for the FE experiment [7].

4. Conclusions

An attempt was made to determine the initial dry density of the GBM in FE experiment based on the *active DTS* data obtained soon after the backfilling was completed. Although the low heating power used for this case, the d*T*-ln*t* data for 3-60 min resulted in a reasonable thermal conductivity profile along the FO cable.

The initial dry density in the FE tunnel determined using the thermal conductivity method was approximately 1300 kg/m^3 around the FO cable along the top section of the tunnel. This value was lower than the average value calculated by the mass balance method (~1450 kg/m^3) at the time of emplacement [1]. However, it should be considered that the latter method calculates the dry density averaged over the entire tunnel volume. Near the crown of the tunnel, the dry density tends to be lower compared to other sections of the tunnel. When compared to earlier studies [2 and 3], the estimated dry densities along the top section around the FO cable generally showed a reasonable agreement.

Acknowledgements

This work has been conducted under the funding of Modern2020 Development and demonstration of monitoring strategies and technologies for geological disposal), Work Package 3 (Research and development of relevant monitoring technologies), Task 3.4 (New in-situ sensors tailored to geological disposal: Development for fiber-optic distributed temperature sensing of thermal conductivity, density and water content in the EBS by means of heatable fiber-optic cables.

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Hybrid seismic surveying for detailed characterization of the shallow and intermediate depths subsurface

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1. Summary

Conventional reflection seismic velocity analysis tools invariably provide unsatisfactory results when applied to seismic data acquired for mapping complex subsurface structures in the near surface depth range until 300 to 500 m.

The method of hybrid seismic surveying, a combination of high-resolution reflection seismic profiling with seismic refraction tomography inversion, overcomes this drawback by extracting more accurate information from the refraction seismic velocity field to be used for the derivation of stacking velocities and of time-to-depth conversion velocities in reflection seismic data processing.

Reciprocal calibration of the seismic reflection and refraction tomography results is instrumental for obtaining spatial imaging congruency resulting in the spin-off product of the best fitting velocity information possible.

In opposition to the conventional "deep target" reflection seismic data processing sequences, the application of weathering and elevation field static corrections is integrated in the steps of NMO correction and final post stack time-to-depth conversion.

Hybrid seismic sections jointly image the subsurface structures and also characterize the stiffness of soil and rock layers. The method can be extended by complementary seismic shear wave refraction tomography data acquisition and inversion for the non-invasive and in-situ derivation of spatially continuous dynamic elasticity parameters such as E-modulus 2D sections.

Guidelines are specified as to the choice of the data acquisition parameters for optimal reflection seismic imaging resolution and for attaining maximum seismic refraction tomography investigation depth.

1. Generic description of hybrid seismic data processing

In Figure 1 to the right, the seismic velocity field is derived by seismic refraction tomography inversion (**1**) from a data set acquired in a single field operation using recording parameters for high reflection seismic resolution, such as small geophone station spacings, and an adequately long active spread lay-out designed for maximum refraction depth penetration.

The velocity information thus obtained is used for NMO correction, common depth point (CDP) stacking and time-to-depth conversion in the reflection seismic data processing flow (**2**).

The refraction tomography velocity field (**1**) is transparently overlain onto the reflection seismic depth section (**2**) for visual correlation purposes, resulting in a hybrid seismic section (**3**), which is then subjected to geological-geotechnical interpretation (**4**).

With hybrid seismic surveying, structural details such as tectonic faulting and depositional layering are portrayed simultaneously with geomechanical rock properties.

The results of (**1**) and (**2**) are completely independent of each other, which reduces the danger of interpretational uncertainties and ambiguities.

2. Prerequisite of spatial congruency

In authentic hybrid seismic data processing, the imaging results of refraction tomography (**1**) and of seismic reflection profiling (**2**) are reconciled by reciprocal calibration for obtaining spatial congruency.
The latter is a measure of accuracy of the derived velocity field (see Fig. 2 on next page).

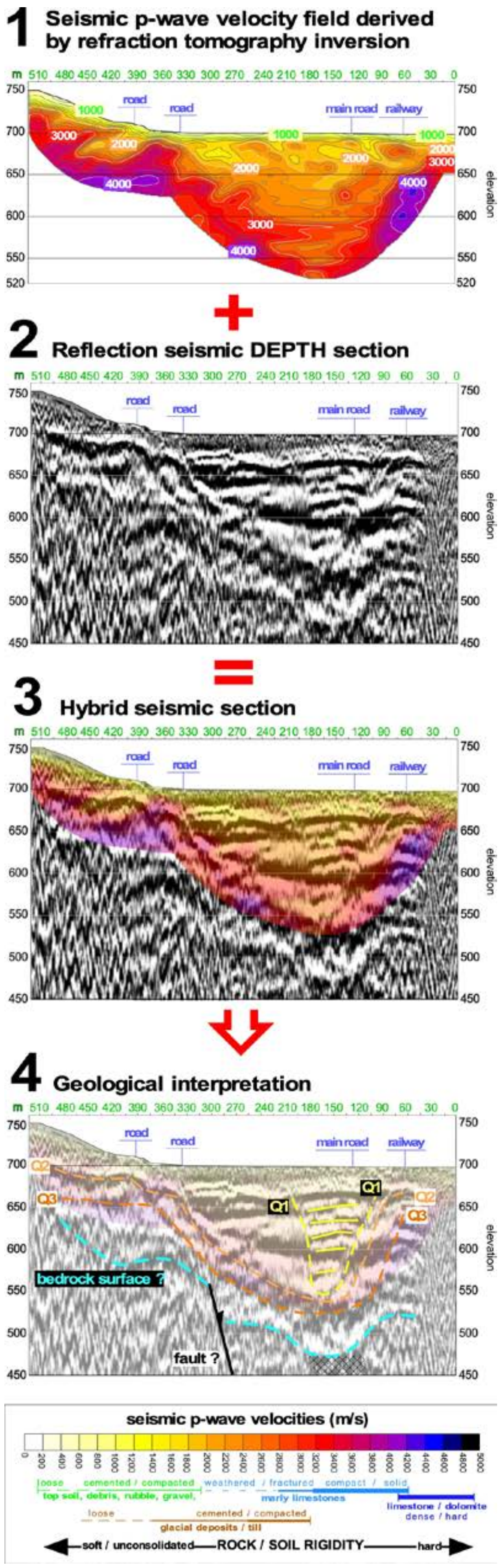

Figure 1: Hybrid seismic data evaluation flow

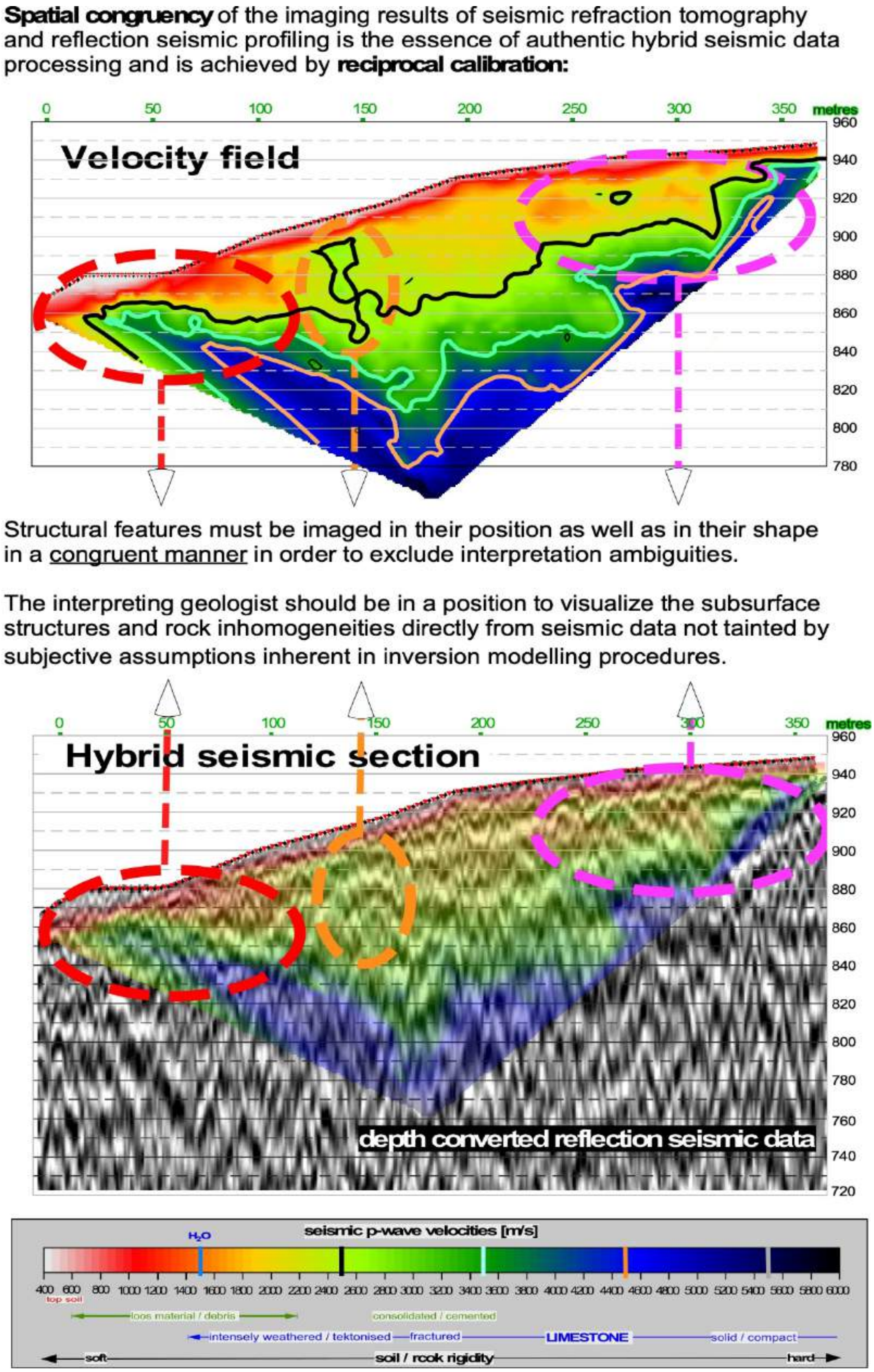

Figure 2: The principle of spatial congruency of the refraction and reflection imaging results

3. The application of static corrections in the reflection seismic data processing flow

In conventional standard reflection seismic data processing, field and residual static correction techniques are used routinely for processing deeper data and are based on the assumption that two-way-time (TWT) anomalies for reflection events below the surface layers are to be attributed to irregularities of the surface topography and/or to strong lateral and vertical velocity variations near the surface. These TWT static-correction values applied to each individual trace within a common-depth-point (CDP) gather are instrumental in obtaining the sharpest possible reflection event on the stacked CDP traces – alas at the expense of the imaging resolution at shallower depths. The collateral damage thus caused by applying these TWT corrections to the entire individual seismogram is that all relevant information in the near surface depth range – which is of interest to the engineering geologist or geotechnical engineer – is corrupted.

In hybrid seismic surveying, no static corrections of any type are applied before CDP stacking. The zero time line refers to the surface relief, no matter how irregular the terrain elevations may be. The field weathering static corrections compensating for near surface velocity anomalies are integrated in the NMO correction by taking into account the velocity function as extracted from the refraction tomography velocity field at each CDP position. Surface elevation statics are applied after time-to-depth conversion of the TWT stacked section. The result is a seismic reflection depth section with structural information from the very surface, which is to be jointly presented with the refraction tomography velocity field as a hybrid seismic section (see Figures 1 and 2 above).

4. Spatially continuous dynamic elasticity parameters derived by hybrid seismic surveying

Quantitative determinations of geotechnical elasticity parameters of Young's **E**-modulus, shear modulus **G** and Poisson's ratio $\boldsymbol{\nu}$ are usually carried out either by laboratory analysis of rock samples from boreholes or obtained from the results of bore hole geophysical wire line logging surveys. The measured parameters needed are the propagation velocities both for P-and S-waves ($\boldsymbol{V_p}$ & $\boldsymbol{V_s}$) and the rock/soil density $\boldsymbol{\rho}$.

Complementary S-wave refraction tomography inversion to P-wave hybrid seismic surveying is highly beneficial for geotechnical construction site characterizations for the following reasons:

- The P- and S-wave velocity parameters ($\boldsymbol{V_p}$ & $\boldsymbol{V_s}$) are of the in-situ type since they have been recorded in an undisturbed environment;
- $\boldsymbol{V_p}$ & $\boldsymbol{V_s}$ velocity fields are recorded along seismic transects, dynamic rock elasticity parameters (for example Youngs' E-modulus) derived are spatially continuous and portrayed as 2D depth sections;
- Surface based non-invasive seismic probing methods are considerably less costly than wire line logging surveys and rock samples collected at discrete bore hole locations.

See Figure 3 on the next page.

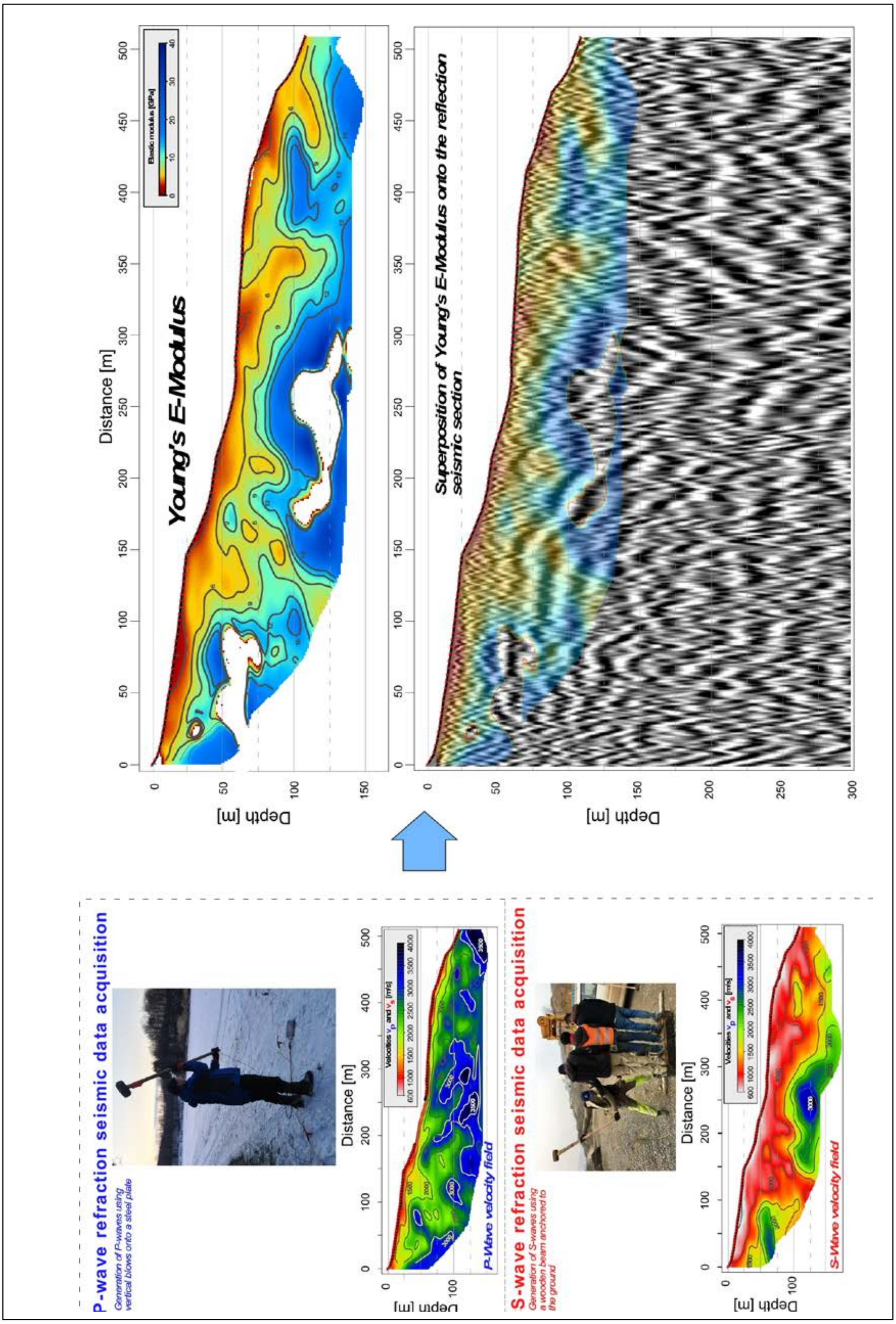

Figure 3: Hybrid seismic non-invasive and spatially continuous geotechnical ground stability assessment by derivation of a 2D E-modulus section.

5. Data acquisition parameters for optimizing imaging resolution and depth of investigation

The resolving power of reflection seismic data is proportional to the spatial data density, defined by the spacing between the receiver stations and the separation between the source points. The smaller the separation between the geophone stations, the higher is the imaging resolution of the seismic data.

The attainable depth of seismic refraction tomography, on the other hand, is a function of the length of the active spread lay-out.

Therefore, even with small receiver spacings, it has to be ascertained that a long enough active spread is to be laid out for attaining the desired investigation depth. For this reason an adequate number of data channels and geophones are mandatory.

Based on the desired depth of investigation, the following basic rules apply for acquiring hybrid seismic data for ensuring an adequate reflection seismic data density and an optimal refraction tomography investigation depth:

1) The receiver station spacing should not exceed 1/50 to 1/30 of the required depth of investigation (depending on the locally attainable data quality and the complexity of the subsurface structures).
2) The length of the active spread should be at least 3 - 4 times larger than the desired depth of investigation.
3) The source point distance is to be chosen not larger than 1 – 3 times the receiver station spacing (depending on the locally attainable data quality and on the complexity of the subsurface structures).

Working example based on the above given rules for a desired investigation depth of 100 m:

- A receiver station spacing of 2 m is appropriate (see rule 1. above).
- The spread length must be 300-400 m, which means that with a geophone spacing of 2 m, the active lay-out is to consist of 150-200 geophones, which means that a recording seismograph should feature this number of data channels (see rule 2. above).
- The source point distance should not exceed 6 m. Under very difficult conditions 2 m – 4 m is preferrable (see rule 3. above).

The use of staggered successive roll-along recording cycles with a move-up distance of half a spread length is recommended, as pictured in Figure 4 below:

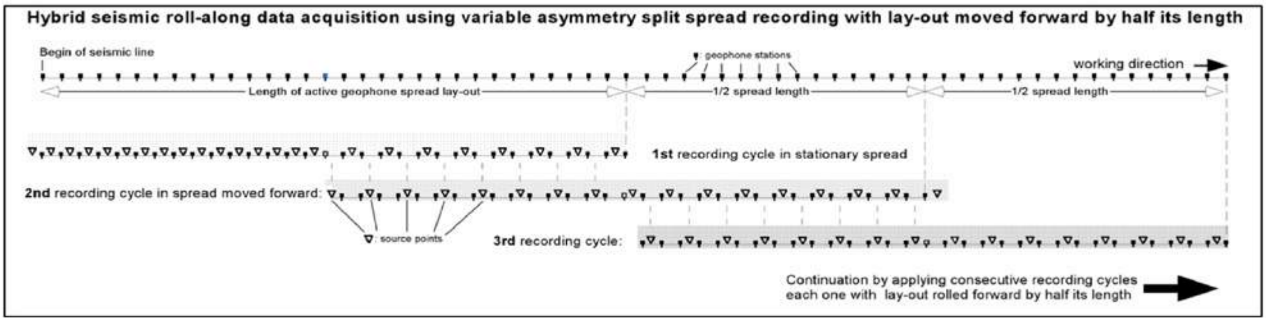

Figure 4: Schematic roll-along recording procedure for full coverage of maximum source – receiver offset data along seismic transects being several times longer than the active spread lay-out.

<u>Recording cycle 1</u>: Start recording in the first spread position with regular source point distances until the center of the spread. Then continue recording with twice the source point distance until the far end of the spread.

<u>Recording cycle 2:</u> Move the entire active spread forward by half its length and relocate the source (hammer or weight dropper) back to the rear end of the spread now in its new, second position. Continue recording at the source points at twice the source point separation distance and between the source point positions activated in cycle 1.

<u>Recording cycle 3:</u> As in cycle 2, move the spread forward by half its length and relocate the source back to the rear end of the spread now in its new, third position. Continue recording as in cycle 2 at every second source point.

Subsequent recording cycles are identical to cycle 3. Make sure that in the last recording cycle of the line regular source point distances are observed over the entire length of the geophone spread.

This staggered roll-along scheme of semi-stationary spreads (Fig. 4) has the advantage that in each cycle maximum offset data both in the forward and reverse directions are obtained for continuous maximum refraction tomography investigation depths.

6. Conclusion

High resolution reflection seismic profiling combined with refraction tomography inversion is a universally applicable tool for mapping shallow subsurface structures down to depths in the order of 500 m.
Detailed velocity information obtained from the refraction tomography velocity field is indispensable for processing reflection seismic depth sections. In hybrid seismic surveying the disadvantanges of one method are compensated for by the benefits of the other.

Apart from the substantially lower costs by reducing the data recording work to one single field operation, the major advantage is to be seen in the enhanced interpretation reliability gained by the joint presentation of the results of the two methods, which are completely independent of each other.

Hybrid seismic surveying maps in great detail structural features in a joint image with the rock/soil rigidity parameters.

The hybrid seismic method can be extended to include shear wave refraction tomography for generating spatially contiuous dynamic elasticity E-modulus 2D sections for geotechnical site characterizations.

Time lapse application of hybrid seismic surveying is an appropriate technique for monitoring alterations of rock mechanical properties around repositories.

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Toward long-term hydrogen monitoring with specialty optical fibers

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Abstract

Hydrogen sensing is an important issue driving many industrial applications such as fuel cells, geothermal wells or nuclear power plants. Hydrogen concentration must be controlled and monitored because it forms explosive mixtures when combined with air for a large concentration range (from 4 to 75 % vol in air). Conventional hydrogen sensors usually rely on a sensitive material, such as tin or tungsten oxide (SnO_2 and WO_3), or metals like palladium (Pd) or platinum (Pt), whose resistive behavior is modified in contact with H_2 gas [1-6].
Optical fiber sensors are well known to be attractive components for harsh and explosive conditions because they allow remote sensing interrogation devices far from the measurement area without any ignition risk from electrical sparks. With appropriate dopants (such as Ge and F) and primary coatings (such as polyimide), silica optical fibers are also resistant to extreme temperature and gamma ray radiations. This is the reason why many types of H_2 optical fiber sensors have been studied for several years, based on H_2-sensitive materials such as WO_3, yttrium oxide Y_2O_3 or Pd compounds. However, the sensitive material is deposited on the external surface of the fiber sensor, which limits long-term operations due to degradation of the film [7].
Fiber sensors with sensitive material embedded within the optical fiber will be ideal for long-term applications, especially for monitoring slow H_2 leakage of nuclear wastes.
In this communication, we report, for the first time to our knowledge, the development of H_2 sensors based on specialty optical fibers with embedded materials. More precisely, the fibers are composed of composed of two stress-applying parts (SAP) placed opposite to each other on the side of the core (Cf. Fig. 1(a)). The SAP act on the properties of light guided in the fiber core by introducing stress fields in the fiber yielding two axes of propagations (i.e. optical birefringence) following the position of the SAP. The diffusion of H_2 gas into such optical fibers induces therefore different variation of the light guiding properties (mainly effective index) of both propagation axes that could be measured by using the high-birefringence fiber loop mirror (FLM) configuration shown in the Fig. 1(b). This configuration consists in splicing a portion of the fiber (under test) between two arms of a fiber coupler. The transmitted spectrum of an FLM is composed of multi-dips yielded by the interference between the two propagation axes. It is worth to note that the FLM configuration is simple to implement because the spectral characteristics are independent of the polarization state of the input light and are weakly sensitive to noise disturbances. This configuration is also very soft, flexible and robust. The fiber was inserted in a hermetic chamber specially designed for diffusing H_2 gas into the

fiber with monitored temperature and pressure. The fiber was optically connected to the arm of the fiber coupler with adapted optical fiber connectors. The diffusion of H2 into the fiber was sensed by measuring the spectral shift of a dip in the transmission spectrum when H_2 gas is introduced into the chamber (at constant temperature and pressure). An example of this measurement is illustrated by the black curve in Fig. 1(c). It is induced by the diffusion of H_2 gas (at 70°C and 60 bar) into a specialty optical fiber with two SAP composed of Silica Alumina Lanthanum (SAL) glass. The two SAP are clearly observable on the photograph of the fabricated fiber shown in Fig. 1(a). When the fiber is exposed to H_2 gas, the dips in the interference spectrum shift to longer wavelength until a plateau that corresponds to the saturation of H_2 diffusion into the fiber. This first result demonstrates the capability of such fiber for H_2 sensing.

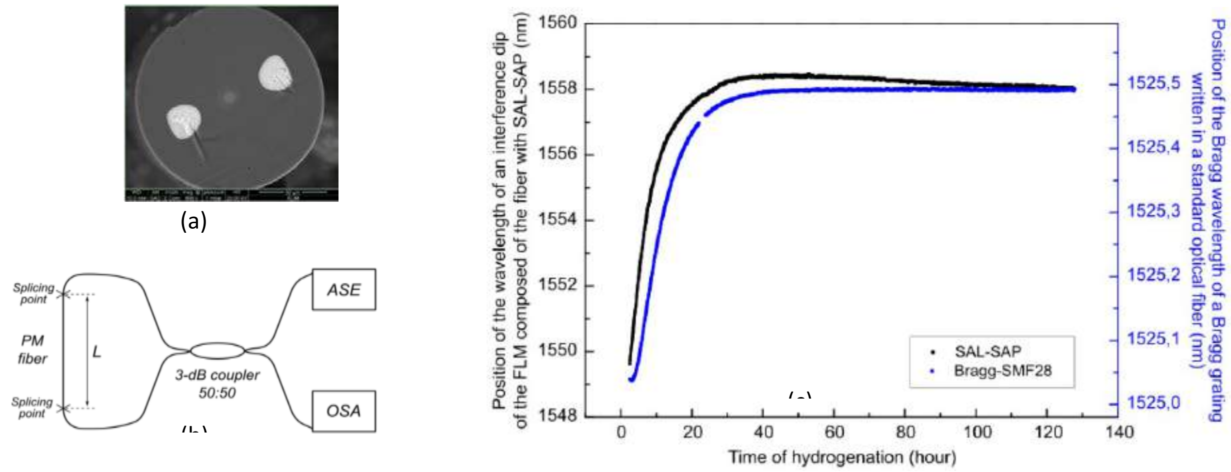

Figure 1: (a) SEM (in backscattered configuration) image of the cross-section of an optical fiber fabricated with two SAP composed of SAL glass. (b) Schematic of a high-birefringence FLM setup. (c) Evolution of the wavelength of an interference dip of the FLM composed of the fiber with SAL-SAP (black curve) and of the Bragg wavelength of a Bragg grating written in a SMF28, measured during the diffusion of H2 within the optical fibers.

It is well known that the optical properties of standard optical fibers are modified when H_2 gas diffuses into the fiber. For example, the backscattered Brillouin frequency could shift to +21 MHz at saturation level of H_2 diffusion [8]. In order to evaluate the sensing performance of the fabricated fiber, we have also inserted a standard optical fiber (SMF28) with a Bragg grating for measuring the variation of the optical properties induced by the diffusion of H_2. The shift of the Bragg wavelength is plotted in blue in Fig. 1(c). The comparison between both fibers shows that the fiber composed of two SAL-SAP enables faster detection of H_2, demonstrating the interest of this new concept for developing robust H_2-fiber-sensor for monitoring slow H_2 leakage of nuclear wastes.

In this communication, we will also present additional experimental evaluations of H_2-sensing performances of specialty optical fibers with SAP composed of boron doped silica (commercial case) or of Pd-particles doped SAL glass. A simulation study corroborating the experimental measurements in function of the diffusion of H_2 in the different optical fibers will also be presented.

Finally, in order to investigate furthermore the performances of this new type of H_2-sensor, we will report on the detection of H_2 concentration below 1.7 % with the FLM configuration. The demonstration highlight the potential of the specialty optical fiber with SAP for sensing H_2 in harsh environments that require robust sensors.

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Online monitoring system for measurement concentration changes of underground water in aperture

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1. Summary

Presented work is focused on measuring device that was specially designed for measuring changes in conductivity in a fractured environment. Measurement concentration changes in aperture caused by advection are complicated as the dimension of the tight aperture is below one millimetre and therefore standard conductometer cells are not usable. The validation of the device functionality was done in a laboratory in a rock block containing an artificial aperture. The measuring device recorded concentration changes during a tracer test in the block. The measuring device is connected to sensors that are equipped with a flat sensing part. The sensor is embedded in a borehole packer to ensure proper sealing. To the measuring device can be connected up to twelve sensors. The measurement can occur simultaneously or in cascade. The device is connected to a PC via a USB connector. The measuring device can be used in various impedance measurement setups.

2. Introduction

The waters in nuclear waste repositories are periodically sampled (e.g. radioactive waste repository Richard located in the Czech Republic)to detect particles that can indicate the leakage of the nuclear material or damage to the multiple-barrier system. A similar safety measure is used for post-closure monitoring of mines [1] where traces of heavy metals are observed. In both cases, the measures should protect underground waters from any contamination. An artificial material can contaminate the underground waters between the sampling periods. In the worst scenario, the leakage will take place as long as is the periodicity of the sampling. The constant monitoring of underground waters with the knowledge of flow-paths would increase public safety. To describe advection of underground waters, many research groups focused on mapping flow in fractures that occur in crystalline rock formations.

Describing flow in fractures [2] is complicated because the width of water-conducting fracture is usually several millimetres or less [3]. Dimensions of standard measuring sensors are in centimetre range, therefore, cannot be used directly in the fracture. A typical example is the conductivity measuring cell of a common conductometer. Conductivity is the first of choice parameter to measure because the anticipated leakage will affect the conductivity [4], [5]. As no others methods were available, the description of the advection inside the fracture was evaluated indirectly from tracer tests. The tracer tests [6] are based on injecting a tracer (saline [7], fluorescein [8] or radionuclide [9]) on a stream inlet and output streams were monitored.

Presented work, extends work published elsewhere [10], is based on the system that was developed to monitor water contaminants that are able to migrate via advection in fractured rocks. Newly developed sensors implemented with borehole packers enable proper sealing of a borehole that is connected to a fracture. Sensors are planar and therefore enable to minimalize the creation of dead volume that would impact measured data. The sensor array is connected to a measuring device that was developed for this purpose [11]. The monitoring is based on measuring of total impedance. A sinusoidal signal is modified in a measuring module and sent to an output clamp. The flowing current is measured on input clamp by a current/voltage converter and synchronous demodulator, which uses a rectangular signal generated on the DDS board by the demodulator. The rectified signal is then filtered by a low-pass filter and converted by a 16-bit AD converter. The measured output signal is used to detect changes is the solution concentration that is changed during tracer tests.

As this measuring device is designed especially for this purpose, raw data are obtained from the AD converter. Therefore, the values are without quantity, but the value corresponds to the total impedance. Purpose of this work is to approximate the obtained values to the conductivity of the solution.

3. Methodology

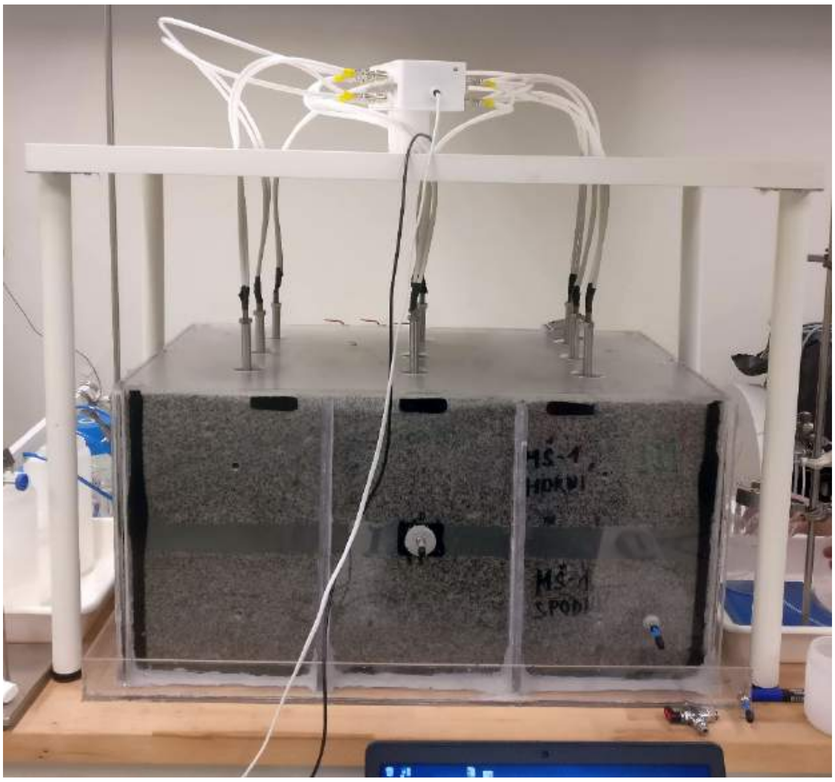

Figure 40: Photography of experimental apparatus for testing the measuring device

Prior to field tests, the apparatus is tested in a laboratory to have better control of various parameters. The experimental apparatus for testing the measuring device is shown in Figure 1. A granite rock (80×56×40 cm) was modified in order to be usable for the testing. The granite block was split in half, scanned and sealed again with three possible input ports on shorter sides (left and right side on the picture) and one input port on the longer sides (the front side and back side of the block). It is possible to use any of the ports as an input or output in this arrangement. The sealed fracture can be distinguished as the sealing material creates a smooth grey line in the centre of the granite block. The bright circle in the middle of the grey line is one port (on the longer side) that is connected to the fracture. The whole block is placed in a basin that keeps the rock saturated.

The borehole packers, arranged into an array at the top of the granite block, are implemented with sensors that are connected to the measuring device. The upper table act as a support for the measuring device and as a separator for the connecting cables. The measuring device is designed to be able to connect up to twelve sensors. And it is connected to a notebook where are all measured data collected. The proper EM shielding of the connection cables is ensured by coaxial cables. Every sensor is connected with one pair of coaxial cables. The measurement is controlled by typed commands in the command line. The operating software is written in a programming language Python. Measured data are recorded in a CSV file. It is possible to set frequency in the range of 1 – 1000 kHz. The amplitude of the signal is fixed to 50 mV. It is possible to switch off the synchronous demodulation. The measured data are evaluating using an algorithm for the digital filtering of values. The measurement can be run on all connected sensors simultaneously or in a sequence. To suppress residual charge that can be generated during measurement, it is possible to enable depletion delay.

The measured data are depicted in a graph where time is on the x-axis and the response from the AD converter is on the y-axis. The graph represents the development of measured response on time. The graph represents changes of total impedance of nine measured sensors during a tracer experiment where was used one input as an inlet and three outputs at the other end of the granite rock. The sides with one input were kept closed for all duration of the experiment. Every color line in the graph represents one sensing point. The measurement is continuous where the measured data are averaged from three second period. The basic response is different for every sensor because every sensor has a different electric characteristic. The background concentration of KCl solution was 60 μS/cm. A solution with the higher concentration of 1125 μS/cm was used as a tracer. In the presented experiment, the tracer was fed for eleven minutes. Sensors responses are recorded as lines (channels) F, G, and H are the closest to the feed.

4. Results

Typically, measured data are depicted in Fig. 2. The development of all channels can be divided into three parts: first steady part, the peak value, and second steady part. The first steady part corresponds to the signal that is obtained when a background concentration of KCl solution is pumped at a steady 20 ml/min. The peak value corresponds to the change in concentration after the feed was changed to the higher concentration. The second steady part corresponds to the background concentration.

The relatively sharp increase of all three lines is with good accord with the assumption that the change in concertation will be sharp as there was a relatively short time for axial diffusion to occur. Others channels exhibit a gradual change in the response. There is also observable the different time when the change starts. That is due to advection flow that determines the propagation of the tracer. At the end of the measurement, there is observable interference around time 15:44. This interference affects responses of all sensors and should be eliminated by using the depletion delay. The different baseline of every sensor will be compensated by a calibration. The calibration enables not only eliminates the differences of the background response but also can be used for determining the actual concertation value of the solution.

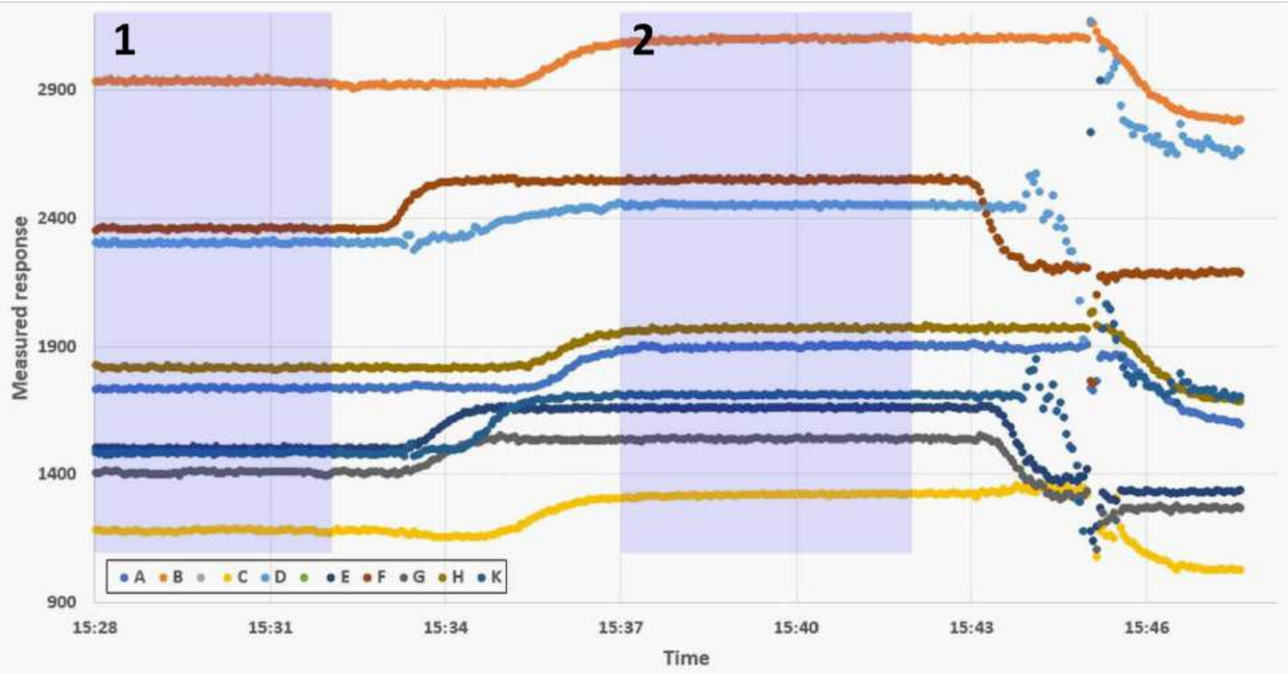

Figure 41: Graph of recorded data during tracer experiment

The data depicted in Fig. 2 are analysed in Table 1. The columns in the table correspond with the measured channel. The abbreviation AM stands for the arithmetic mean and the abbreviation SD stands for standard deviation. Data from all measured sensors were analysed in five minutes interval that corresponds to 108 records. The time intervals are highlighted in the graph (Fig. 2). Interval 1 (15:27 – 15:32) analyse baseline for all sensors and the interval 2 (15:37 – 15:42) analyse the response after the increase of values due to higher concentration solution in the aperture. ΔAM represent the difference between AM1 and AM2. This difference can be interpreted as the resolution of the measurement. The ΔSD is calculated as a difference between SD1 and SD2. The difference correlates error of the measurement for low and high concentration solution. The lower the difference is the more the measurement error is independent on the concentration. The value E characterise the resolution of the measurement (the difference of standard deviations divided by the difference of arithmetic means). The purpose of the analysis is to quantify measured response.

Table 13: Summary analysis of measured data

	A	B	C	D	E	F	G	H	K
AM1	1736,7	2935,4	1180,0	2305,0	1503,4	2360,7	1408,9	1816,9	1484,5
SD1	2,9	5,2	4,2	3,4	2,3	3,1	4,7	4,5	3,6
AM2	1897,6	3097,5	1319,8	2451,3	1661,2	2550,7	1539,3	1968,4	1710,5
SD2	9,0	8,5	6,3	4,5	2,4	3,3	3,4	8,7	3,3
ΔAM	160,9	162,1	139,8	146,3	157,8	190,0	130,4	151,5	226,1
ΔSD	6,1	3,3	2,1	1,1	0,1	0,2	-1,3	4,2	-0,3
E	6%	5%	5%	3%	1%	2%	4%	6%	2%

The average value of ΔAM is 163 points. Only one sensor (G) have value around 130 and only one sensor exceeds the value of 200 points (K). There is no obvious correlation between the absolute value of the impedance and error of the measurement. The highest error is 6 % shown in the channel A. If we assume linear change of the total impedance on the concentration (in the measured range), the change of one point represent a change in concentration of 6,5 µS/cm. As the average measurement error is 1,7 points, the measuring system can determine the change in concentration with accuracy approximately ± 11,3 µS/cm. This value must be calculated for every channel independently to obtain accurate errors.

5. Discussions

The accuracy of the measurement provided here is dependent on the sensor. The position of the sensor in the aperture affects the value of total impedance. The thicker the gap between the sensing part and wall of the aperture is, the lower are values of the total impedance. Therefore, the differences in ΔAM can be caused by different width of the gap under the sensing part. The surface of the rock below the sensing part of a sensor can affect the measurement ass well. The wall surface was prepared by cracking the rock block in half. The fracture is therefore inhomogeneous and even if all sensors would be in the same distance from the wall the surface of the fracture is different and that will affect the measurement as was described above.

Another way of adjusting the device performance would be the optimisation of the sensor part. The sensing part consists of two golden wires with the surface area below of 1 mm^2. The bigger surface area of the sensors enables to use higher voltage imputes. That would lead to the clearer signal output. The surface limits the higher voltage input because the usage of higher voltages would lead to creating bubbles on the electrode surfaces.

The function for the depletion delay was enabled after presented experiments were measured. The depletion delay should eliminate the signal interference that is observable in Fig. 2 at 15:45. The decrease of the response to the background concentration, compared to the first steady part, is probably caused by the interference. Prior to this tracer experiment, all sensors were separately tested to confirm that the changes in the signal responses are reversible and there is no hysteresis effect.

6. Conclusions

Even though the measuring system is still in the developing phase, current results are very promising. The developed system can be used for monitoring flow in fractured rock and therefore can help to better understanding and description of advection flow. The description and monitoring of flow-ways that surround underground repositories increases public safety. This presented system can be potentially used for monitoring underground water for detecting changes in concentrations.

The versatility of the measurement device enables using the device in different applications where changes in total impedance are determined.

Acknowledgements

The authors thank for the financial support by the Technology Agency of the Czech Republic in the project TH02030543.

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Pore-Water Pressure Monitoring by Minipiezometers

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1. Summary

Running in-situ experiments in underground laboratories successfully, requires generally collecting many reliable data from the rock at a minimum of man-made disturbances. In case of a claystone formation for instance, porewater pressure, gas-threshold pressure and the permeability are of particular interest. For this purpose, GRS developed the *minipiezometer* system. This extended abstract provides a description of the *minipiezometer* and gives examples of applications in the field as well as measurement results.

2. The system

2.1. Theory

In its present design, the system is foreseen to be installed in boreholes with a diameter of 20 mm. The small diameter has been chosen to avoid disturbances of the rock mass to the highest possible degree in order to acquire realistic data. It is difficult to maintain the correct borehole direction for long boreholes with such a small diameter. For application farther away from openings, a larger borehole is drilled (typically 40 mm diameter), and only the last half metre is drilled with the small diameter to minimise disturbance.

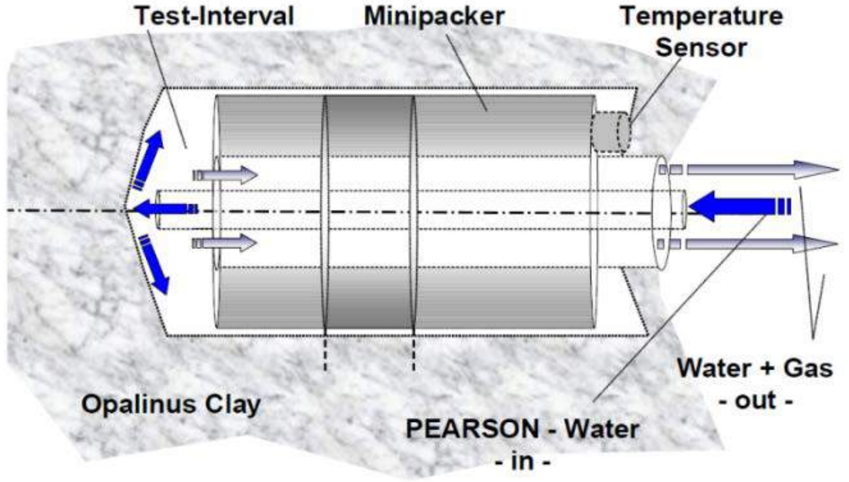

Figure 1: Sketch of the minipiezometer system used in Mont Terri URL; [3]

The construction of the *minipiezometer* system as well as its emplacement in-situ is shown in Fig. 1. It is placed close to the end of the borehole. A coaxial double tubing reaches out of the *minipiezometer* allowing for injection and extraction of fluids resp. synthetic pore water (e.g. Pearson water). If the temperature at the measurement point is also of interest, it is possible to place a temperature sensor, like a PT100, at the backside of the *minipiezometer* system.

2.2 Installation

The *minipiezometer*, which is shown in Fig. 2, is pushed into the borehole until its teeth at the front end reach the end of the hole. Now the teeth grab into the rock providing resistance for screwing the *minipiezometer* parts together. By the screwing the *minipiezometer* the rubber part gets squeezed together and expands laterally into the borehole providing eventually a provisional seal against water flow.

Figure 2: Foto of installed minipiezometer for demonstration purpose

To improve the sealing by the rubber part of the *minipiezometer*, the borehole behind the test interval is subsequently backfilled with resin. Losses of test fluid as well as collapsing of the borehole are thereby precluded. The test volume is then filled with the test fluid under a comparatively low pressure. With time (typically a few days), the pressure in the test interval will equilibrate with the surrounding pore pressure. The tube for outflow is connected to a pressure transducer for measurement. Most of our experiments use several *minipiezometers* in borehole arrays. In this case, the pressure transducers can be assembled in a rack. Such an arrangement is shown in Fig. 3. The picture was taken at an experiment setup at the Mont Terri rock laboratory.

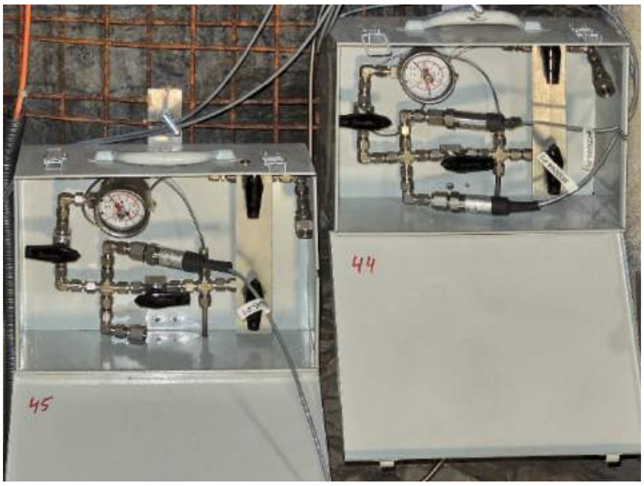

Figure 3: Sensor rack for pressure measurement connected with minipiezometers in boreholes

3. Data

3.1. Accuracy of the measurement system

In general, the accuracy of the measurement system depends on several different factors. The first and most obvious thing is the pressure transducer at the end of the tubing. Secondly, the coaxial tubing needs special attention during the installation process, because one tube is used for the pressure measurement and the other one is used to get fluid or gas pressure into the test interval. Since most common tube fittings are not designed for a coaxial tubing, a special solution is necessary. It is only possible to take reliable measurements if there are no leaks in the tubing or the connections of the tubing system. The third and most challenging factor is the installation of the packer itself. If the backfilling with resin does not fill the entire cross-section of the borehole, the injected fluid or gas will spread out uncontrollably along the entire borehole. If going undetected this would compromise the whole test.

Concerning the obtainable data accuracy it should be pointed out that in earlier experiments using *minipiezometers* it was even possible to see tide effects in the pore-water measurement data. The data were recorded in 2002 in the Mont Terri rock laboratory and showed periodical pressure changes of 1-4 kPa due to the daily alternating influence by gravitation of moon and sun and by centrifugal forces [5]. Seeing such effects in the data indicates a good communication between the water bearing intergranular pore spaces and thereby demonstrates also nicely the accuracy of the measurement system. In several experiments, the systems have worked properly for several years and delivered reliable data.

3.2. EZ-G experiment

The *minipiezometer* system has already been used in several projects for measurements in the Opalinus clay ([1], [2], [3], [4]). For instance, it was used in the EZ-G experiment at the Mont Terri rock laboratory, which was a mine-by experiment. It was meant to show the development of the porewater pressure during nearby mining activities. Fig. 4 shows a data plot from the beginning of the EZ-G experiment obtained with the *minipiezometer* system for the first two weeks after the installation to show the early-phase behaviour [4]. At the boreholes EZ-G6 and EZ-G7 the pressure was equilibrating with the pore pressure right from the beginning on. EZ-G8 does not show the expected reaction. Some remaining air in the test interval was suspected here. A water injection test after one week, performed in order to determine the rock permeability, displaced the air. Afterwards, the *minipiezometers* in the three boreholes were working properly and showed the same behaviour of a slowly increasing porewater pressure in the equilibration process. Fig.5 shows the pressure plot of the whole experiment. The pore-water pressure of all 3 boreholes is later decreasing during the experiment. The drastic changes of the porewater pressure that can be seen at the end of the experiment are caused by the mining activities. The piezometers had been placed around the future tunnel. When excavation drew close to the piezometers the pore pressure first increased due to increased loading of the rock and afterwards dropped when excavation passed the piezometer.

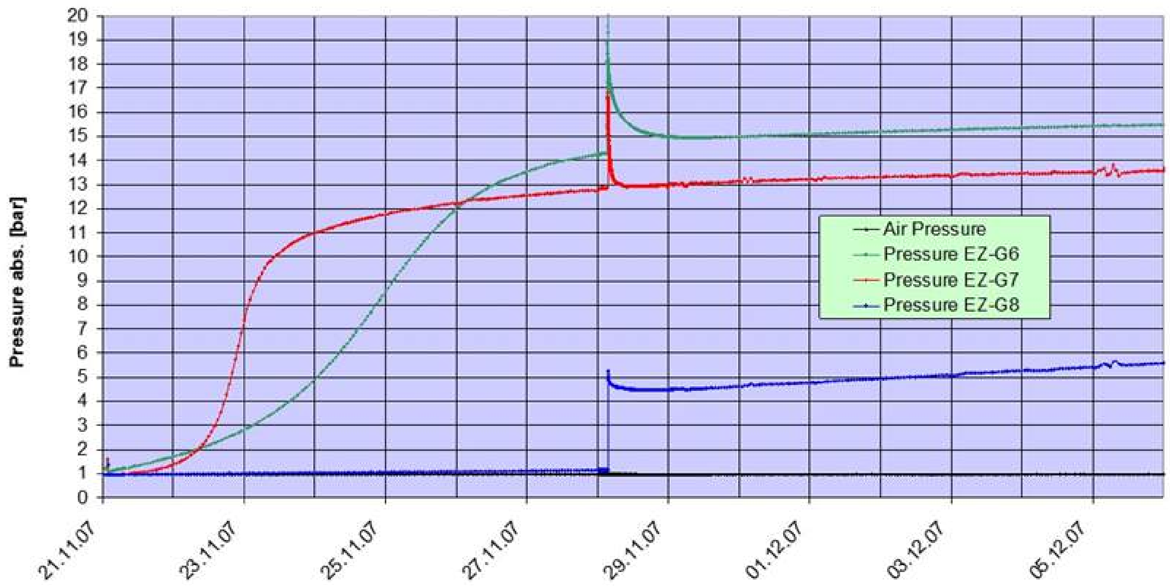

Figure 4: Pore-water pressure data obtained with the Minipiezometer system; [4]. The pressure spike on 28.11.07 corresponds to a liquid injection test

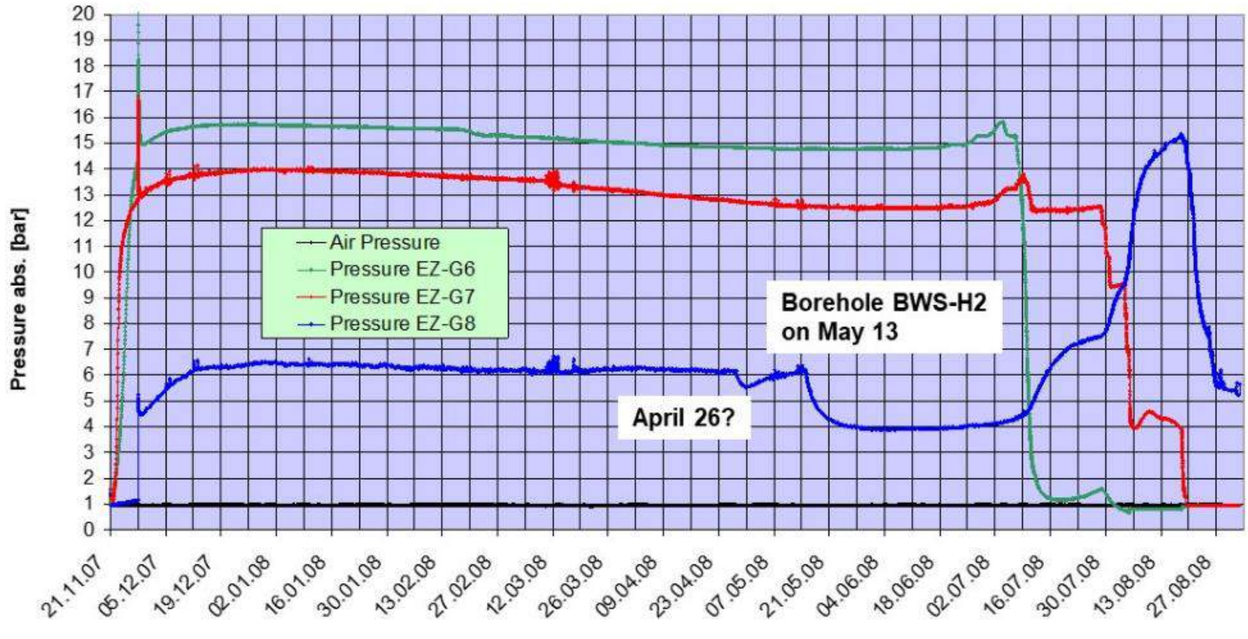

Figure: 5 Pore-water pressure data of the EZ-G experiment

3.3. FE experiment

While the EZ-G experiment was planned to last a bit less then a year, the FE experiment was envisaged for a time period of more then 10 years. This experiment was initiated by Nagra and is a presently ongoing 1:1 scale test of the storage of nuclear waste according to the swiss disposal concept using electrically heated dummy canisters in a disposal gallery. The porewater pressure around the concrete plug of the gallery is measured by *minipiezometers*. The porewater pressure plot of four of the installed *minipiezometers* is shown in Fig. 6. These four *minipiezometers* were installed around the front part of the FE experiment gallery. While they show a different behavior in the early phase after installation, the pressure distribution homogenises with time, as was expected. In the later phase, a gradual increase in pressure can be observed which is due to the temperature increase of the rock caused by the heat output of the canisters. This increase is superimposed by a seasonal pressure change which is also caused by temperature change.

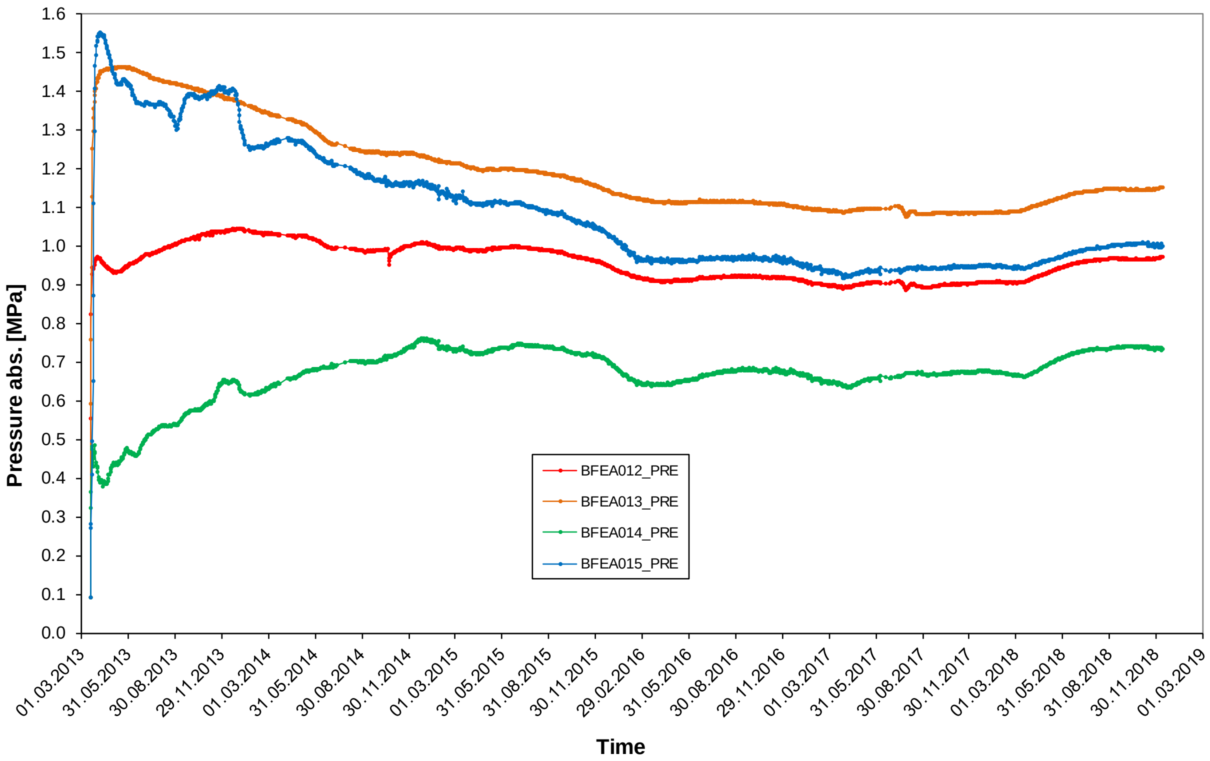

Figure 6: Pore-water pressure data of the FE experiment

4. Comparison with conventional multipacker probes

During the EZ-G experiment, two different types of piezometers have been installed. At first there were only 3 *minipiezometers* installed. Later, also a multipacker system was installed in the same rock formation. This offered the possibility to compare the data of the *minipiezometers* with the data from the traditional multipacker. The comparison is shown in Fig. 7.

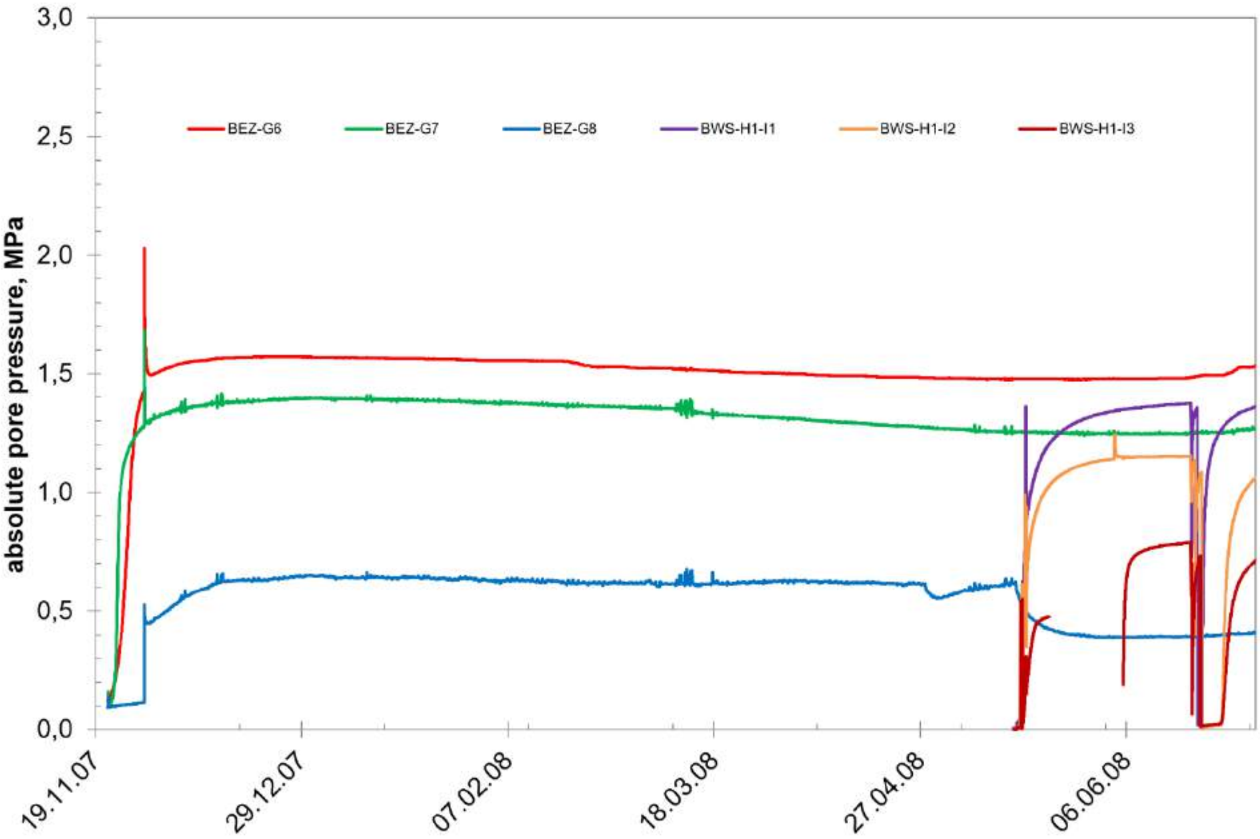

Figure 7: Pore-water pressure data from minipiezometer and multipacker

The boreholes BEZ-G6, BEZ-G7 and BEZ-G8 have been instrumented with *minipiezometers* while the BWS-H1 borehole was drilled later and was then instrumented with a multipacker with 3 intervals. It can be seen, that the measured porewater pressure of the first interval of the multipacker is close to the value from borehole BEZ-G6, where the *minipiezometer* is installed at nearly the same distance fom the tunnel wall as the first interval of the multipacker.

Since the borehole is filled with resin after the installation of the *minipiezometer*, it isn't reusable. Compared to a multipacker system, however, this procedure lowers the disturbances of the hostrock, because the *minipiezometer* does not induce any stress onto the hostrock. The boreholes for a multipacker also have to have a larger cross-section than the boreholes for a *minipiezometer*. On the other hand, the multipacker system allows to measure the porewater pressure at different positions in one borehole while the *minipiezometer* system is restricted to one measurement spot per borehole.

5. Future Developments

Over the years the *minipiezometer* system has been extensively used for data collection, particularly in the Mont Terri underground rock laboratory in Switzerland. During this time, it has become obvious that reliable data are obtained. However, an optimisation of the installation procedure with a view to specific aspects, e.g., prevention of leakage due to insufficient resin bonding, is desirable. Respective ideas are currently evaluated and will be tested.

6. Conclusion

The *minipiezometer* system is a reliable measurement system, which can be set up at comparatively low costs compared to the expenses for a multipacker system. Only a borehole with a quite small diameter of 20 mm is required. This makes it attractive for setups with many measurement points. Due to the small borehole diameter the disturbances in the rock are kept at a minimum. The additional mechanical load on the rock exerted by a single- or a multipacker system can be entirely avoided with the *minipiezometer* system. Because of its simplicity, it is a robust system producing reliable data, even years after its installation.

Acknowledgements

We would like to thank the Federal Ministry for Economic Affairs and Energy (BMWi) for financing our experiments at the Mont Terri rock laboratory under contracts 02 E 10116, 02 E 10689, 02 E 9773, and 02 E 10377.

Further thanks go to the staff of the Mont Terri rock laboratory for unfailing support.

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Qualifying distributed strain sensing systems based on optical fiber for the monitoring of radioactive waste repository

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Abstract

In the framework of Cigéo, the planned French underground radioactive waste repository center, and Modern2020 European Project, Andra developed and qualified a monitoring system to provide distributed measurements of four parameters, namely temperature, strain, hydrogen and radiation. Optical fiber sensors are exploited for their resistance to harsh environment and their ability to provide distributed measurement thanks to different scattering processes. Fluorine doped fibers with a carbon coating are recommended for strain sensing in order to endure respectively radiation and hydrogen. Results were obtained thanks to the cooperation between MODERN2020 partners (Andra, IRSN France, SCK-CEN and University of Mons in Belgium) and research partners such as Hubert Curien Laboratory, iXBlue and Solifos companies.

1. Introduction

Andra is in charge of the radioactive waste management in France and has planned to build an underground repository center, where high-level (HL) and intermediate-level long-lived (IL-LL) wastes will be host in cells under 500 m of clay rock. The structural health of these cells and other physical parameters should be monitored, as retrievability of waste should be possible for at least one hundred years after the start of the exploitation. However, due to the presence of waste, the sensing system should endure harsh conditions such as mechanical stresses, radiation, temperature up to 90°C, hydrogen, humidity. Distributed strain measurements would rely on optical fiber selected for their tolerance to harsh environment, paired with a Brillouin scattering acquisition device. The frequency shift is known to be proportional to both strain ($\Delta\varepsilon$) and temperature variations (ΔT) via the so-called Brillouin central frequency shift $\Delta\nu_B$ following the equation

$$\Delta\nu_B = C_T\Delta T + C_\varepsilon\Delta\varepsilon,$$

where C_T and C_ε are the temperature and strain sensitivity coefficients (in MHz/°C and MHz/µε respectively) of the fiber used as the sensitive element for the distributed measurements [1].

It is known that the single influence of temperature, radiation [2] and hydrogen [3] impacts the optical fiber sensor properties, compromising strain results and measuring performances. There remains to analyze the coupled impact of these parameters affecting simultaneously the sensor, as the coupled influence of radiation and temperature and the impact of hydrogen on irradiated fibers. For this reason, different tests were set up by Andra together with IRSN, SCK-CEN and University of Mons, in order to understand the impact of radiation ageing under other physical constraints.

2. Coupled temperature and radiation

Materials and methods

Within the first century of exploitation, where monitoring needs to be operative, the first hosted HL waste will release a representative total dose of 1 MGy. In IRMA ^{60}Co facility of IRSN (France, Modern2020 partner) this dose is reachable in only two weeks at a dose rate of 3.2-3.4 kGy/h. There, samples (of 30 m) of two different fibers where put under irradiation in November 2017: one Ge-doped fiber and a MODERN2020 custom F-doped fiber. The first comes from Fibertronix (now Fibercore), with 5.2% Ge-SiO2 core and pure silica cladding, with a carbon-polyimide primary coating; the second from iXFiber (now iXBlue), with 0.3 wt% F core and 2.3 wt% F cladding with a polyimide primary coating.

At the same time, the samples were packaged inside thermally-controlled silicones in order to be irradiated at different temperatures, representative of the targeted application: room temperature (RT), 80 °C, 100 °C and 120 °C. Temperature is monitored and recorded by three thermocouples inside the silicone, while another thermocouple is placed near the RT sample, to guarantee the independence of results from chamber temperature variations. Fibers were coiled with a 9 cm diameter to limit curvature influence.

Every sample was connected to the Neubrescope measuring device, located in a radiation-free zone, performing online measurements. Each sample was measured on a specific optical line, thanks to the Neubrescope switch, and each $\Delta\upsilon_B$ is recorded all along the fiber. For example, the trace at 80°C is displayed in Figure 1. For the two samples, Ge and F-doped, a single value per measurement time is taken into account, which is the mean value of central values.

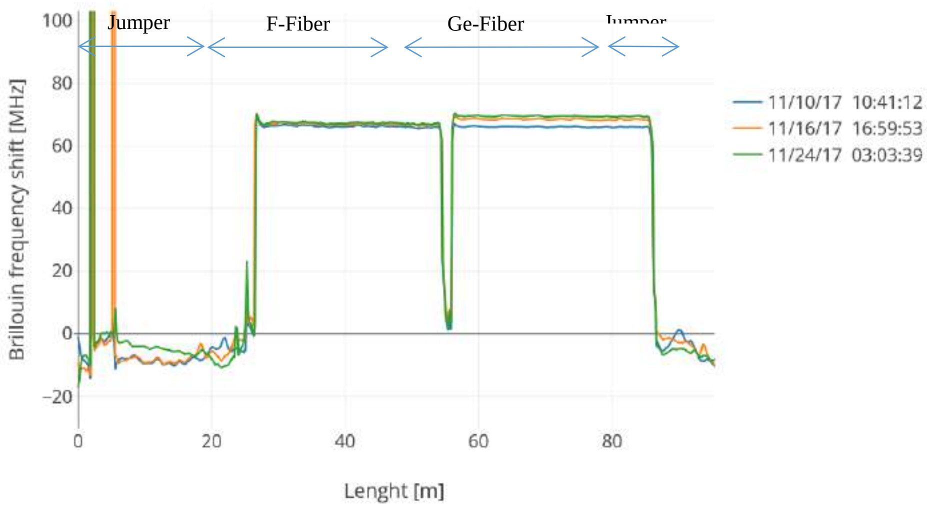


Figure 42: Single optical line measurement

Results

In Figure 2 the coupled influence of temperature and radiation on Brillouin frequency shift is shown, for Ge-doped (a) and F-doped fibers (b). The F-doped samples are able to better withstand radiation, as the corresponding $\Delta\nu_B$ is less with respect to Ge-doped fibers, while no temperature influence is noticeable.

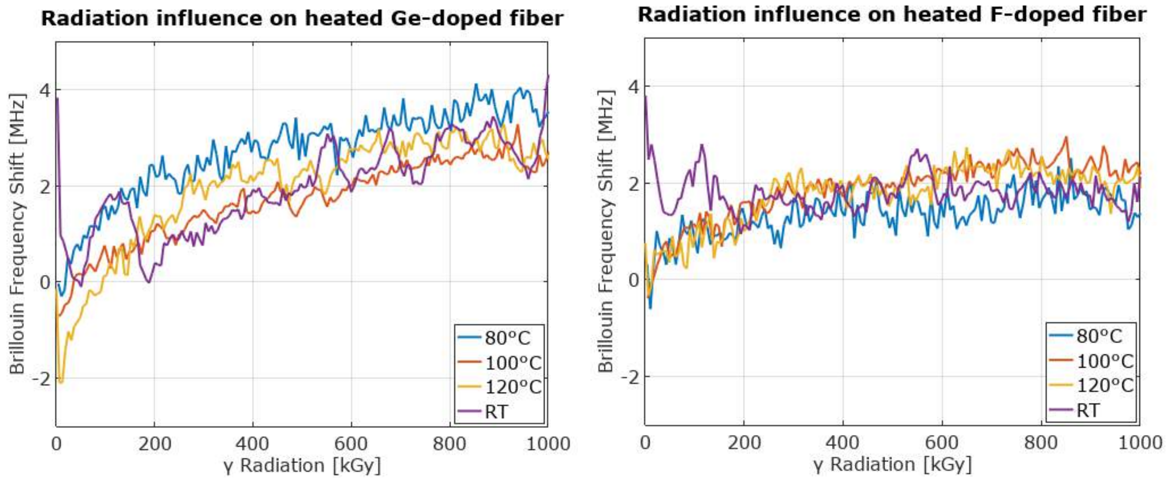
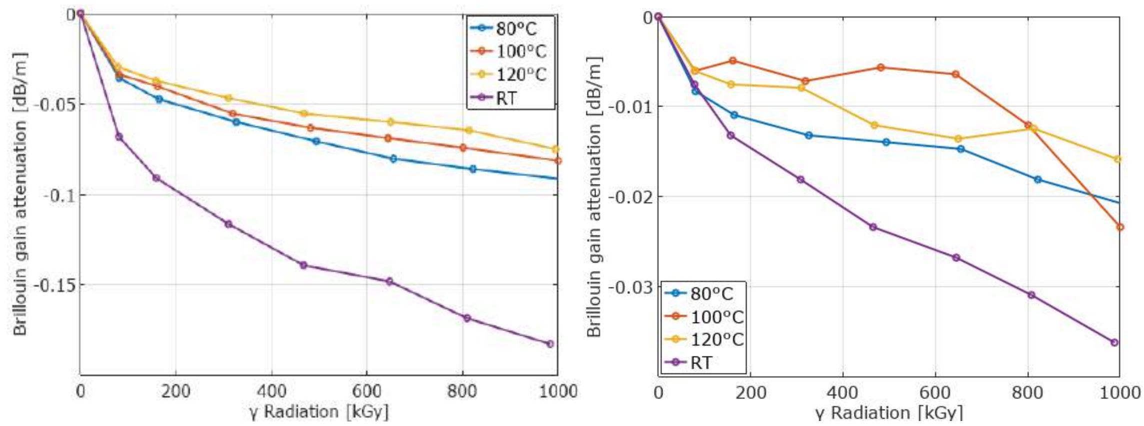


Figure 43: Brillouin frequency shift of Ge (a) and F-doped (b) fibers under coupled temperature and radiation influence

Looking at the radiation induced attenuation (Figure 3), it is possible to see that, again, the Ge-doped fibers are more affected by radiation than the F-doped ones. In this case, however, it is possible also to see the temperature influence. In particular, the presence of temperature of around 100°C is good for the final application, as it reduces the attenuation due to radiation.



a) **b)**

Figure 44: Brillouin radiation induced attenuation for Ge-doped (a) and F-doped (b) fibers

3. Carbon coating hermeticity: coupled hydrogen and radiation influence

Materials and methods

Hydrogen diffuses through the constitutive silica of optical fibers. It is reversible and reaches saturation, whose value and kinetics depend on pressure and temperature, however hydrogen diffusion induces optical losses and frequency shifts. It means that maximum distance range would diminish and that accuracy would be affected.

Carbon coated fibers are proven to be hermetic to hydrogen, however it is important to understand the possible influence of radiation on the coating degradation. For this reason, with the collaboration of the irradiation facility MOL SCK-CEN and the University of Mons (MODERN2020 partner), ageing test were conducted putting a carbon coated under a total dose of 10 MGy with a ^{60}Co source. The total dose is representative of the maximum total dose that an optical fiber sensors would undergo in a real case, over 100 years of exploitation.

The fiber under test has a Ge-doped core and an F-doped cladding, with a carbon-polyimide coating. Two samples of 30 m of this fiber are selected, of which one is put under irradiation, reaching 10 MGy with a dose rate of 370 Gy/h. Months after, both samples are placed in a hydrogenation chamber, undergoing different cycles of hydrogenation at 95 bar and 80°C (Figure 4) while being interrogated with an optical spectrum analyser (OSA) and a supercontinuum laser source. Measuring the attenuation spectra of the fibers before and after hydrogenation, especially the absorption zone at 1245 nm, it is possible to follow the eventual hydrogen migration inside the fiber.

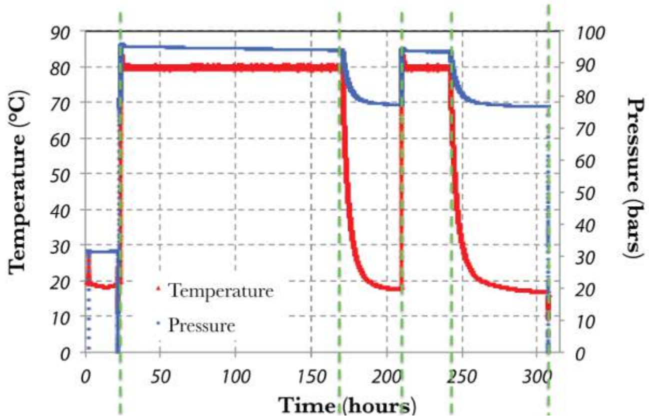


Figure 45: Hydrogenation cycles

Results

In Figure 5 results are reported. It is possible to notice that an absorption peak is present at around 1245 nm for the irradiated fiber after hydrogenation, while it is not present for the non-irradiated one. The wavelength is the one at which a strong peak of absorption is noticeable when fibers undergo hydrogenation [3]. Even if the peak is weak (5 dB versus 25 dB when coating is acrylate), this proves that the fiber lose its hermeticity to hydrogen after absorbing a total dose of 10 MGy.

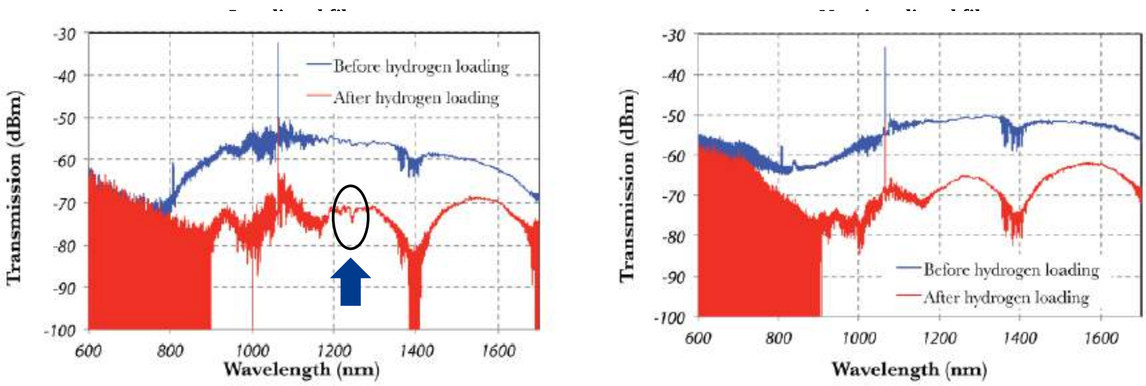


Figure 46: Absorption spectra for irradiated and non-irradiated fibers, before and after hydrogenation

4. Insertion of the qualified optical fiber into a strain sensing cable

Thanks to MODERN2020 and given the importance of radiation hard fibers with hydrogen hermeticity for strain sensing, Andra has managed to insert an F-doped fiber with a carbon acrylate coating inside a strain sensing cable. The chosen cable is the BRUsens V9 from Brugg Cables (now Solifos AG). This resulted after several tentatives as particular accouterments are necessary in order to insert a special fiber inside a commercial sensing cable.

5. Conclusion

In this abstract some results obtained thanks to the collaboration of Andra and other MODERN2020 partners are presented. F-doped fibers with carbon coating are mandatory in order to withstand respectively radiation and hydrogen, however i) temperature helps fiber recovering from radiation induced attenuation, without affecting the Brillouin frequency shift and ii) carbon coating hermeticity is reduced after absorbing a total dose of 10 MGy. Further analysis will be performed on the MODERN2020 custom cable, to follow its mechanical behaviour after being irradiated.

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Xenon radioisotopes measurement as monitoring tool for transuranic radioactive wastes

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1. Summary

Radioxenon is mainly produced as fission product by nuclear power plants but also by spontaneous fission of transuranic isotopes as Pu-240. Xe is a noble gas characterized by chemical inertia and high mobility in the underground so it could be of interest for the monitoring of Pu-240 in the wastes, given its high yield of spontaneous fission and its constant production rate. The release of radioxenon could impact the isotopic composition of the total xenon outgassing form the subsurface giving an early warning signal of leakage form transuranic wastes. Pu-240 is actually present in the Italian radioactive waste inventory, with a total activity of about 200GBq. In Italy there is only one facility that performs analysis of radioactive isotopes of xenon in the atmosphere and it is hosted by ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic. ENEA traceability Laboratory performs radiometric controls and assessments of radioactive contamination in several kinds of different samples: environmental samples as air (Atmospheric Particles and Dissolved Noble Gas), water (Sea, River and Lagoon) and sediments soils vegetables; industrial samples as building materials tiles (floor and walls) and metals fuels check for decommissioning of power plants; food samples as milk, water (Drinking), cereals, wine, meat, vegetables and so on. ENEA Noble Gas laboratory is also supporting activities of the Italian National Data Centre for the Comprehensive Test Ban Treaty (CTBT), participating since four years to the RadioXenon Intercomparison exercises. The development of an "early warning" tool or the identification and management of eventual nuclear accidents and the monitoring and control of the repository for the storage of radioactive wastes have been included in the research activities of ENEA Traceability laboratory. The methodology for the noble gas monitoring in the proximity of a radioactive waste disposal to better understand the origin of xenon emission will be presented.

2. Introduction

Transuranic (TRU) waste is any material that have radiological contamination consisting of isotopes with a higher periodic table value than uranium. The majority of the Italian TRU waste inventory has been generated by the operation and decommissioning of reprocessing and fuel fabrication plants as well as by the decommissioning of former Italian nuclear power plants. It includes several types of solid and liquid materials, as sludge or liquid from reprocessing, technological waste, filters and resins.
The radioactivity of the TRU waste is considerably smaller with respect to the high-level waste or spent fuel, nevertheless, due to its long lifetime and high radiotoxicity, this type of waste requires

disposal in a geologic repository. Before the final disposal, it shall be conditioned and packaged in containers suitable for storage; generally, the conditioning consists in solidification in cement in case of liquids, and super-compaction and cementation for solid materials.
Several transuranic isotopes have significant spontaneous fission decay modes producing short-lived radioactive xenon isotopes. The Pu-240 decays primarily by α-emission and a small fraction of the decays (5.7E-08) occurs by spontaneous fissions, with a half-life of 1,14E11 years. Consequently, radioxenon is continuously produced by spontaneous fission of Pu-240 incorporated in the wastes, and due to its chemical inertia it is able to escape the surroundings and transferred to the subsurface layers and ultimately to the atmosphere.
The xenon production rate is a function of the spontaneous fission rate and the fission yield of the isotopes. Thus, considering the decay constant of 1,93E-19 s^{-1} from the spontaneous fission half-life of plutonium-240, and assuming the xenon-133 fission yield of 7,02%, the production rate of xenon-133 results of 1,35E-20 atoms per second per atom of plutonium-240 (that is equivalent to a production rate of 3,39E+01 atoms per gram of plutonium-240 per second). Considering a total activity of 200 GBq for the Italian inventory of Pu-240, the production rate of xenon-133 results of 807 atoms per second, corresponding to 1,2E-03 Bq/sec.
Radioxenon gases can be collected by gas sampling methods using cryogenic absorption on activated charcoal traps and measured by gamma spectrometry using a High Purity Germanium detector.
At ENEA Noble gas laboratory, a complete system made of a sampling mobile unit and a laboratory based gamma spectrometric system has been implemented and it has been tested to achieve low value of Minimum Detectable Activity, for the purpose of monitoring the atmospheric sample in the proximity of a radioactive waste repository.

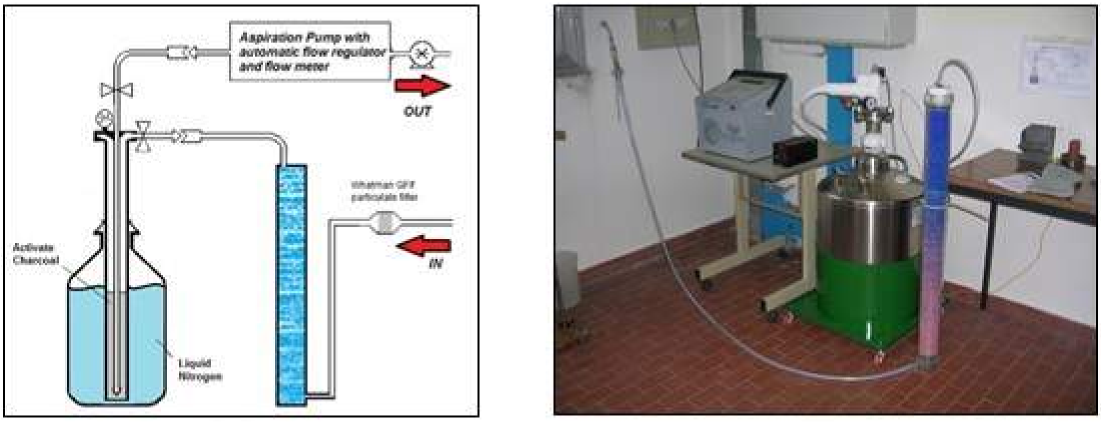
3. Methodology

3.1 Description of the system

The design and the implementation of the noble gas facility at the ENEA laboratory were based on a step by step approach that led to divide the facility into three different and separate units, each one characterized by efficiency limiting factors that should be properly addressed in order to achieve a good overall efficiency.
The three units are: air collection (sampling and adsorption), processing (gas extraction and purification) and measurement (gamma-ray spectrometry analysis). Bearing in mind this division, a different location was specially designed for gamma-ray spectrometry analysis in order to be able of improving the sensitivity of the measurements.
This strategy triggers the design of a sampling and collection system that can be transportable in order to be used also in monitoring campaigns while the improvement and test of the other two units (gas extraction and gamma spectrometry) can be carried on without affecting the sampling device.

3.2. Air collection

For the purpose of testing the efficiency of collection, the sampling equipment was designed and set up at the upper floor of the laboratory building in order to collect the most representative sample of the atmospheric air and to minimize the radon component in the sample. In order to minimize any possible interference with the other activities of the laboratory, the specific air inlet is located far from the discharge tubes of the chemical gases arising from the laboratory chemical hoods. As for the sampling technique, an active sampling system was chosen in order to collect a large amount of ambient air and so to obtain a higher xenon enrichment in the final air sample. Active sampling involves the collection of a known volume of air by pulling air through a collection device in which an appropriate medium is used to concentrate the xenon fraction that has to be measured. This sampling technique does not depend upon the wind speed, so it can be used in different environmental and meteorological conditions. The sampling process is based on dynamic cryogenic adsorption on activated charcoal particles. (Fig. 1) [1, 2]. The sampled air flow is about 0,6 m^3/h for a total of 100 m^3 after a one-week sampling. The incoming air stream is partially separated from aerosol (through a filter GF/F) and water (through silica gel); this is necessary because water would adsorb on the charcoal column of the system reducing its adsorption capacity for xenon. Then the gaseous sample fluxes through an adsorbent cartridge containing activated charcoal particles (0,3 – 0,5 mm diameter) cooled at cryogenic temperature (-197°C) by liquid nitrogen in order to achieve a higher xenon adsorption efficiency.

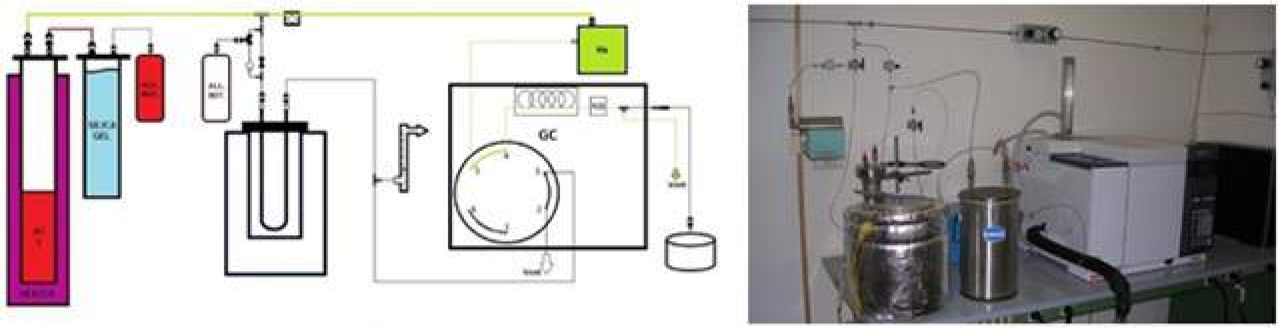


(a) *(b)*

Figure 47: Sampling device: scheme (a) set up (b).

3.3. Processing

The extraction phase is based on the temperature-controlled desorption with Helium as carrier (Fig. 2). The desorption process was carried out at 280°C for 1 h at a pressure up to 200 - 300 mbar. The gas sample is flushed into an aluminum sample container equipped by a valve for the vacuum pumping and the transfer of the sample. The transfer of the sample to the calibrated container previously cleaned with nitrogen is performed by using inert gas carrier (Helium) at a pressure of about 1,5 – 1,8 bar. Some molecular sieves are used for removing effectively any remaining H_2O and CO_2 and consequently also radon. Radon has to be removed because its activity concentration in air can be several orders of magnitude higher than the activity of xenon and so with its progenies it would increase the background for the spectrometric measurements. The total processing time (time between the end of the sampling and the start of measurement) is about 8 h and it includes desorption, sample transfer and preparation for radiometric measurement. Further processing of the gas sample is necessary in order to further purify the gas sample, to increase the xenon concentration in the sample and to determine the amount of sampled xenon. This final step is performed by using gas chromatography.



(a) *(b)*

Figure 48: Desorption device: scheme (a), set up (b).

3.4. Measurement

The detection and measurement of the radioxenon isotopes contained in the gas sample is performed by high-resolution gamma-ray spectrometry. All four xenon radioisotopes of interest emit X-rays in the 30 keV region with a total branching ratio of about 40 - 50 % except for ^{135}Xe which has only a 5 % X-ray emission probability; the main gamma-rays emitted are from ^{133}Xe (81 keV) and ^{135}Xe (249,8 keV) [3, 4]. The X- and gamma-ray spectrometry was chosen because it allows for a direct detection of all the four xenon radioisotopes with a high spectral resolution. The detector used is high purity germanium coaxial detector p-type 'Extended Range' installed inside a low-background shield made of old lead (150 mm) with a layer of electrolytic copper (35 mm) to remove the 70-keV X-rays induced in the lead by ambient gamma-ray radiation. The main HPGe characteristics are: 60% relative efficiency and 1,95 keV FWHM on the 1332 keV 60Co γ-ray, 70,5 mm length, 68 mm external diameter and 89 mm end-cap diameter. The system included a cryo-cycle cryostat to keep at cryogenic temperature the HPGe detector.
The minimum detectable activities (MDA) for the Xe radioisotopes, have been calculated according to the Currie formulation [5] and they are listed in Table 1:

Table 14

	Energy (keV)		**Yield (%)**	**MDA (Bq)**
^{133}Xe	81		37,10	0,042
^{131m}Xe	163,9		1,96	1,861
^{133m}Xe	233,2		10,30	0,385
^{135}Xe	249,79		90,30	0,039

These values show that the implemented system has the capability to detect low concentration of Xe isotopes in atmosphere.

4. Conclusion

At ENEA laboratory for Xenon radioisotopes, measurements in air samples has been implemented and tested. The system consists of three separated units: air collection (sampling and adsorption), sample processing (gas extraction and purification) and gamma spectrometry analysis. The system would allow periodic sampling and monitoring of radioxenon content in atmosphere and could support the design of an early warning system for the monitoring of transuranic isotopes stored at the radioactive waste repository.

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Calibration of heated fiber-optic cable for monitoring dry density and water content in granulated bentonite mixture in the Full-scale Emplacement experiment

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Abstract

Actively heated fiber-optic (FO) cable combined with distributed temperature sensing (DTS), referred to as active DTS, has been receiving much attention recently as a tool for estimating soil moisture (e.g. Ciocca et al., 2012). The method involves electric heating of the FO cable and measurement of temperature responses along the cable, which are strongly affected by the thermal properties of the soil. Active DTS allows estimation of thermal properties along a long profile. In unsaturated porous media, the thermal conductivity depends on dry density and water content, which can be estimated with active DTS along decameter or longer profiles after careful calibration. Thermal conductivity, dry density and water content are important parameters for an engineered barrier system (EBS) consisting of a granulated bentonite mixture (GBM). Dry density distribution is a quality control indicator at the time of emplacement of the EBS to ensure, for example, low permeability. Water content provides information on resaturation of the EBS due to water influxes from the rock formation.

Nagra has installed a set of heatable FO cables in the Full-scale Emplacement (FE) experiment (Müller et al., 2017) underway at the Mont Terri Rock Laboratory in Switzerland. Based on numerical and experimental studies conducted by Nagra (Sakaki et al., 2017 and 2018), a new experimental project on estimating density and water content of GBM using active DTS was initiated in 2016 under the EBS lab framework at the Grimsel Test Site (GTS). These studies allowed the lab experiments to be designed, the optimum heating power and DTS setting parameters to be identified, possible boundary effects during the heating of the FO cable to be investigated and identification of the most accurate procedure for computing the dry density and/or water content from the raw temperature data during the heating tests.

Estimation of dry density of GBM

The lab experiments with varied dry density showed that active DTS can generate temperature data that are sufficiently sensitive to the dry density of the GBM surrounding the FO cable. The experimental boxes were prepared with controlled dry densities to find the method that provides the best calibration. Three methods were examined: 1) thermal conductivity, 2) temperature change and 3) cumulative area methods (Sakaki et al., 2017; 2018).

Thermal conductivity method: The method uses the relationship between the thermal conductivity and the dry density under fixed water contents of GBM. The thermal conductivity was computed using the dT-lnt data for various heating powers Q. When Q is low (0.5 or 1.0 W/m), the resulting temperature changes were insufficient so that the signal to noise (S/N) ratio was low. Higher Q of 2 to 5 W/m, on the other hand, induced sufficient temperature changes with high S/N ratio. The estimated thermal conductivity values for the controlled dry densities showed a good agreement with those measured separately with the thermal conductivity meter (KD2 Pro, Decagon Devices ©, 2015).

Temperature change method: The temperature reached on the d*T*(*t*) curves at a certain time (e.g. at the end of the heating) estimated using fitted lines was found to be a sensitive indicator for predicting the dry density. The raw temperature data, on the other hand, showed some noise which was directly transferred to the selected reached temperature if the raw values were used. It was thus strongly suggested that the reached temperature values should be determined using the fitted lines. It was also shown that it would take a significantly long time for a plateau to be reached.

Cumulative area method: The cumulative areas under the d*T*(*t*) curves also showed potential for predicting the dry density. The noise in the raw temperature data cancels out in the area computation, thus no fitting was necessary. Increasing the heating power and heating duration both showed a linear impact on the cumulative areas. In case more cumulative area is needed, either the heating power or heating duration or both can be increased in such a way that does not cause unnecessary moisture movement around the FO cable.

Comparison of the three methods: Examination of the above three methods indicated some pros and cons for each one. The thermal conductivity estimated with the slope of the d*T*-ln*t* data was practically consistent with the actual thermal conductivity of the GBM around the FO cable. It therefore suggested that the results were independent of the FO cable.

The temperature changes and cumulative areas are directly affected by the cable properties, such as diameter, thickness of the sheath, etc. Therefore, with these methods, calibration is not only a function of the GBM state (dry density and water content) but also of the type of FO cable, suggesting that a cable-specific calibration is necessary.

Estimation of degree of saturation of GBM

The experiments with varied water content showed that active DTS also has a high potential to estimate the degree of saturation of the GBM surrounding the FO cable.

The thermal conductivity method was used to determine the water content under fixed dry density conditions. The thermal conductivity was computed using the d*T*-ln*t* data for various heating powers *Q*. As observed in the dry density estimation, higher *Q* (2 to 5 W/m) was preferred to induce sufficient temperature changes with high S/N ratio. The estimated thermal conductivity values generally showed a good agreement with those measured separately with the thermal analyzer.

The FO cable calibrated to the degree of saturation of the GBM used in the FE experiment. The fitted linear function showed a high r^2 value of 0.914 and the 95% confidence intervals were narrow (± 1.6 % in terms of saturation).

Conclusion

The relationships between thermal conductivity and dry density and thermal conductivity and water content were established. These calibrations are used successfully to estimate the state of the GBM along the 250 m FO cable in the FE experiment.

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Demonstration of a two-staged, wireless transmission chain out of the LTRBM borehole to the surface of the Tournemire plateau

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1. Summary

As part of WP4 of the Modern2020 project [6], Andra, IRSN, and NRG successfully demonstrated in a combined effort a full data transmission solution that allows transmitting wirelessly sensor readings out of the Long-Term Rock Buffer Monitoring borehole (LTRBM) to the earth's surface. The demonstration used a combination of wireless technologies for short and long distance and consists of three contributions: 1.) the LTRBM borehole, prepared by IRSN, backfilled with bentonite and hydrated in the second part of 2018, 2.) two vibrating sensors of Andra, placed inside the LTRBM and transmitting wirelessly sensor readings every six hours to a receiver unit in the main gallery, and 3.) a long range data transmission system developed by NRG that transmitted Andra's sensor data out of the Tournemire tunnel through 275 m of overburden to the surface. The two sensors are pore-water pressure sensors dedicated to characterize the bentonite swelling. This technology is based on vibrating wire technology that provides high accuracy measurements. The sensors are connected to a prototype of miniaturized wireless transmitter with a range of 20 metres. For the long range data transmission, a 110 mW transmitter was placed in the northern part of the Tournemire tunnel, and a receiver on the Tournemire plateau. The set-up of the long range system was based on two earlier field measurement campaigns that allow a systematic approach to optimize the system for the specific conditions present in Tournemire. In five runs, about 280'000 bits of data were transmitted. Data transmission could be achieved at 8.6 kHz with bit error rates of 0.002% for QPSK and 0.03% for BPSK. Undetected errors in data transmission did not occur for the QPSK transmission and for the BPSK transmission with a checksum. Most transmission errors could be easily identified as such, and the use of a checksum allowed restoring most of the transmission errors. The energy efficiency achieved by the long range transmitter does not represent any practical limitation for the application case. Still, day-night, diurnal, and seasonal variability are not covered by this test, and for a real application, daily differences in background noise should be analysed, and their effects on the performance should be tested in order to achieve an optimum balance between performance and energy need.

2. Introduction

Wireless systems allow the monitoring behind natural and engineered barriers without the use of cables that may impair the safety function of these barriers [1]. The barriers of interest include borehole plugs, sealing's of disposal sections and shaft sealing, and require wireless solutions that can bridge distances from a few meters up to several hundred meters. Most commercial applications make use of high-frequency radio waves that are strongly attenuated by solid materials, raising the need to build customized solutions for repository monitoring [2]. Several specific solutions where developed and tested in MoDeRn ([3], [4]) and Task 3.2 of Modern2020 [5].

As part of WP4 of the Modern2020 project [6], Andra, IRSN, and NRG demonstrated in a combined effort a full transmission chain that allows transmitting wirelessly sensor readings out of the Long-Term Rock Buffer Monitoring borehole (LTRBM) to the earth's surface. The demonstration used a combination of wireless technologies for short and long distance and is discussed in this paper.

3. Methodology

3.1. Set-up of the combined wireless demonstrator

Located in a 1,885 metres long former railway tunnel built over 135 years ago, the Tournemire URL provides access to a shale formation. It offers a unique opportunity to observe 135 years of disturbances generated by an excavated underground engineering structure, and to perform experiments under realistic conditions. As part of Modern2020's WP4, the LTRBM borehole was created in the Tournemire URL, and is hosting wired and wireless monitoring devices, some of them developed in WP3 of Modern2020.

Andra placed as part of this demonstration two vibrating sensor units (VSUs) in the LTRBM borehole. Each VSU is composed of a vibration pore-water pressure sensor (PWPPS) and an electronic device that fulfil three functions: a vibrating sensor reading, a measurement recording (up to 15 measurements kept in memory) and a short range data wireless transmission base on low frequency (below 10 kHz) in order to transmit through bentonite and rocks with little attenuation (Fig. 1).

Figure 1: A vibrating sensor unit placed in bentonite block before introduction in LTRBM borehole.

VSU monitoring results are transmitted wirelessly through a concrete plug to a receiver unit in the main gallery (Fig. 2). Andra's two VSUs transmit their readings every day to a receiver node that records the incoming data. The information in the receiver's database contains a table with the date and time of measurements, the voltage of the transmitter battery, the sensor data and the temperature. Two kinds of measurements were done on the vibrating wire extensometer: the natural frequency of the vibrating wire for pore-water pressure measurement and the electrical resistivity for temperature measurements.

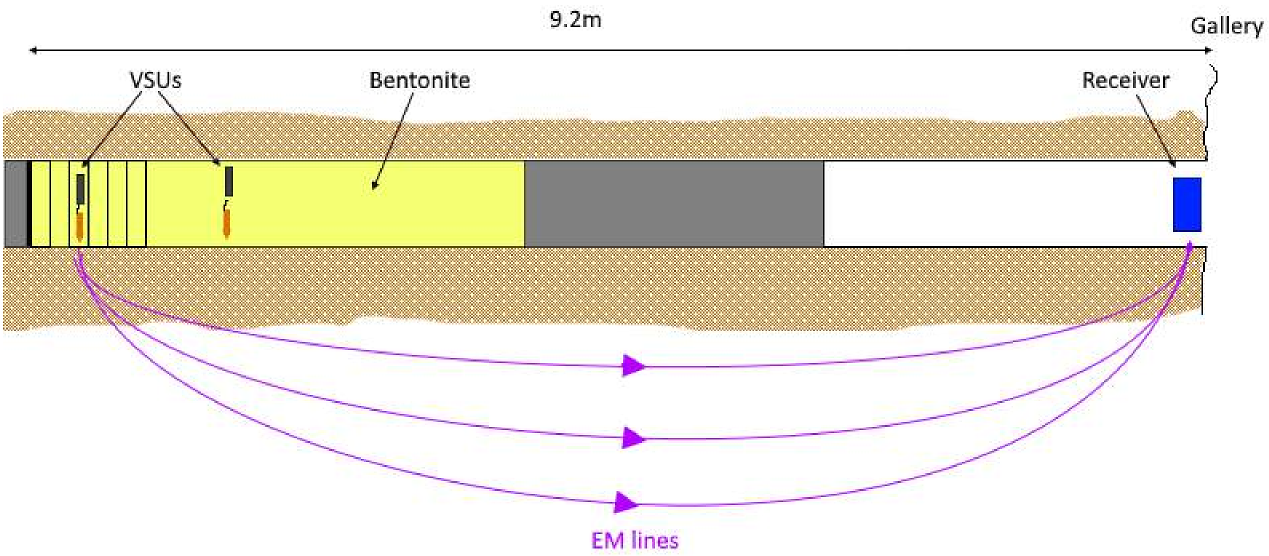

Figure 2: Short range data transmission in the LTRBM (Top view)

The data stored in Andra's receiver were downloaded and transferred to the NRG's long range transmitter. For the transmission out of the Tournemire tunnel through the of overburden to the earth's surface, NRG placed a long range transmitter in the northern part of the tunnel, and a receiver 275 m higher on the Tournemire plateau, on top of the transmitter (Fig. 2).

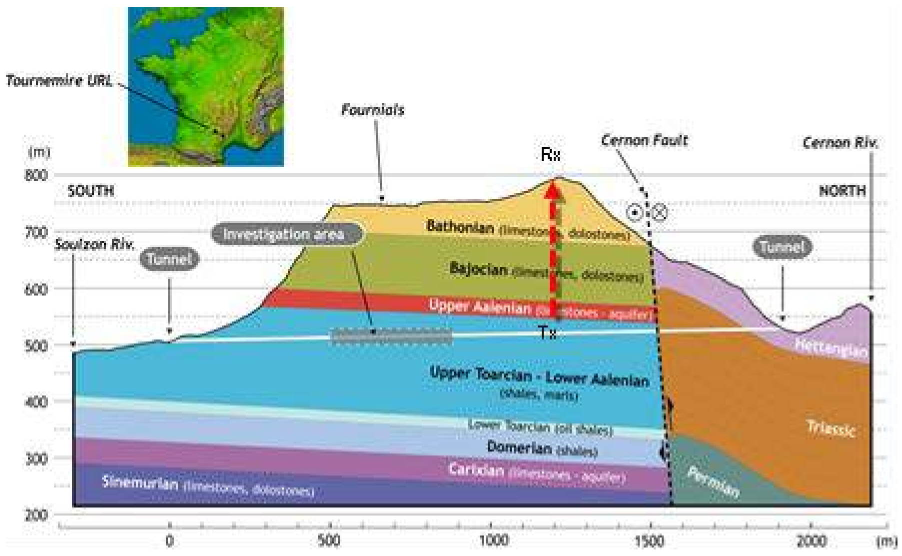

Figure 2: Long range data transmission at the Tournemire URL. 'Tx' indicates the subsurface transmitter, 'Rx' the surface receiver. Transmission distance is 275 m.

3.2. Database pre-processing and coding

Prior to data transmission, the readings from Andra's vibrating wire sensor stored in a database structure had to be processed. Each of the vibrating sensors of Andra has its own sequential database file containing the date and time step of the measurement, the battery voltage, three parameter readings from which the natural frequency of the vibrating wire for strain measurement can be computed, and the temperature. Andra's sensor unit takes measurements every six hours, which resulted in 528 database entries recorded between the 20th of July and 29th of November for each sensor. Figure 3 shows the database structure.

J09150010_S009_Sensor.csv

20-07-18 18:00	3.285	1.568	1.443	4.930	32.117
21-07-18 00:00	3.290	1.568	1.443	4.622	32.115
21-07-18 06:00	3.275	1.568	1.443	4.487	32.126

Figure 3: Excerpt of the Andra wireless sensor database.

Because currently no clear design target for the required quality of the data link can be given, two different methods of data processing are applied and compared, to aid future discussions on requirements on data integrity. All data collected by Andra were transmitted successively, rather than with a six-hour interval as the original recordings. The transmitted data stream included some non-essential data as date and time of the sensor readings, decimal points and data separators.

For the first sensor, the data is arranged in blocks of 16 measurements. In the first line of each block, all parameter values except the battery voltage are transmitted twice, preceded by a date number. In the following 15 lines, the differential value with respect to the first line is given for the three sensor parameters and the temperature. The differential value is relative to one thousands of the absolute difference, and allows to fully reconstruct the original data after reception. Together with a variable-length coding scheme, this method allows compressing the data to 6.2 kB. Figure 4 shows the structure of the transmitted data file.

2	3.275	1.656	1.396	6.907	32.614	3.275	1.656	1.396	6.907	32.614
-6	0	454	-75							
-13	0	137	35							
-19	0	-74	23							
-19	0	-225	20							
-19	0	-22	0							
-25	0	-459	5							
-25	0	-348	27							
-25	0	-367	-3							
-31	0	-116	9							
-31	0	-978	-14							
-38	0	-1060	7							
-38	0	-847	-6							
-38	0	-350	-66							
-38	0	-584	-49							
-38	0	-444	-24							
6	3.275	1.618	1.396	6.522	32.612	3.275	1.618	1.396	6.522	32.612
-6	0	109	7							

Figure 4: Excerpt of the data transmitted for Sensor 7.

For the second sensor, a different approach is followed. Here, all data values are transmitted, followed by a checksum for the three sensor parameters and the temperature. This allows detecting and correcting errors in the data transmission for the most relevant parameters. The date and time is transmitted as a number rather than in the date/time format of the original file. The checksums provide additional robustness but come at a price: the resulting data file is almost three times larger as the first one (±18 kB in the applied variable-length coding scheme), and was split up into two parts (9a and 9b) to keep the transmission duration below one hour. Figure 5 shows the structure of the transmitted data.

1.8	3.285	1.568	1.443	4.930	32.117	r	j	n	l
2.0	3.290	1.568	1.443	4.622	32.115	r	j	l	j
2.3	3.275	1.568	1.443	4.487	32.126	r	j	u	l
2.5	3.290	1.568	1.443	4.360	32.133	r	j	k	j
2.8	3.285	1.568	1.443	4.622	32.110	r	j	l	e
3.0	3.285	1.568	1.443	4.225	32.125	r	j	k	k
3.3	3.295	1.568	1.443	4.425	32.119	r	j	m	n
3.5	3.280	1.568	1.443	4.475	32.138	r	j	r	o
3.8	3.285	1.568	1.443	4.875	32.115	r	j	v	j

Figure 5: Excerpt of the data transmitted for Sensor 9.

3.3. Field demonstration

In February 2019, the final demonstration of the combined demonstrator was performed. A battery-based coil driver was used that supplied about 110 mW to the transmitter antenna. This value was estimated as a reliable power level to allow robust data transmission with bit error rates <<0.1%, however, also two lower power levels were tested (73 and 52 mW). The transmitter antenna was placed in the northern part of the tunnel, about 1230 m from southern entrance and about 660 m from northern entrance, at a height of about 520 m a.s.l. (Figure 6, bottom). The receiver antennas (Figure 6, top) were situated at the surface on top of the transmitter, at about 795 m a.s.l. (GPS coordinates: 43°59.312' N, 3°00.920' E), resulting in the transmission distance of 275 m.

In five runs, about 280'000 bits of data were transmitted, covering data from both sensor units. In these runs, two transmission modes (BPSK and QPSK) were tested, because the limited testing performed in Tournemire in 2018 [5] did not allow to give clear preference to one of these modes. The transmission frequency used was 8.6 kHz.

Figure 6: Data receiver on top of the surface plateau (top) and data transmitter in the Tournemire tunnel (bottom)

4. Results

4.1. Wireless vibration wire sensor & short range data transmission

Pressure data from the VSUs have been successfully transmitted with the short range data transmission system over four months. The batteries included in the transmitters are designed to allow about three years of sensor reading and wireless transmission. Measurements show no sign of weakness from the batteries and provide coherent physical values for the pressure data that need to be compared to others measurements of LTRBM.

The EM signal level received by wireless transmission receiver reveal that the wireless transmission communication is excellent: the receiving signal is fifteen times higher than the EM noise level, and no transmission error occurred.

4.2. Long range data transmission

For the analysis of the long range data, three types of transmission errors are distinguished:

- identified transmission error, where the data could be restored
- identified transmission error, where the data could not be restored (i.e. missing data)
- unidentified transmission error (i.e. erroneous data value)

For the determination of the transmission power, the current and voltage supplied into the transmitter antenna were measured. The transmission protocol makes use of stop bits, resulting in a net data rate for the transmitted data lower than the overall symbol rate (30 bit/s): 21.8 bit/s and 22.8 bit/s for the data files of sensor 7 and 9, respectively. The calculated power per bit is consequently determined for the transmitted data bits rather than for the overall bit stream. For the five transmission tests performed, Table 1 summarizes the results, including the achieved bit error rates and their effects on the data transmission:

Table 1: Results of the data transmission tests. The number of transmitted data values includes date & time indication and battery voltage, but is exclusive error codes and repetitions.

transmission mode	data file	file length [bit]	power [mWs/bit]	BER [%]	number of data values			
					transmitted	restored	missing	erroneous
QPSK	sensor 7	49735	5.0	0.002	2171	–	1	–
BPSK	sensor 9	72911	4.8	0.03	1778	16	4	–
	sensor 7	49735	5.0	0.02	2171	1	2	4
			3.3	0.14		24	38	7
			2.4	>0.3		*n.d.*	*n.d.*	*n.d.*

5. Discussion

5.1. Long range data transmission

For the long range data transmission, the energy need is one of the most important factors, hence the main target in the demonstrator was to provide a robust data link with as little energy as possible. In Modern2020 and MoDeRn, methods have been developed and successfully applied that allow to quantify transmission behaviour of a particular geological setting by in situ measurements in a structured and detailed manner. Together with a detailed characterisation of the background noise and local interferences, these measurements allow the estimation of the power necessary for data transmission.

The chosen set-up and energy level for the demonstration performed in Tournemire were based on two field measurement campaigns that allowed a systematic approach to optimize the transmission system for the specific conditions present. The energy efficiency achieved by the set-up custom tailored to the local conditions does not represent any practical limitation for the application case, however, other facilities may require more power. The selected power level was close to the optimum, additional tests with lower power level led to clearly increasing error rates.

Data transmission could be achieved with bit error rates of 0.002% for QPSK and 0.03% for BPSK. QPSK is thus more robust under the given circumstances, which was not so clearly visible from the previous experiments, where much less and repeating data were used. 50’000 transmitted bits or more is therefore recommendable to allow substantial conclusions on the performance of a long range transmitter. Still, day-night, diurnal, and seasonal variability are not covered by this test, and for a real application, daily differences in background noise should be analysed, and their effects on the performance should be tested in order to achieve an optimum balance between performance and energy need.

Undetected errors in data transmission did not occur for the QPSK transmission and for the transmission with a checksum. Most errors could be easily identified as such, because the used coding method makes it less likely that a numerical value is exchanged by another numerical value in case of a transmission error. However, the use of a checksum allowed restoring most of the transmission errors, but coming with a price in terms of redundant data and thus the overall energy need.

6. Conclusion

By combining different expertises and solutions on short and long range, Andra, IRSN, and NRG successfully demonstrated an overall transmission chain that allows transmitting sensor readings out of the LTRBM borehole to the earth's surface.

Within Task 3.2, the basic set-up and technology for short and long range data transmission were developed and tested. The combined solution demonstrated in Task 4.3 consists of three contributions:

- The LTRBM borehole that has been prepared by IRSN. The borehole was backfilled with bentonite and hydrated in the second part of 2018, and contains a variety of sensors and wireless technologies, partially developed in WP3.
- A vibrating sensor of Andra was placed inside the LTRBM and transmitted over several months wirelessly every six hours sensor readings out of the LTRBM to a receiver unit.
- A long range data transmission system developed by NRG transmitted successfully more than 200'000 data bits representing about 8'000 data points from the tunnel through 275 m of overburden to the surface. The system was adapted to the local conditions, and signal and data transmission was achieved at a very low power level (5 mWs/bit of transmitted data).

Acknowledgements

The authors greatly acknowledge the kind support of the IRSN staff during our experimental work at the Tournemire URL, France. The Modern2020 project is co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme, and by COVRA.

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Long Distance Data Transmission Through The Underground: Lessons Learned From Two Demonstrators

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1. Summary

Monitoring during the post-closure phase is considered a promising option because it answers to relevant concerns with respect to costs and risks related to extended operational periods. Post-closure monitoring requires the ability to transmit monitoring data wirelessly through hundreds of meters of overburden with a reasonable low amount of energy. As part of the EU projects MoDeRn and Modern2020, NRG developed technologies for wireless data transmission through the underground and demonstrated them successfully over distances up to 275 m at the HADES and Tournemire underground research laboratories (URLs) in Belgium and France.
The experience gained at the HADES and Tournemire URLs raises confidence that long range transmission over much larger distances (500 - 1000 m) can be achieved as well. The relevant parameters that define the overall performance and energy need were determined. At Tournemire, data transmission was demonstrated with less than 2 mWs per transmitted bit, which provides no constraints for the application case. Methods and tools that have been developed and successfully applied to measure the key parameters on-site allow estimating the expected performance on each location of interest with reasonable efforts.
In conclusion, long range wireless data transmission is a promising technology for repository monitoring in post-closure phase, and important progresses were achieved in MoDeRn and Modern2020. General principles are well understood, and further research should aim at testing, demonstrating and optimizing wireless technologies under repository conditions.

2. Introduction

Monitoring in support of retrievability during the post-closure phase is considered a promising option because it answers to relevant concerns with respect to costs and risks related to extended operational periods. Post-closure monitoring requires the ability to transmit monitoring data wirelessly through hundreds of meters of overburden with a reasonable amount of energy, supplied either by conventional chemical batteries or alternative power supplies [1]. As part of the EU projects MoDeRn and Modern2020, NRG developed technologies for wireless data transmission through the underground and demonstrated them successfully at the HADES URL in Mol (Belgium) and at the Tournemire URL (France) over distances of 225 and 275 m, respectively [2, 3]. The poster will summarize the work performed and lessons learned of NRG's engagement on long distance data transmission.

3. Methodology

Long distance data transmission through the underground makes use of low frequency magnetic fields generated by a loop antenna. By forcing a current I through the antenna, a magnetic moment m_d can be generated as function of the loop area (A), the number of turns of the loop N and the current:

$$m_d = A \cdot N \cdot I \qquad \text{(Eq. 1)}$$

In a conducting half-space, magnetic field propagation at the surface can be estimated by:

$$H_{radial} = \frac{m_d}{2\pi d^3} T_{radial};\ H_{vertical} = \frac{m_d}{2\pi d^3} T_{vertical} \qquad \text{(Eq. 2)}$$

with

$$\left.\begin{matrix} T_{radial} \\ T_{vertical} \end{matrix}\right\} = \int_0^\infty \frac{x^3}{x + \sqrt{x^2 + iG^2}} \exp\left(-\sqrt{x^2 + iG^2}\right) \left\{\begin{matrix} J_1(xD) \\ J_0(xD) \end{matrix}\right. dx \qquad \text{(Eq. 3)}$$

where J_0 and J_1 are Bessel functions of the first kind, d the axial and ρ the radial distance to the transmitter, $G = d\cdot(\sigma\mu\omega)^{½}$, and $D = \rho/h$. Additional analyses are available that allow to analyse e.g. horizontal stratified media (e.g. [4, 5]). The validity of these equations is limited to the near-field, under the condition where both G and $G\cdot D$ <<1. However, as discussed in [2], the optimum transmission efficiency can be found in the extended near-field, and some caution in interpreting the calculated field strength under these conditions is necessary.
F
Because the electrical conductivity of the transmission path leads to strong signal attenuation at higher frequencies, very low frequencies are applied (few hundreds Hz to few tens of kHz). The application of low frequencies has a number of drawbacks, e.g. a low receiver antenna sensitivity, a need for large open spaces to deploy efficient transmitter antennas, and strong man-made and natural background interferences in this part of the electromagnetic spectrum. Because the data transmitter will be buried inaccessible in the disposal, the most important figure of merits of this technology is the energy efficiency, expressed as energy need per transmitted bit of data (mWs/bit).

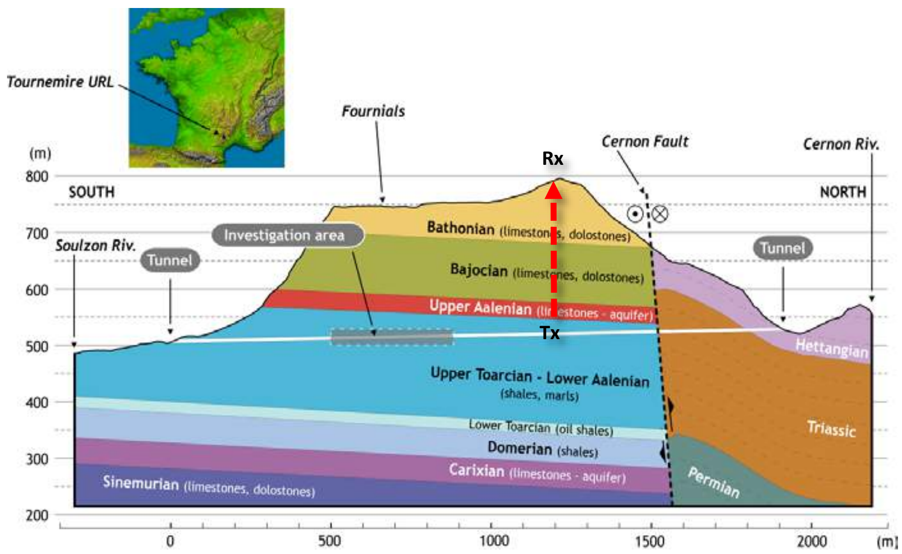

Figure 1: Long range data transmission demonstrator at the Tournemire URL (F). 'Tx' indicated the subsurface transmitter, 'Rx' the surface receiver. Transmission distance: 275 m.

To develop energy efficient transmission solutions, for each location of interest, relevant design parameters have to be adapted to meet the local conditions. Key parameters are therefore measured and tested on-site in a two-step approach: in a first step, background noise and interferences are determined, and the signal propagation through the underground is characterized. In a second step, a proof-of-principle of data transmission is performed on location, accompanied by several tests of different modulation schemes and data rates. These measurements provide a good understanding of all key parameters and allow to provide an optimized solution for each location.

The set-up used for signal and data transmission experiments consists of a signal source, a coil driver for the transmitter antenna, a (tuned) transmitter antenna, a (tuned) receiver antenna, a preamplifier for the receiver antenna, an analog-to-digital converter (ADC), and a (software) demodulator and decoder. Figure 1 and Figure 2 show the experimental set-up as used in Tournemire: the long distance transmitter is placed in the main tunnel north of the test facility ("Tx position"), and the receiver antenna is situated at the surface plateau, right on top of the transmitter ("Rx position"). The chosen location avoids large interferences from a high voltage power line on top of the main facility, and allows transmission distances of about 275 m. For the data transmission experiments, a battery-based coil driver was developed, that supplies about 60 mW to the transmitter antenna. A comparable set-up was used for signal and data transmission experiments performed at the HADES URL in Mol over a distance of 225 m [2].

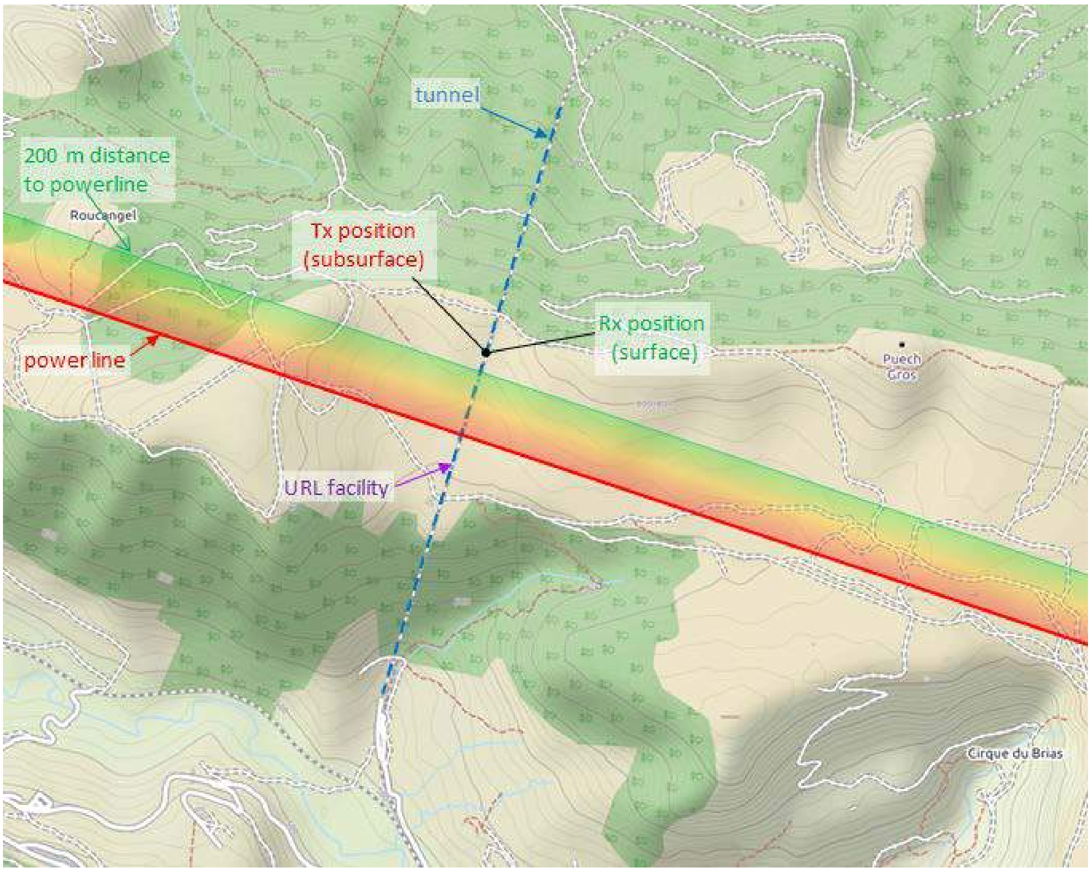

Figure 2: Top-down view on the Tournemire URL. Background map © OpenStreetMap contributors (www.opendatacommons.org/licenses/odbl).

In Mol and in Tournemire, several field measurement campaigns were performed by NRG, involving:

- characterization of local interferences and background noise of the radial and vertical field,
- measurement of frequency-dependent signal attenuation by the transmission path,
- quantifying of the sensitivity of the receiver set-up under field conditions,
- testing of different transmission channels, and
- testing of the performance of different transmission mode and data rates under local conditions.

4. Results

Wireless data transmission was successfully demonstrated at the HADES URL and the Tournemire URL over distances of 225 and 275 m, respectively [2, 3].

Figure 3 shows some example results of the site characterization performed at Tournemire, giving evidence for the strong vertical direction of the field with little frequency-dependent attenuation by interactions with the medium. Only a weak frequency-dependent attenuation by the overburden was found, implying an effective electrical conductivity of 1 mS/m or less. However, a frequency-independent overall attenuation by a factor of three was found as well. The radial field strengths in north-south and east west directions are much smaller than the vertical field strength, consistent with the low electrical conductivities found. Radial field strengths in north-south direction are lower than in east-west direction. From both can be concluded that the presence of the rails in the former railway tunnel of the Tournemire URL does not artificially favour the overall signal propagation, but has a clear adverse effect on propagation behaviour of the vertical field. It is estimated that the rails in the tunnel attenuates the field by about a factor of three, equivalent to an increase of the transmission distance to about 400 m.

The frequency range of 8 - 9 kHz is identified as the most suitable for data transmission. Alternatively, a range with lower background noise was found between 6.0 and 6.5 kHz. On basis of these measurements, a critical, low power level for the transmitter has been chosen (60 mW), and several transmission modes and data rates have been tested to study the effect of the specific local interferences on the transmission performance. Data transmission has been achieved at a transmission frequency of 8723 Hz with data rates of 30 and 60 bit/s.

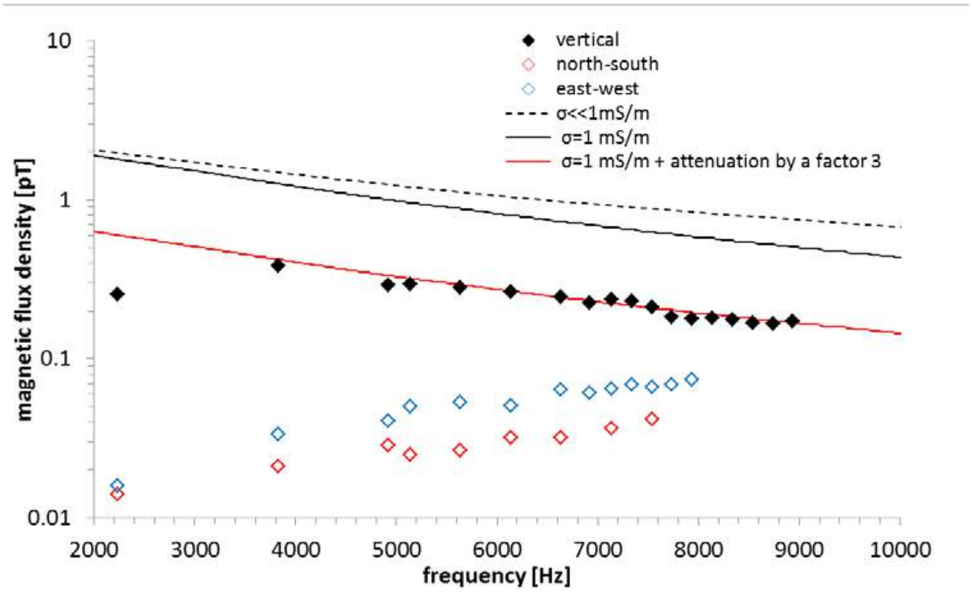

Figure 3: Measured (closed diamonds) and modelled (lines) vertical field strengths at the Tournemire URL (France). Open diamonds represents the radial field in east-west and north-south directions.

Table 1 summarizes relevant transmission parameter and performances as achieved at both locations:

Table 3: Transmission parameter and demonstrated data transmission performances at the HADES URL (Mol, Belgium) and the Tournemire URL.

	HADES URL	Tournemire URL
Transmission distance	225 m	275 m
Effective electrical conductivity	30-50 mS/m	≤1 mS/m
Transmitter antenna diameter	3.6 m	4.5 m
Local background noise	> 50 fT/√Hz	3-7 fT/√Hz
Transmission frequency	1.8 kHz	8.7 kHz
Data rates	10 - 100 bit/s	30-60 bit/s
Energy need	1100 mWs/bit	2mWs/bit

5. Discussion

In Tournemire, data were transmitted with about 2 mWs per bit: these small energies should not present any limitation for the application case: e.g. a continuous supply of 100 µW of electric power, as can be achieved by thermoelectric harvesting of high-level waste's decay heat or by wireless energy transmission [1, 6, 7] allows to send hundred sensor readings daily.

The better performance at Tournemire compared to Mol is based on a number of factors:

- the lower conductivity in Tournemire allows to select a larger transmission frequency,
- there is less local background noise present in Tournemire, and
- the larger cross section in Tournemire allows to deploy a larger transmitter antenna.

The geological facilities for final disposal of radioactive waste are typically situated two or three times deeper than the HADES or Tournemire URLs. This raises the question if the current performances can be extrapolated to such a situation: a two or three times deeper facility would require in first instance considerable more energy due to the - in the worst case - cubic decay of the field strength with the distance (Eq. 2). On the other hand, in a repository situation it is expected that larger open spaces allow for larger, more efficient transmitter antennas than used in the current demonstrators, compensating the higher energy needs at larger depth (Eq. 1). Dependent on the actual local situation, both effects could probably compensate each other. More significant for an extrapolation of the current results is that for most disposal designs, the electrical conductivity will be closer to the situation in Mol, requiring the application of lower and less efficient frequencies than in Tournemire. However, it should be possible to realize a less noisy environment than was present in the Mol case, which would easily lead to a decrease of the necessary signal strength by a factor of ten. In conclusion, a simple generic extrapolation of the current results cannot be given, but locations need to be assessed case wise. One of the most relevant outcomes of this work might be that suitable methods, models and tools have been developed to measure the key parameters on-site, allowing to estimate the expected performance on each location of interest with reasonable efforts. In summary, larger depths may very likely increase the energy need, but not necessary to a level that makes this technology unfeasible. More precise estimations of the expected performance can be gained by analysing field data of the locations of interest, and a proper workflow and technical tools to do so were developed in MoDeRn and Modern2020.

6. Conclusion

Wireless data transmission was successfully demonstrated at the HADES and Tournemire URLs, over distances of 225 and 275 m. The relevant parameters that define the overall performance and energy need were determined. The performance of the developed technology depends on a number of factors, and at Tournemire, data transmission through the underground over distances of 275 m was demonstrated with an antenna energy of less than 2 mWs per transmitted bit.

The experience gained at the Hades and Tournemire URLs raises confidence that long range transmission over much larger distances (500 - 1000 m) can be achieved as well. The methods and tools that have been developed and successfully applied to measure the key parameters on-site allow to estimate the expected performance on each location of interest. The lessons learned from such a field assessment can be used to prepare and perform a first, simple proof-of-principle of data transmission, in support of the estimated energy need.

The large (man-made and natural) interferences in the 1 - 10 kHz range are a challenging feature of low frequency data transmission and strongly affect the overall performance. A better understanding of the variability of noise and interferences on a day to-day level may allow improving the reliability of the data link under unfavourable conditions (e.g. thunderstorm), and more sophisticated data processing methods for location specific noise pattern may significantly improve the overall performance of a system.

In conclusion, long range wireless data transmission is a promising technology for repository monitoring in post-closure, and important progresses were achieved in MoDeRn and Modern2020. General principles are well understood, and further research should aim at testing, demonstrating and optimizing wireless technologies under repository conditions.

Acknowledgements

The authors greatly acknowledge the kind support of the EURIDICE and IRSN staff during our experimental work at the HADES URL in Mol, Belgium and the Tournemire URL in France.

This study has been carried out as a part of MoDeRn and Modern2020. The MoDeRn and Modern2020 project is co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the FP7 and Horizon 2020 Framework Programme, respectively. MoDeRn was cofounded by the Dutch Ministry of Economic Affairs, Agriculture and Innovation, and Modern2020 is cofounded by COVRA.

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Thermal Energy Harvesting From High-Level Waste

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1. Summary

Within Task 3.3 of the Modern2020 project, NRG performed a feasibility study on the ability to use decay heat of High Level Waste (HLW) containers to power wireless sensors units (WSUs) in a geological disposal facility. The focus of this research was to understand the feasibility to harvest very small temperature differences (<2°C), and to quantify the performance and efficiency of the different subcomponents of the energy harvesting system under disposal conditions. A combination of TEG and conversion electronics has been successfully assembled and tested in a dedicated thermoelectric test bench, and parameters affecting the overall efficiency have been determined. The outcomes showed that temperature differences of less than 0.5 °C can be harvested, allowing to provide electrical power for more than 100 years. By collecting and storing energy over a longer period, sufficient power can be made available for a WSU. The decreasing heat output of the HLW and consequently power output of the TEG on the longer term can be easily compensated by increasing the measurement intervals: this should be no problem for parameters that evolve only very slowly a few decades after disposal. Further research is needed when it comes to qualifying the used materials and components with respect to long-term reliability and moderate radiation fields as present in the considered disposal situation. In conclusion, the results show the principal potential to convert the heat dissipated by HLW containers into electrical power under very low temperature gradients as expected in a disposal situation after 100 years of interim storage.

2. Introduction

Among the prior technical issues that remained to be investigated in the follow-on projects of the former MoDeRn project were the power supply sources capable of extending the expected life time of the wireless data transmission systems, as an alternative to chemical batteries [1]. Within Task 3.3 of the Modern2020 project, NRG performed a feasibility study on the ability to use the decay heat of heat generating High Level Waste (HLW) containers to power wireless sensors units (WSUs) in a geological disposal facility [2]. The scope of this study are the rather small temperature gradients expected in a disposal situation after 100 years of interim storage, as relevant for The Netherlands. The focus of this research was to understand the feasibility to convert thermal energy at very small temperature differences (<2°C), and to quantify the performance and efficiency of the different subcomponents of the energy harvesting system under disposal conditions.

Heat flow can be converted into electrical power by the use of a Thermoelectric Generator (TEG), making use of the so-called ‘Seebeck effect’. Thermal analyses performed for the generic Dutch OPERA disposal concept in Boom Clay [3], assuming a surface interim storage period of 100 years, showed that the TEG must be able to operate at a temperature difference of 2°C or less. The voltages generated by a TEG at these temperature differences are too small to be directly used to power any electronic device (tens of millivolts), and require the use of an oscillator-based conversion electronics to upconvert these small voltages. The matching between TEG and conversion electronics is not straightforward, because these oscillators show a complex, voltage dependent load resistance. To estimate and optimize the performance of the overall thermoelectric harvester (TEH) solution, detailed measurements were carried out to quantify the key parameters of the TEG and the conversion electronics, and their interactions at the low temperature differences of interest.

3. Methodology

3.1. Feasibility analyses

The system of interest, for which the feasibility analyses are performed, is the generic Dutch OPERA disposal concept in Boom Clay [3]. In this concept, heat producing HLW mainly consist of vitrified, reprocessed waste. The heat produced by this type of waste is due to the radioactive decay of the fission products contained in the glass. The OPERA disposal concept makes use of a supercontainer for vitrified waste that limits the radiation dose rate at the surface to less than 10 mSv/hr.

Figure 1 shows the evolution of the temperature differences between different positions in a disposal gallery for vitrified waste: over the supercontainer buffer, over the backfill, over the gallery support, and in the first meter of Boom Clay. The differences are calculated using a semi steady-state thermal model for a minimum surface interim storage period of 100 years. For longer interim storage periods, the differences are even smaller. Hence, in order to provide energy over a relevant period of time, the TEH must be able to operate at temperature differences of 2°C or less.

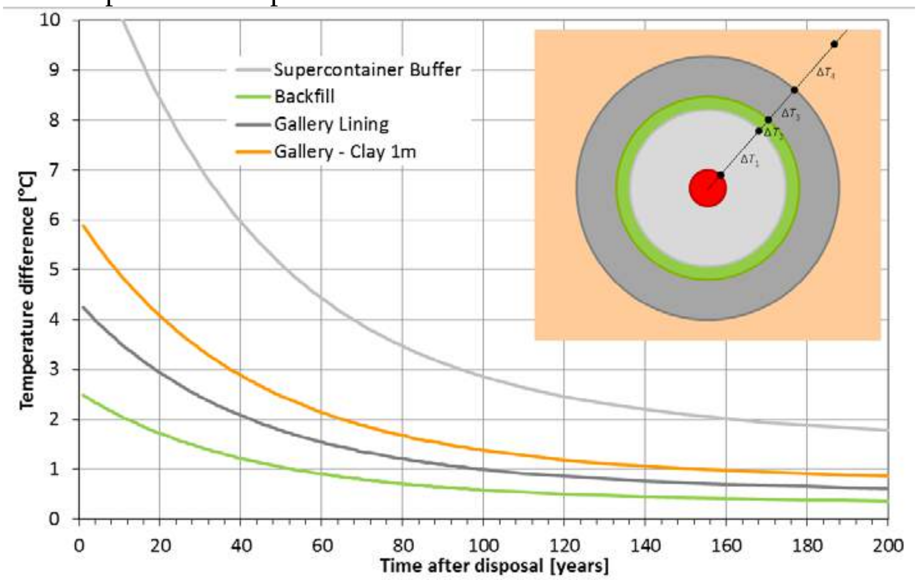

Figure 1: Estimated temperature differences between several positions in the OPERA disposal concept for a Cogema CSD-V container after 100 years of interim storage

3.2. Experimental set-up

A thermoelectric test bench was set-up to characterize the relevant performance parameters at very low temperature differences (Fig. 2). Resistance temperature detectors (RTDs) above and below the

TEG allow precise quantification of very small temperature differences over the TEG element (<0.001°C).

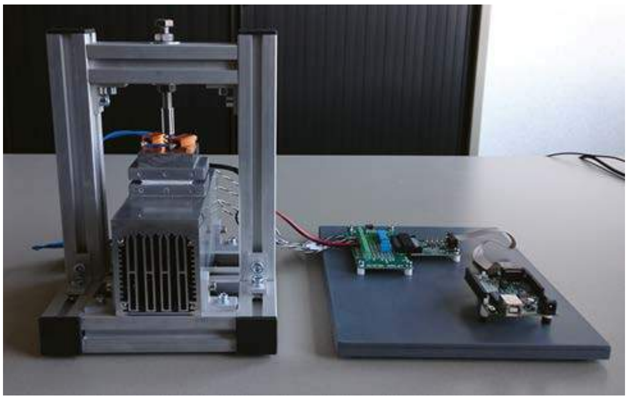

Figure 2: Thermoelectric test bench

4. Results

Several measurements in the test bench were performed. The output voltage for two different types of 40 x 40 mm TEGs, TEG-1 (287 p-n legs) and TEG-2 (199 p-n legs), was measured with and without load. For the used TEGs, an output voltage of respectively 110 and 66 mV/°C was determined, dropping to 28 and 43 mV/°C with a load of 3.3 Ohm. The input resistance of the conversion electronics as function of the input voltage was measured as well. Finally, the overall performance of the TEG plus conversion electronics was determined, at output powers of 0, 1, 5, 10, 100 and 200 µW. A conversion efficiency of the used electronic of about 16 % was estimated, including an estimated power leaking of about 35 µW. The minimum temperature difference necessary for supplying any energy to a sensor was 0.50 °C and 0.44 °C for the tested TEGs. Figure 3 summarizes the outcomes.

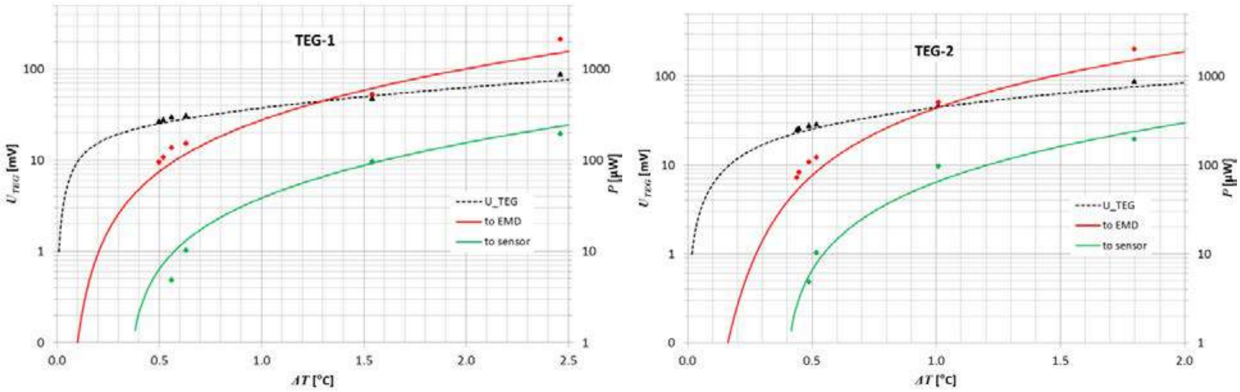

Figure 3: Calculated (lines) and measured (diamonds) TEG output voltage (black), power from the TEG to the harvester electronics (red) and output power from the harvester (green).

Based on the measurements and lessons learned, the results were translated to an application case, the OPERA disposal concept in Boom Clay. Six aspects were considered when setting-up a concept design and quantifying the overall performance:

- the effective output voltage of the TEG
- the minimum input voltage of the conversion electronics
- the self-power consumption of the conversion electronics

- the conversion efficiency of the TEG
- the conversion efficiency of the conversion electronics
- the thermal losses due to heat conduction in the TEH

The first three aspects mainly affect the minimum temperature difference from which the TEH can provide power, the latter three affect the efficiency of the TEH. The first five parameter were determined by measurements, the last by design. Two conservative design requirements were applied, in order to minimize interactions with the disposal concept:

- the TEH should not alter the overall heat flow, and
- the TEH should not bridge more than one EBS component.

For the first requirement, the overall thermal conductivity of the TEH should match with the thermal conductivity of the EBS component where the TEH has to be placed in. With respect to the second requirement, two cases were analysed:

- a TEH situated inside the backfill, and
- a TEH situated inside the gallery lining.

Although a larger temperature difference exists over the supercontainer buffer and the first meter of the Boom Clay (Fig. 1), these cases are not considered, because both components have important safety functions. The TEH design to be placed inside the gallery lining has a length of 50 cm, the design for the backfill has a length of 15 cm. The temperature difference for the latter case is about 40% less than for the gallery lining (Fig. 1). For both designs, two TEH diameters are considered: 5 and 10 cm. All TEHs are based on TEG-2. The considered designs are summarized in Table 1.

Table 1: TEH designs analysed

Design	EBS position	Length	Diameter
TEH-1S	Gallery lining	50 cm	5 cm
TEH-1L	Gallery lining	50 cm	10 cm
TEH-2S	Backfill	15 cm	5 cm
TEH-2L	Backfill	15 cm	10 cm

From the geometry and material properties, the thermal losses inside the TEH are calculated: a TEG is typically thinner than 4 mm, i.e. only a fraction of the overall TEH length, resulting in lower harvestable temperature difference at the TEG. Besides, heat might flow alongside the TEG. These losses are expressed as thermal design efficiency η_{cond}, which defines the fraction of temperature difference over the TEH available for the TEG (Table 2). For each design, the thermal resistance R_{th} and an equivalent area can be calculated that represents the area of the backfill or gallery lining with a thermal resistance equivalent to the TEH. Furthermore, Table 2 depicts the minimum (external) temperature difference for which the TEH is expected to supply energy. For the temperature evolution as calculated for the case of the OPERA disposal concept (Fig.1), the TEH power output at different time steps can be estimated for all four TEH designs. Table 2 gives an overview of the power output at 0, 50 and 100 years after disposal.

Table 2: Performance parameter of four TEH designs

Design	η_{cond}[1] [%]	R_{th}[2] [K/W]	A_{eq}[3] [m²]	T_{min}[4] [°C]	P_{out}[5] [µW] 0 yrs	50 yrs	100 yrs
TEH-1S	55	1.1	0.45	0.64	500	78	20

TEH-1L	78	0.8	0.64	0.46	1020	170	54
TEH-2S	80	0.8	0.66	0.46	370	52	8
TEH-2L	92	0.7	0.76	0.40	490	72	14

[1]Thermal design efficiency , [2]Thermal resistance, [3]Equivalent area, [4] Minimum temperature difference to supply energy, [5]Power output

Figure 3 shows the calculated power output as function of the time after disposal.

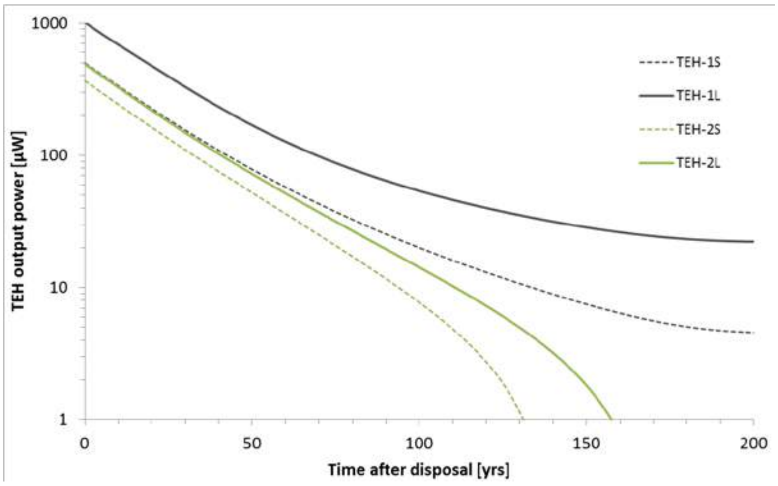

Figure 3: Thermoelectric test bench

5. Discussion

Performance analyses results show that harvesting of decay heat should be possible over periods of more than 100 years. The TEHs situated in the gallery lining harvest more power due to the larger temperature difference. The TEHs with the larger diameter perform better than the smaller ones, due to lower losses during heat conduction. However, even the smallest TEH is able to provide power over a period of 100 years.

6. Conclusion

A combination of TEG and conversion electronics has been successfully assembled and tested in a dedicated thermoelectric test bench, and parameters affecting the overall efficiency have been determined.

The results above show the principal potential to convert heat dissipated by HLW containers into electrical power under very low temperature differences as expected in a disposal situation after 100 years of interim storage. Conservative performance analyses were conducted under the assumptions that the TEH is situated in a single EBS component, and that the overall heat flow in the disposal cell is not altered. A better overall performance can be achieved when less restrictive design criteria are applied. It could be shown that the considered TEH designs are able to provide power over a relevant period of time.
The quantitative outcomes showed that temperature differences of less than 0.5 °C can be harvested. Efficient conversion and storage of energy harvested at low differences (one to several hundred µW) can provide reasonable amounts of energy to WSUs with a low duty cycle: by collecting and storing energy over a longer period, the small energy amounts can be accumulated until sufficient power is available to perform a measurement cycle of a WSU. The decrease in output power in course of the

time can be compensated by increase the intervals between measurement cycles: this should be no problem for parameters that evolve only very slowly a few decades after disposal.

Several options have been identified to improve the overall efficiency, however, since improvement of one performance parameter is likely to result in a lower performance of others, the specific needs and requirements of a particular WSU need to be known to be able to design the optimum TEH for certain application. Limiting factors for the overall performance are the minimum input voltage of the harvester electronics, its efficiency and power leakage. Both might be improved in future, however, the harvestable heat will be a limiting factor as well when it comes to temperature differences much below 0.5 °C.

Further research is needed when it comes to qualifying the used materials and components with respect to long-term reliability and moderate radiation field as present in the considered disposal situation. In general, the results of this study show the principal feasibility to use decay heat of HLW containers to supply reasonable amounts of power to repository monitoring WSUs.

Acknowledgements

This study has been carried out as a part of Modern2020 Task 3.3. The Modern2020 project is co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme and by COVRA.

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Wireless Energy Transfer Through Electrical Conductive Media

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1. Summary

A feasibility study has been performed by NRG on the ability to transfer energy wirelessly through the host rock or components of the engineered barrier system (EBS) into a disposal cell by magnetic induction techniques. The focus of this study is a) to analyse the feasibility of wireless energy transfer by magnetic induction over larger distances through saturated media such as argillaceous host rocks or (partially) saturated EBS components that can be characterized as electrical 'good conductors', and b) to quantify the performance and efficiency of the different subcomponents as can be expected under disposal conditions.

Analyses showed that for the wireless distance of interest (10 m), interactions with the medium need to be considered in the case of argillaceous host rocks, (saturated) bentonite or cementitious materials. These interactions strongly depend on the pore water composition. In case of higher conductivities (>50 mS/m), lower frequencies than 125 kHz should be preferred in order to avoid large performance losses.

It was demonstrated that energy transfer through an electric conductive media is feasible. With an optimized antenna design, link efficiencies of several hundred ppm over a distance of 7.5 m were achieved with co-planar antennas - roughly equivalent to a wireless distance of 10 m in a coaxial configuration - despite of interactions with the conducting medium. In conclusion, wireless energy transfer is shown to be feasible through relevant distances of highly conductive media, and careful evaluation the key parameter allow to optimize transfer efficiencies.

2. Introduction

Among the prior technical issues that remained to be investigated in the follow-on projects of the former MoDeRn project were power supply sources capable of extending the expected life time of the wireless data transmission systems, as an alternative to chemical batteries [1]. This paper summarizes a feasibility study on the ability to transfer energy wirelessly through the host rock or components of the engineered barrier system (EBS) into a disposal cell by magnetic induction techniques [2]. The study was performed by NRG as part of Modern2020's Task 3.3. The specific focus of NRG's contribution was directed to understand wireless energy transfer through saturated media such as argillaceous host rocks or (partially) saturated EBS components that can be characterized as electrical 'good conductors', and to quantify the performance and efficiency of the different subcomponents under conditions as can be expected under disposal conditions.

3. Methodology

Wireless energy transfer is an area of increasing research interest in the last decade. Much research on wireless energy transfer over short distances has been performed in this period. Some research is also performed on wireless energy transfer over longer distances (larger than the loop diameter), but that work is mostly limited to transfer through air, often using high frequencies in the MHz range. General approaches for energy transmission on short distances can be found in the wider literature, and several industrial solutions are available. However, for the application in repository monitoring, much larger distances (around 10 m) need to be bridged, leading to very low efficiencies (ppm range). Besides the additional technical challenges that arise from the very low efficiencies, key design parameter and their interactions need to be understood and carefully evaluated to be able to transmit energy with reasonable efforts.

The focus of the current study was therefore to analyse the feasibility of wireless energy transfer by magnetic induction over larger distances through electrical conducting media and to quantify the performance and efficiency of the different subcomponents of the transfer system. Of particular interest was to gain a good understanding of the effect of the electrical conductivity of the material in the transmission path on the energy transmission, since in many disposal concepts the host rock and/or the EBS contain relevant amounts of pore water. Additional complications may arise by alterations of the electrical conductivity of the transmission medium by hydration processes in the EBS.

The general experimental set-up used is summarized in Figure 1. A mobile, battery powered inverter provides high currents to the inductive load of the transmitter antenna. As transmitter antenna, a 5 turn loop antenna with a radius of 2.25 m was used (L = 0.51 mH, R = 0.50 Ω). The receiving 20 turn loop antenna had a radius of 0.5 m (L = 0.93 mH, R = 0.44 Ω). The receiver antenna was terminated by different load resistors in order to determine the optimum link efficiency.

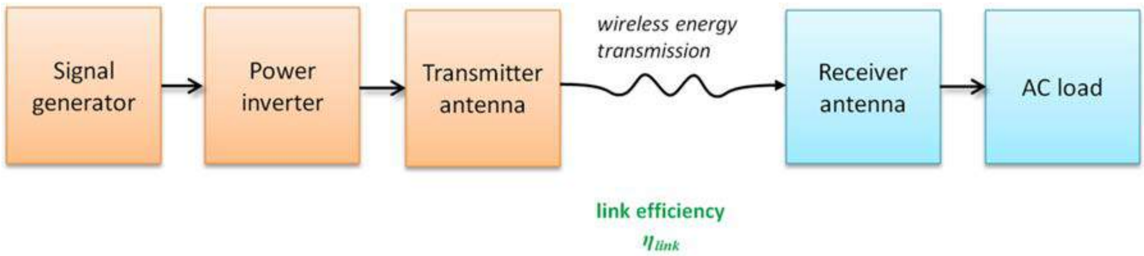

Figure 1: Set-up of the wireless energy transfer system

To study the interactions with a conductive media, all wireless energy transfer experiments were performed in a coplanar configuration, with the antennas situated directly on the ground. This configuration is a reasonable replacement of a coaxial configuration and allows a system evaluation of interaction with a conductive medium outside an URL facility (see e.g. [3]). However, a coplanar configuration leads to an antenna coupling that is lower than the (more favourable) coaxial configuration: a coplanar configuration with a centre-to-centre distance of 7.5 m has roughly the same link efficiency than a coaxial configuration at 10 m distance.

4. Results

For the purpose of the study, the general interactions between the wireless energy transmission system and a conducting environment were analysed. It was elaborated that the electrical conductivity affects the wireless energy transmission in several ways:

- it attenuates the magnetic field propagation,
- it affects the resistance of the antennas, and
- it affects the reactance of the antennas, and hence the resonance frequency tuning.

These effects are relevant for the design, since optimum antenna geometries for transmission through saturated media might be differ from the geometries successfully used for transmission through air, rock salt or granite. Based on the lessons learned, several wireless energy transfer experiments were performed in order to a) substantiate potential interactions with saturated media, and b) to demonstrate that efficient wireless energy transmission is possible over relevant distances through saturated media.

The principal effect of a conducting environment on the antenna parameter was demonstrated by measuring the receiver antenna's impedance at several heights above the surface and directly on top of an unsaturated and an almost saturated grassland. Figure 2 shows the effect of different heights and saturation degrees on the frequency dependent impedance of the loop antenna. Besides the wire resistance of 0.44 Ω, an additional resistance of 0.31 Ω was determined at the resonance frequency in the wet grassland. The effect of the conductive media will be even larger when the antenna is covered on all sides.

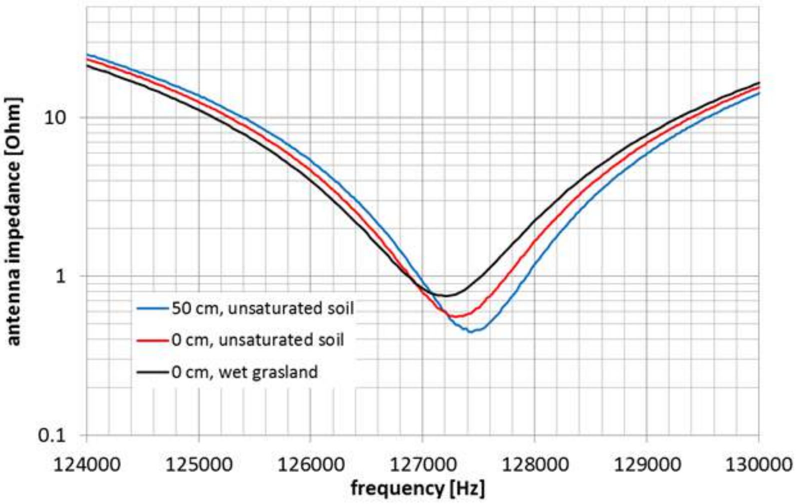

Figure 2: Field measurement of the receiver antenna's impedance with a 1.68 nF serial capacitor at two heights above an unsaturated soil and on top of wet grassland.

The reactance changed little, resulting in a small decrease of the antenna's resonance frequency from about 127.5 to 127.2 kHz (Fig. 2). Although the experiment did not allow to determine a precise value for the effective electrical conductivity of the antenna's surrounding, from existing equations a conductivity of about 0.02 S/m is estimated, assuming that effective conductivity seen by the antenna is half of this value.

Wireless energy transfer experiments were performed through an unsaturated sandy soil and a wet grassland. The optimum load resistance was 50 kΩ, resulting in 2 - 700 µW of harvestable power over distances of 5 - 15 m (transmitter power: ±150 mW). On the shortest distance (5 m), the measured power is comparable for both situations. However, with increasing distance, increasing attenuation by the medium was observed for the wet grassland. Table 1 compares the maximum power determined at a load of 50 kΩ. At 5 m wireless distance through wet grassland, 40% more power is measured in the load than through unsaturated sandy soil, despite the higher conductivity. This result is assumed to be related to experimental errors, e.g. variations of the inverter output power or slight detuning of the antennas.

Table 15: Maximum load power measured in unsaturated sandy soil (Petten) and wet grassland (Ursem).

d [m]	P_{load} [μW_{rms}] Petten	Ursem
5.0	690	970
7.5	64	77
10	14	11
15	2.4	0.6

The measurement results allow some analysis of the link efficiency. The measured link efficiency η_{link} is the ratio between the input power P_{link} in and the maximum load power P_{load} measured at the receiver antenna (Table 1).

Table 2 summarizes the measured link efficiencies η_{link} as determined through an unsaturated sandy soil (Petten) and a wet grassland (Ursem). Furthermore, key parameters were calculated, assuming no interactions with the media. In general, the measured efficiencies were about one order of magnitude below the calculated efficiencies. Part of the lower efficiency can be attributed to experimental aspects, e.g. slight detuning of the antennas from the optimum resonance frequency or measurement errors. Part of it, in particular for the smaller wireless distances, is related to the estimation of the mutual inductance: the applied approximation is valid for small antennas only.

Table 16: Link efficiency measured in Petten (unsaturated sandy soil) and Ursem (wet grassland)

wireless distance *d* [m]	measured link efficiency η_{link} [ppm] Petten	Ursem
5.0	3835	5386
7.5	423	503
10	90	72
15	16	4

However, part of the differences between expected and measured link efficiencies can be attributed to interactions with the medium. Table 3 summarizes the link efficiencies calculated for several conductivities and wireless distances, accounting for a) the additional antenna resistance that affects the tuning quality factor *Q* and hence the link efficiency, and b) the signal attenuation. Because the antenna are positioned in a conducting half-space, for the calculation of the resistance, an effective conductivity equal to 50% of the value given in Table 3 is used.

The calculated link efficiencies in Table 3 show a strong decrease for higher conductivity values and larger wireless distances, and compared with the values calculated without assuming conductivity, these values are much closer to what is measured in Petten and Ursem. Looking to the largest wireless distances, where the effect of the conductivity is the strongest, and the relative contribution of the experimental error the smallest, electrical conductivities of about 0.02 S/m and 0.05 S/m could be reasoned for the Petten and Ursem situation, respectively.

Table 3: Calculated link efficiencies for two coplanar loops, including interactions with the electric conductivity of the medium.

link efficiency η_{link} [ppm]					
distance d [m]	electric conductivity σ [S/m]				
	0.01	0.02	0.05	0.1	0.2
5.0	14189	8405	3755	1972	916
7.5	1814	1131	543	277	106
10	394	257	122	55	15
15	45	30	11	3	0.4

5. Conclusion

The potential interactions of a wireless energy transfer system with electric high conductive media were studied. The concept of skin depth allows a first simple estimation whether interactions are relevant for a given distance and conductivity of the medium. Several approaches for a closer analysis of a disposal situation were summarized, addressing the signal attenuation by the medium. Additionally, the effects of the conductive media on the antenna properties were discussed. Wireless energy transfer through conductive media was demonstrated in a coplanar configuration with a set-up optimized for link efficiency. Power levels between 10 µW and 1 mW have been demonstrated over distances between 5 and 10 m, with a transmitter power of about 0.15 W. At the chosen input power level, load voltages are more than 2V at 10 m distance, allowing direct AC-DC conversion with rectifiers. However, higher voltages at the receiver antenna are beneficial for the AC DC conversion efficiency and can be realized e.g. by an increase of the input power.

It was shown that for the frequency range considered, the interactions of the antenna with the media need to be considered in the system design. Unlike for energy transfer through air or low conducting media as granite, the optimum antenna size for a high conductive media might be smaller than the available open space in a disposal facility: while large antennas are general favourable for high link efficiencies, a larger antenna might result in radiation resistances that limit the achievable Q-values and hence affect the overall performance. The conductivity of the media affects the antenna's reactance, and thus the resonance frequency. However, the effect is relatively small, and for many disposal conditions, it might not be necessary to compensate for the effect of the variable saturation level of EBS components.

In conclusion, wireless energy transfer is shown to be also feasible through relevant distances of highly conductive media, and careful evaluation the key parameter allow to optimize transfer efficiencies.

Acknowledgements

This study has been carried out as cooperation between VTT and NRG as a part of Modern2020 Task 3.3. The Modern2020 project is co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme and by COVRA.

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Wireless energy transfer with data transfer add-on through low-conductivity host rocks

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1. Summary

Wireless energy transfer by applying low-frequency (LF) magnetic fields through the repository barriers has been proposed as one long-term power sourcing option of geological repository monitoring sensors. The general goal of this research has been to investigate the applicability and basic limitations of the wireless energy transfer for the powering of nuclear repository monitoring sensors. Another goal has been a feasibility study and pilot implementation of a wireless bi-directional data transfer add-on in the wireless energy transfer system without compromising the energy transfer performance. The main research methods have been performance analysis with 10 m operation distance by applying existing theory of inductive coupling and power transfer, and a 125 kHz pilot system design and experiments through medium representing repository barriers consisting of host rock with relatively low conductivity. The research until now has demonstrated that the wireless energy transfer through repository barriers is a relevant powering technology of wireless repository monitoring sensors. Tests of the pilot system also indicated that the wireless data transfer add-on can be implemented without compromising the power transfer performance significantly. Further elaboration of the pilot system towards the final repository monitoring implementations is needed for maintaining the antenna resonance during the long-term use, including an interim energy storage for sensor payload supply power conditioning, improving the immunity of the data uplink to the external noise, and the design of the TDM based protocol for powering, data uplink and data downlink. This paper gives an overview of the research carried out in this topic by VTT as a part of the European project Modern2020 Task 3.3. A more detailed description of the results can be found in Modern2020 deliverable D3.3.

2. Introduction

Electric power is necessary for sensor units in geological repositories for the storage of nuclear waste as well as for running electrical devices in general. Since cables through nuclear repository barriers entail risks of radionuclide transport out from the repository, sensor units embedded in nuclear repositories should be linked preferably by a cable-free interconnection between the repository and its outer environment. In addition to the wireless communication of the sensor data, the cable-free operation of the sensor units concerns supplying the electric power for the sensor operations. On the other hand, supplying the power by chemical batteries is not a reasonable solution, since the chemical batteries feature relatively short lifetime due to their limited energy storage capacity and self-discharge, as well as materials not permitted inside some nuclear repositories.

Wireless energy transfer has been proposed as one long-term power sourcing option of repository monitoring sensors. In general, the transmission through rock or typical engineered barrier materials like concrete and bentonite can be difficult because of the high attenuation by the medium. The high attenuation is caused by the conductivity of the material – the electric field is strongly attenuated by the conductive material components such as water or metals. The attenuation increases rapidly with the increasing frequency and can exceed even 10 – 200 dB/m, i.e. the signal power is attenuated by a factor of 10^{-1}–10^{-20} per metre depending on the conductivity of the material and the frequency used [1].

Based on the earlier studies, the most potential solution to obtain a reasonable wireless operation distance is to apply low-frequency (LF) magnetic fields and inductive coupling between wire loop antennas at opposite sides of repository barriers. A system model for this is illustrated in Figure 1. The general goal of the research of this technology in Modern2020 has been to investigate its applicability and technical limitations in the powering of nuclear repository monitoring sensors through repository barriers, which requires much longer wireless distances than its conventional applications such as wireless charging of mobile devices. Another goal has been a feasibility study and pilot implementation of a wireless bi-directional data transfer add-on in the wireless energy transfer system without compromising the energy transfer performance.

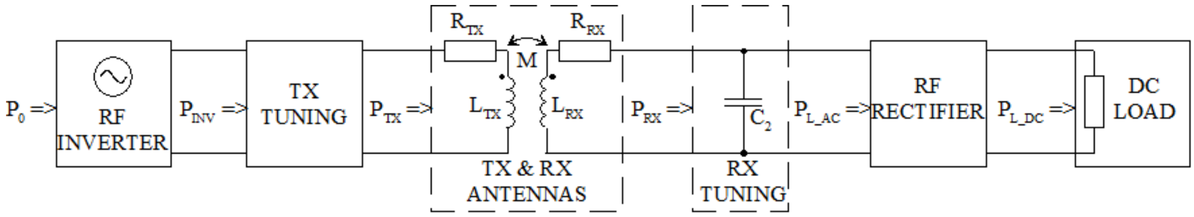

Figure 49: Block diagram of an inductive energy transfer system (data transfer add-on not included). The left side shows the repository external transmitter part and the right side the repository internal receiver part.

3. Methodology

3.1. General

The main research methods have been performance analysis by applying existing theory of inductive coupling and power transfer, and a 125 kHz pilot system design and experiments through medium representing repository barriers consisting of crystalline host rock with relatively low conductivity. For the comparison, corresponding experiments with the same pilot system through the air have also been made. The theoretical study has also involved sensitivity analysis of the energy transfer performance with respect to design parameters such as antenna dimensions. The pilot system and its verification have also involved the RF and data modem parts of the wireless bi-directional data transfer add-on for telemetry data uplink from the power receiver to the power transmitter and telecommand data downlink at the opposite direction. Because of the long distance between the devices, the data uplink is based on an active RF transmitter in the power receiver and not on load modulation scheme that is applied e.g. in existing RFID (radio-frequency identification) systems.

Figure 50: The pilot system in co-axial antenna configuration through host rocks with low electrical conductivity (Espoo, Finland). The left photo shows the power receiver and the right photo the repository external power transmitter.

3.2. Theoretical power transfer efficiency

By assuming the tuning components lossless, the total power transfer efficiency for the system in Figure 1 is:

$$\eta_{TOT} = \eta_{INV} \cdot \eta_{LINK} \cdot \eta_{REC}, \quad \text{(Eq. 1)}$$

where $\eta_{INV} = P_{INV} / P_0$ is the RF inverter efficiency, $\eta_{LINK} = P_{RX} / P_{TX}$ is the link efficiency, and $\eta_{REC} = P_{L\_DC} / P_{L\_AC}$ is the RF rectifier efficiency. In long-range inductive energy transfer systems the total DC-to-DC power transfer efficiency is dominated by the link efficiency η_{LINK}. For the theoretical estimation of the link efficiency, the antennas and their coupling can be characterised by the following parameters:

$$k = \frac{M}{\sqrt{L_{TX} L_{RX}}}, \quad \text{(Eq. 2)}$$

$$Q_{TX} = \frac{2\pi f L_{TX}}{R_{TX}}, \quad \text{(Eq. 3)}$$

$$Q_{RX} = \frac{2\pi f L_{RX}}{R_{RX}}, \quad \text{(Eq. 4)}$$

where in addition to the symbols in Figure 1, k is the coupling coefficient between the antennas, Q_{TX} the transmitter antenna Q-factor, Q_{RX} the receiver antenna Q-factor, and f is the carrier frequency.

Maximising the link efficiency requires proper receiver antenna tuning and mutual matching of the load impedance and the receiver antenna inductance. In addition, the tuning and the impedance matching of the transmitter antenna is required for minimising the losses of the RF inverter and for adjusting the transmitted RF-power. By electrical network analysis, the following equation for the maximum theoretical link efficiency of long-range ($k^2 Q_{TX} Q_{RX} << 1$) inductive energy transfer systems according to Figure 1 can be derived [2]:

$$\eta_{LINK\_MAX} = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{k^2 Q_{TX} Q_{RX}+1}\right)^2} \approx \frac{k^2 Q_{TX} Q_{RX}}{4}. \qquad \text{(Eq. 5)}$$

The maximum link efficiency according to the previous equation with a specific receiver load requires tuning and matching of the receiver by applying the optimal values of L_{RX} and C_2 according to the following equations:

$$L_{RX\_OPT} = \frac{Q_{RX}\sqrt{k^2 Q_{TX} Q_{RX}+1}}{2\pi f\left(k^2 Q_{TX} Q_{RX}+Q_{RX}{}^2+1\right)} R_{L\_AC} \approx \frac{Q_{RX}}{2\pi f\left(Q_{RX}{}^2+1\right)} R_{L\_AC}\text{, and} \qquad \text{(Eq. 6)}$$

$$C_{2\_OPT} = \frac{Q_{RX}{}^2}{(2\pi f)^2 L_{RX\_OPT}\left(k^2 Q_{TX} Q_{RX}+Q_{RX}{}^2+1\right)} \approx \frac{Q_{RX}{}^2}{(2\pi f)^2 L_{RX\_OPT}\left(Q_{RX}{}^2+1\right)}, \qquad \text{(Eq. 7)}$$

where R_{L_AC} is the equivalent AC load resistance comprised by the rectifier and the DC load in Figure 1.

3.3. Maximum link efficiency by coupling coefficient approximation

In the case of two co-axial antennas with negligible effect of the intermediate and surrounding materials to the magnetic field, the coupling coefficient can be roughly estimated from the antenna diameters and the distance between the antennas as follows [3]:

$$k \approx \left(\frac{D_{TX} D_{RX}}{4x^2+D_{TX}{}^2}\right)^{\frac{3}{2}}, \qquad \text{(Eq. 8)}$$

where D_{TX} is the transmitter antenna diameter, D_{RX} is the receiver antenna diameter that is assumed to be smaller than D_{TX}, and x is the axial distance between the antennas. Based on the coupling coefficient, the maximum link efficiency can be estimated by applying Eq. 5 with antenna Q-factors Q_{TX} and Q_{RX} that are measured from antenna prototypes in the final operation environment, estimated by simulations or pre-set as target values based on earlier experience of similar antennas.

3.4. Maximum link efficiency by mutual inductance calculation

In the case of two co-axial antennas without negligible effect of the intermediate and surrounding materials to the magnetic field and the power receiver antenna diameter remarkably smaller than the power transmitter antenna diameter, the mutual inductance (M in Figure 1) can be estimated from the antenna diameters and the wireless distance between the antennas as follows [3]:

$$M = \frac{\mu_0 \pi N_{TX} N_{RX} D_{TX}{}^2 D_{RX}{}^2}{4\left(4x^2+D_{TX}{}^2\right)^{3/2}}, \qquad \text{(Eq. 9)}$$

where, in addition to the symbols in Chapter 2.3, μ_0 is the permeability constant, and N_{TX} and N_{RX} are the number of turns of the transmitter antenna and the receiver antenna respectively. By applying Eq. 2 with the antenna self-inductances that are measured in the final operation environment, the coupling coefficient between the antennas can be calculated from the mutual inductance. The antenna self-inductances can alternatively be estimated by simulations or by existing engineering formulas such as those in [4]. The maximum link efficiency can then be calculated by applying Eq. 5 as described in Chapter 2.3.

4. Results

Table 1 summarises the estimated power transfer performance of the pilot system in Figure 2 by the estimation methods in Chapter 2.3 and 2.4 and by measurements. The estimations were based on the antenna coil parameters measured from the prototypes in open space:

- power transmitter antenna: L_{TX} = 0.146 mH, Q_{TX} = 71.4, D_{TX} = 2.26 m, N_{TX} = 4,
- power receiver antenna: L_{RX} = 6.28 mH, Q_{RX} = 105, D_{RX} = 0.168 m, N_{RX} = 256.

Table 17: Measured vs. estimated power transfer performance of the pilot system in Figure 2.

Medium	Estimated by coupling coefficient approximation		Estimated by mutual inductance calculation		Measured by the pilot system	
	10 m air	7 m rock + 1 m air	10 m air	7 m rock + 1 m air	10 m air	7 m rock + 1 m air
Transmitted DC power	100.3 W	25 W	100.3 W	25 W	100.3 W	25 W
Receiced DC power	132 µW	123 µW	56 µW	52 µW	50.5 µW	79.4 µW
DC-to-DC efficiency	1.32 ppm	4.93 ppm	0.56 ppm	2.08 ppm	0.504 ppm	3.18 ppm

The results in Table 1 also indicate that the host rock between the power transamitter and the power receiver does not feature any significant degradation of the power transfer performance. Based on the performance analysis in general, the following relations concern the diameter of the antennas and the wireless operation performance through air or host rock with low electrical conductivity:

- The received power level is inversely proportional near to the sixth power of the wireless distance.
- Doubling the diameter of both antennas will almost double the maximum wireless distance.
- Doubling the diameter of the receiver antenna will increase the received power by a factor of 4 - 8.

Figure 3 and Figure 4 present measured signal graphs of the data downlink and the data uplink through the air with co-axial antenna configuration and 10 m wireless distance. In the data downlink, the unmodulated carrier power level was the same as in the energy transfer, corresponding 100 W inverter DC supply power. In the data uplink, the unmodulated carrier power level was about 100 mW. A 110 Hz square wave was used as a test modulation envelope in both data uplink and data downlink.

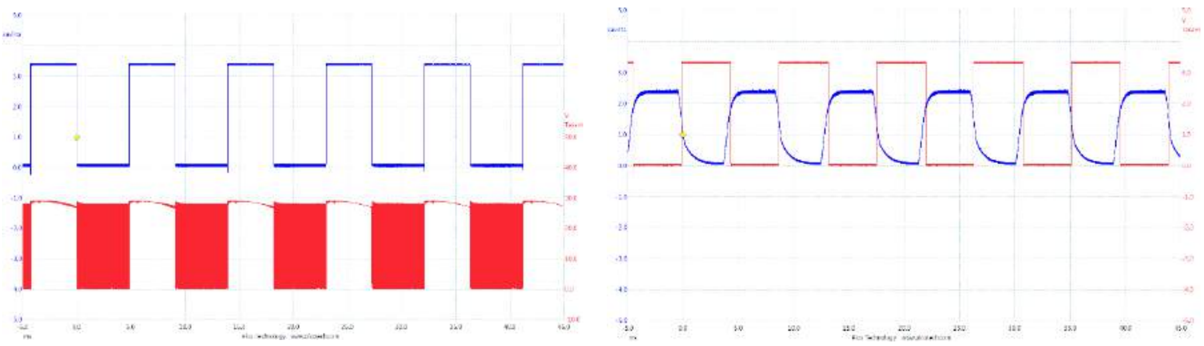

Figure 51: Oscilloscope graphs of the data downlink through the air by the pilot system with co-axial antenna configuration and 10 m wireless distance. The leftmost graph presents the transmitted downlink modulation envelope (blue) and the antenna signal (red) in the reader part. The rightmost graph presents the received rectified antenna signal (blue) and the regenerated downlink modulation envelope (red) in the sensor part.

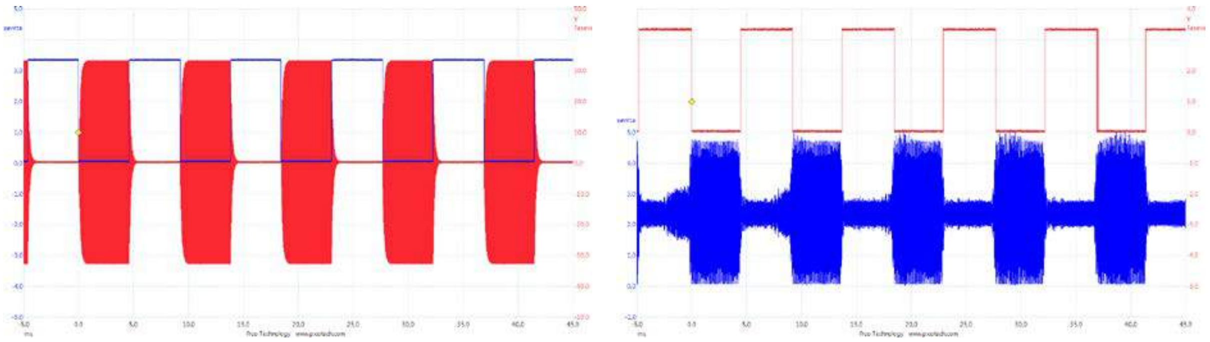

Figure 52: Oscilloscope graphs of the data uplink through the air by the pilot system with co-axial antenna configuration and 10 m wireless distance. The leftmost graph presents the transmitted uplink modulation envelope (blue) and the antenna signal (red) in the sensor part. The rightmost graph presents the received antenna signal (blue) and the regenerated uplink modulation envelope (red) in the reader part.

5. Discussion

The research until now has demonstrated that the wireless energy transfer through repository barriers is a relevant powering technology of wireless repository monitoring sensors. Up to 10 m operation distance through host rock with low electrical conductivity can be achieved with reasonable antenna diameters (e.g. 2 m transmitter antenna and 180 mm receiver antenna). With 100 W DC power supply at the transmitter side, the measured received DC power level was around 50 µW, which anyway necessitates long-term accumulation of the received power into an interim energy storage for low duty cycle operation of the sensor. Even remarkably higher power levels are feasible by increasing the antenna diameters. For example, according to the inductive coupling models, doubling the receiver antenna diameter will increase the received power by a factor of 4 - 8. By 125 kHz magnetic fields, the field attenuation caused by low-conductivity crystalline host rock in the pilot measurements in Espoo (Finland) was negligible, which was concluded by comparing the test results with those of the reference measurements through the air.

The tests of the pilot system also indicated that the wireless data transfer add-on can be implemented with a power leakage that is clearly below 5 µW and thus without compromising the power transfer performance significantly. In this, a TDM (time division multiplexing) scheme between the energy transfer, telemetry data uplink and telecommand data downlink is the most straightforward approach. A shared antenna coil can be applied at the energy transmitter end, but separate antenna coils at the power receiver end are necessary with such a low antenna coupling as in the pilot system with 10 m operation distance. The benefits of a combined system compared to separate wireless energy and data transfer systems are a more compact implementation and the elimination of possible co-existence problems (mutual interferences) of two independent radio systems.

Contrary to the alternative long-term electric power sourcing options of repository monitoring wireless sensor units investigated in Modern2020, no additional radioisotopes (as in the nuclear batteries) nor placing the power source close to the waste canisters (as in the thermal energy harvesting from the high-level waste) are needed. Thus, the impact to the disposal concept is in general lower than with the other power sourcing alternatives [5]. However, the repository external wireless energy transmitter requires some additional arrangements such as space and wired powering.

6. Conclusions

The research carried out by now provides an improved readiness for the design of a wireless energy transfer system for repository monitoring sensors with long-term operation of up to several decades. For this, the research has resulted in relevant input by investigating the adaptation of the wireless energy transfer to the nuclear geological repositories under development and construction, as well as its fundamental limitations that may also require balancing of the sensor unit operation to be inside its powering constraints. The pilot system design can also serve as reference material in the development of the wireless energy transfer system with data transfer add-on for the final repository monitoring applications.

Further elaboration of the wireless energy transfer towards final repository monitoring implementations is needed for maintaining the antenna resonance with nearby moisture and other materials with electrical conductivity, permittivity and magnetic permeability. Another challenge is the interim energy storage with appropriate energy and output power capacity for the sensor operations, long lifetime and low self-discharge rate. For the integration of the bi-directional data transfer, the most important development needs are improving the immunity of the data uplink to the external noise e.g. with more advanced modulation technologies or increased RF power level, and the design of the TDM based protocol for powering, data uplink and data downlink.

Acknowledgements

The research on the wireless energy transfer in project Modern2020 Task 3.3 has been carried out as cooperation between VTT (Finland) and NRG (the Netherlands).

The research has received funding from the Euratom research and training programme 2014-2018 under the grant agreement no. 662177.

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SmartCell – Pressure and Humidity measurementfor EBS

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Abstract

There is a quite extensive range of total pressure cells on the market for the measurement of total pressure in soils. They usually come in 230mm diameter flat cylinder form with transducer attached via steel tube. Typical transducers used in those cells are based on vibrating wire principle (GeoKon), pneumatic (GLOTZL) or lately fibre optics. The Czech Technical University (CTU) has developed and it uses such pressure cell for civil engineering applications over 20 years now. Although these sensors are reliable, there are some disadvantages of their usage for EBS. In particular, their big size and the necessity to use them in combination with other sensors to get full state of EBS, which is even more space demanding and measurements are done in different places. Together with cabling and necessary data loggers, system becomes complicated.

The new cell is targeted especially (but not exclusively) for measurements in the EBS system and to mitigate these problems. Although it is named as pressure cell, it is designed as “all in one” package. Along with the total pressure sensor, it integrates temperature, pore pressure sensor, RH sensor and electronics into the same cell body. This design solution allows to gain complete picture of EBS state in particular position at once with much lower demands on space, cabling and power.
The main objective for smart cell design were:

- Small size – less than 100 mm diameter
- All in one solution in compact body
- Measurement of
    - Total pressure
    - Pore pressure
    - Relative Humidity (optional)
- Low power design - long-term battery operation
- In-place signal processing and DAQ
- Integrated data logging for independent operation (optional)
- Digital interface (RS485, SDI-12)

From the data acquisition (DAQ) point of view, the aim is to completely process the signal from sensors inside the cell electronics and give the user digital output with no further processing required. This setup will eliminate the noise and other issues (e.g. parasitic capacitance) from analogue cabling and techniques such as oversampling can be employed to further increase of precision. Moreover having smart sensors also enables wide range of possibilities for measurement management and communication. With further development of its programming, the cell can take measurement as

necessary (triggered by various events) and send the data as one package at a later stage or raise immediate alarms.

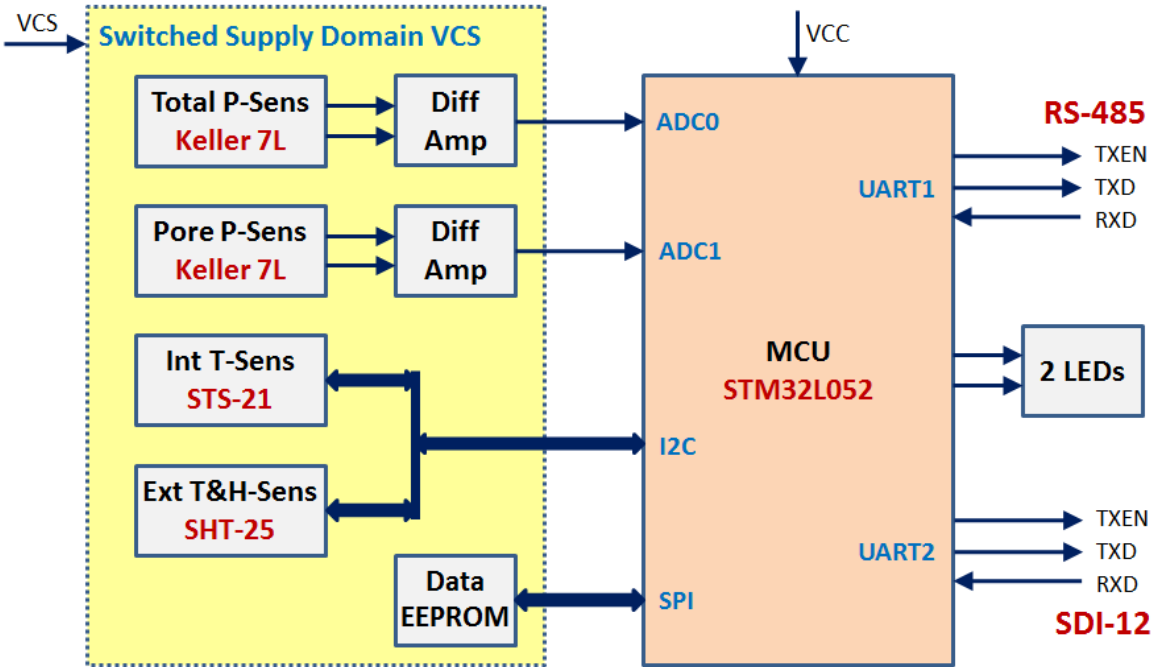

Figure 53: Core electronics

Core electronics of the smart sensor cell is described in Fig.1. All components must work at voltage given by a lithium single cell battery, i.e. in range from 3.3 V down to 2.0 V as close as possible. From an electronical point of view, the **Pressure Sensor** is a resistance full bridge. Diagonal output signal is amplified with a single operational amplifier in a simple differential wiring. Digital output of the **Temperature & Relative Humidity (RH) sensor** SHT-25 and **Temperature sensor** SHT-21 are read by I^2C interface. **Data EEPROM Memory** connected by SPI interface stores measured data. Supply of all above mentioned components (Supply Domain VCS) is switched off between measurements to conserve a battery energy. **Microcontroller** STM32L052K8 is powerfull (32-bit ARM Cortex-M0+ core) yet low-power MCU suitable for battery operated devices.

RS-485 is a standard, wide-spread and well-known industrial communication interface. Its driver chip requires 5 V with sufficiently high supply current but it works at high baud rates and long distances. **SDI-12** is a special interface for slow data rate sensors (e.g. meteorological) connected to a datalogger. It works half-duplex over single wire at 5-V-logical levels with baudrate 1200 Bd. The cell is connected to a remote data converter either stand-alone RS485/Ethernet or notebook's RS-485/USB or to a datalogger (SDI-12) with standard 4-pair shielded UTP cable. The cell communicates at RS-485 baudrate 115.2 kBd that makes possible using the cable with length up to 300 m.

Firmware in the MCU fulfills following functions of the cell:

- At internal battery supply
  - Sleeping only (OFF)
  - Sleeping | Periodical sampling & storage in memory
- At external supply
  - Periodical sampling & storage in memory (without a communication)
  - Connected by SDI-12 (V1.3): on-demand sampling & data sending

- Connected by RS-485 (115.2 kBd, ASCII messages with parity):
  - ✓ On-demand sampling & data sending
  - ✓ Download of acquired data from the memory
  - ✓ Execution of auxiliary commands
  - ✓ Firmware update by the built-in bootloader & PC application

Since a record of one measurement sample contains 8 items of 16-bit integer number (compressed date, compressed time, 2×pressure, 2×temperature, humidity, battery voltage) the 32-Mbit data memory can store up to 262144 samples i.e. 3 samples/hour for 10 years.

From the mechanical point of view the design of smart cell is driven by the necessity to combine the pressure exchanger, which transfers total pressure from the surface of the cell into pressure sensor itself and housing for the electronics and other sensors. The classic setup of pressure cell is a flat disc (around 200-250mm in diameter) filled with fluid with pressure transducer attached via short pipe. Piezometers and other sensors are typically cylinders (5-30mm diameter) with sensing part at the top of cylinder and cable on the other end. Just stacking those sensors together would create bulky device with irregular shape and fragile protruding parts, which is unacceptable. Even if the piezometer and other sensors were integrated into pressure transducer body of the pressure cell, the arrangement could not be used for two reasons:

- It occupies a lot of space
- The sensor housing is far away from place of measurement (cylinder) therefore even if additional sensor would be added they would measure in completely different place

To solve this problem the shape of sensor housing was changed into low profile cylinder and pressure exchanger was placed on one of the cylinder bases. The target for integrated cell was set to 80mm in diameter and 30 mm height with no protrusions going out of the main body (except cable). This size was selected as a balance between the miniaturisation and precision of measurement (total pressure measurement needs large pressure exchange area). Although it may still seems big, it poses significant engineering challenge to integrate all sensors into such limited space while providing protection for electronics.

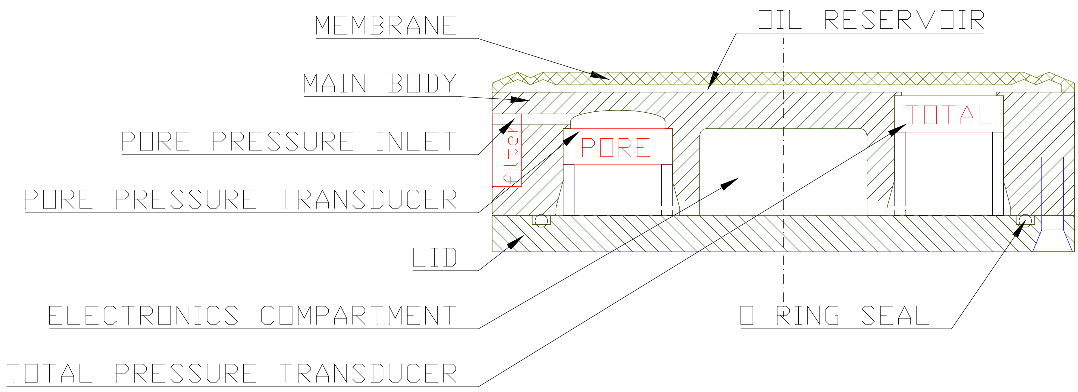

Figure 54: Schematic cross section

The design of the new integrated cell is cylindrical 80mm in diameter and 25mm height. It consist of the main stainless steel body, which has welded membrane on top and steel lid on bottom covering the electronics compartment.

The main body is major structural element. It holds all the sensors in place and provides shielded space for the electronics. The total pressure is measured using piezo resistive sensor submerged in

the oil reservoir at the top of the main body. The reservoir is enclosed by welded on membrane on the top of main body. It effectively acts as pressure exchanger transferring total pressure from environment into sensor. The pore pressure is measured using same type of pressure transducer directly connected to the environment via side holes in the body and porous stone acting as filter. The usage of same sensor types allowed simplifying the electronics. Both sensor ranges can be individually selected in order to accommodate for expected total and pore pressures.
The RH sensor is exposed to the environment in similar way as pore pressure sensor. It sits in side chamber and porous stone protects it. It also serves for measurement of temperature along thermometers on electronics board.
The electronics compartment occupies approximately ½ of the inner space of the cell body. It offers protected space sealed by bottom steel lid. At final stage before the in-situ installation, the compartment (electronics) is filled with conformal coating for additional protection against moisture.

Czech Technical University (CTU) and Technical University Liberec (TUL) have performed the development of the smart cell jointly. The design of the electronics, board prototypes and firmware development has been performed by TUL. The design of the mechanical part, sensors selection, final assembly and testing has been performed by CTU. Several revision of the body has been prepared and manufactured. 3D modelling and rapid prototyping using 3D printing have aided the design. The cell is designed to mitigate problems arising when using stock cells in EBS environments (big size, several sensors needed, line noise,..). This has been achieved by integration of all sensors and electronics into one body.
The main advantages of the new smart cell are:

- Simultaneous measurement of total pressure, pore pressure and/or relative humidity
- Integrated electronics with data logging capability and industrial digital interface
- Low power design with up to 10 years independent operation on integrated battery
- Customisable measurement range selection
- Small size

The electronic core of smart cell has been developed by TUL. It provides signal conditioning, signal processing, communication and data storage in small form factor. The electronic core has been specifically designed and optimised for long term operation on integrated battery.
The smart cells has been tested in the laboratory and its design is continuously improved. The second version is installed in the Long Term Rock Buffer Monitoring demonstrator (LTRBM; MODERN WP4) for further in-situ testing.

D.b – Session on Citizen Stakeholder Participation

Nuclear Culture and Citizen Participation: Networked and distributed artworks

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1. Summary

This poster introduces the Nuclear Culture project's artistic and curatorial strategies for engaging citizens in an interdisciplinary and indepth discourse about long-term radioactive waste management through networked and distributed artworks.

There is an established humanities discourse on the relationship between social and technical challenges of long-term radioactive waste siting, monitoring and site marking, to which the visual arts can make a valuable contribution. Although there is a significant volume of contemporary visual art produced about this topic, there is a severe lack of curatorial work to establish its contribution to the wider arts, humanities and Radioactive Waste Management (RWM) discourse. The Nuclear Culture project aims to readdress this balance, enabling curatorial and artistic research to contribute new knowledge to the field of nuclear arts and humanities, and to be embedded in nuclear sites and museums around the world.

At the same time RWM is interested in the role that visual artists and their work can play in the public consultation and stakeholder engagement around geologic storage of high-level radioactive waste. Government directives encourage wide ranging forms of public engagement with the issues, hoping to establish public acceptance. However, the instrumentalisation of art for political ends will always be resisted by contemporary art. Instead the visual arts can provide a more complex and nuanced form of citizen participation, to establish social and technical networks for contemporary art where creative partnerships across sectors and disciplines build new knowledge within the deep time politics of the nuclear. In this way, art can create a space for a wider cultural debate, which includes voices of protest and dissent within the framework of nuclear heritage, present and futures.

In this poster curator Ele Carpenter and artists Andy Weir, Jon Thomson and Alison Craighead argue that the only way to commission contemporary art in response to the nuclear is to fully understand the cultural and artistic context, as well as the social and technical challenges of RWM. They argue that this can only be achieved through working in partnership with professional curators, arts organisations, galleries and museums to ensure that the work can productively contribute to public cultural discourse and archives. These partnerships require long-term strategic commitments from the industry, university and art museum sectors.

2. Introduction

The Nuclear Culture project, curated by Ele Carpenter, has successfully engaged over 100,000 people with artworks investigating radiological deep time and nuclear aesthetics by commissioning new artwork, curating exhibitions, organising site visits and roundtable discussions in partnership with arts organisations and nuclear agencies. The project has an ongoing impact on the contemporary debate about long-term storage of radioactive waste through publishing, reviews, book chapters, journal papers and touring films and artworks. The findings of the project are regularly presented at conferences on nuclear culture, nuclear history, nuclear humanities and European research programmes on art, archives, and site markers.[1]

Following the success of the 'Perpetual Uncertainty' exhibition[2] and The Nuclear Culture Source Book[3], Carpenter's curatorial research in Nuclear Culture is now focusing on articulating a range of curatorial methodologies for commissioning artwork in nuclear contexts. Whilst there is a significant body of artwork being produced in response to deep time aesthetics, there is an important need for curatorial frameworks to enable artwork to contribute to the production of knowledge in the field through academic, social, public and artistic discourses and contexts. This abstract and poster focuses on the curatorial methodology of commissioning networked and distributed artworks through consultation with the Records, Knowledge & Memory (RK&M) project.[4]

The aim of commissioning artwork that has 'distributed' characteristics is to enable it to exist in many places at once, forming a network between sites, communities, digital and physical platforms. A distributed network was Paul Baran's proposal for an indestructible communications system in the event of a nuclear war (Fig.1). Ele Carpenter applies the internet logic of Baran's distributed network topology to socially engaged and new media artworks that can function on an international scale across public and archival platforms. These artworks include: Thomson & Craighead's Temporary Index, currently being commissioned by the NDA for the Nucleus Archive at Wick, Scotland; and Andy Weir's Pazugoo figures which are being modified for nuclear sites and museum collections around the world.

3. Methodology

The Nuclear Culture Research group employs a range of visual art and curatorial practice based research methods. These include situated field research, unstructured interviews, materials testing, and the iterative conceptual development of the relationship between theory and practice in the process of making. Collaborative methodologies for inter-disciplinary, multi-disciplinary and socially engaged practice are used to engage exhibition audiences, stakeholders and cross-sector agencies in indepth dialogue. Pedagogic workshops enable young people to participate in the creative development and production of the artwork. The public engagement with the work is an essential part of its iterative development and dissemination, and includes academic seminars, doctoral research, artistic production and curatorial production. Artworks are developed through testing the concept in nuclear and museum sites, drawing on the specific local context and issues. Artists and curators regularly consult with nuclear scientists, anthropologists, ethnographers, materials scientists and radiation protection advisors in the planning and implementation of their work.

The curatorial methodology to commission artwork that has 'distributed' characteristics enables it to exist in many places at once, forming a network between sites, communities and platforms. Influenced by Paul Baran's network topologies for an indestructible communications system in the event of a nuclear war (Fig 1). Ele Carpenter considers the open source logic of Baran's distributed network as a way of mapping socially engaged and new media artworks that operate across multiple digital, analogue and physical platforms.

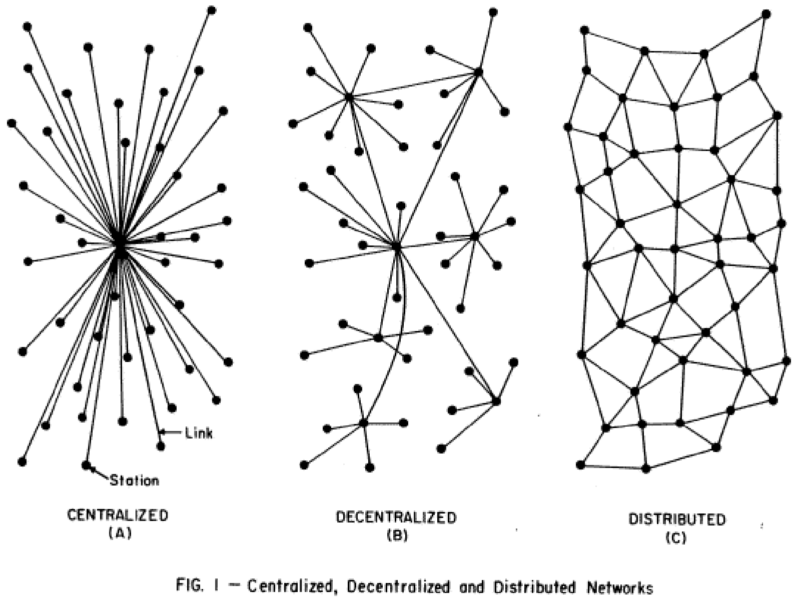

Figure 1: Paul Baran, Distributed Networks, 1964. On Distributed Communications: I. Introduction to Distributed Communications Networks. Santa Monica, CA: RAND Corporation. Available at: http://www.rand.org/pubs/research_ memoranda/RM3420

A centralized network (A) is based on an analogue communications structure such as radio, where one person can broadcast to many people, but the flow of communication is generally in one direction, from the center to the periphery. The decentralized network (B) starts to map our social networks, where community groups are able to communicate through smaller hubs. However note that they all connect to a central hub or node. The distributed network (C) uses the same network of stations or nodes, but provides links between as many of the nodes as possible. The survival strategy relies on information being able to communicated through multiple routes, like the internet packet switching capacity. When thinking about distributed networks we can consider how physical sites such as the art gallery or museum function within a network of groups, archives, records and practices. We might consider a network as a constellation of human and non-human actors that support the development and distribution of ideas across time and space.

If artwork is to be sustainable over generations it needs to operate across different networks, platforms, sites and contexts. It needs to be preserved through online and physical archives, in public and private sites, in industrial and artistic locations and discourses. The role of the curator of contemporary art is to build a context for art within wider socio-political as well as art-historical or museological frameworks. At the same time the preservation of Records, Knowledge and Memory of radioactive waste sites also requires this kind of curatorial knowledge to support its work.

4. Results

4.1 Andy Weir

Two distributed and networked artworks developed through the Nuclear Culture project include Thomson & Craighead's *temporary index*, currently being commissioned by the NDA for the Nucleus Archive at Wick, Scotland; and Andy Weir's *Pazugoo* figures which are being modified for nuclear sites and museum collections around the world.

Andy Weir is an artist investigating knowledge and agency within deep timescales through strategies of complicity and fiction. His artwork *Pazugoo* is a distributed constellation of figures proposed to be buried at specific sites of nuclear waste storage.

The collectively modifiable figures are based on Pazuzu, the Assyrian-Babylonian protective demon of contagion, epidemic and dust. Filtered through the 'gooey' glitched plastic materiality of current digital design and printing technologies, they become Pazu*goo*.

Religious and secular belief systems are a significant part of the debate about nuclear semiotics and how to communicate important knowledge into the deep future.[5] Weir's project creates a thread of digital mutation through replicating the figure of Pazuzu who warns against dangers as intangible as dust and viruses, highlighting the invisibility and mutating force of radiation through a physical modification of the 3D model.

Figures 2 and 3: Andy Weir, Pazugoo, workshop designing and printing figures, Bildmuseet, Umeå University, Sweden, November 2016.

As part of the work, Andy Weir runs workshops to create and distribute *Pazugoo* figures (Figs 2. and 3.). Participants draw on online museum databases of scanned artefacts, and reconfigure them according to the Pazuzu morphology, leading to the production of combinatory designs and printed objects (Figs. 4 and 5).

We are now working on a proposal for both relay and deep time placement of the objects in URL sites. Andy Weir has made a series of small figurines in different materials which are planned to be placed at the entrance to every repository, echoing the placement of St Barbara at the head of Underground Research Laboratories in Meuse/Haute-Marne, Bure, in northern France and HADES, Mol, in Belgium.

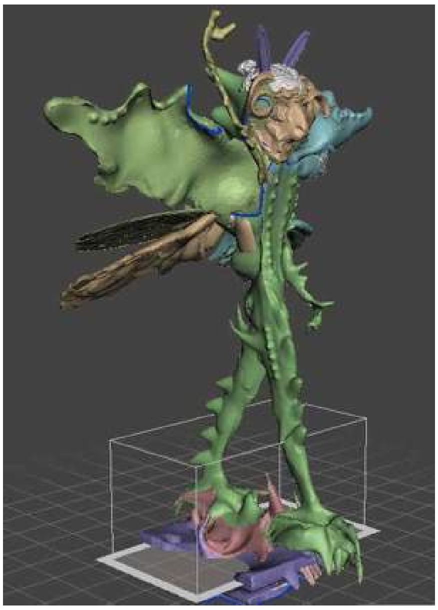

Figure 4: Andy Weir, Pazugoo, design from workshop. Bildmuseet, Umeå University, Sweden, November 2016.

Figure 5: Andy Weir, Pazugoo Prototype S1N1 (2016), polylactic acid, 14cm x 9cm x 4cm.

Through the work, Weir proposes the importance of mythic fiction as a method for navigating between the immense timescales of nuclear storage and human cognition in the present. *Pazugoo* speculates on this through the fabulation of double-flight, a figure with an “excess of wings”,[6] it can be imagined flying billions of years into radiological deep time futures and back to the present.

This use of myth connects two temporal registers of the work: firstly, it draws attention to itself as a material object, slowly decaying over long timescales and becoming a future part of the earth in which it is buried; secondly it enters into discussions around waste now, opening critically engaged debates around responsibility, memory, fiction and materiality.

As a distributed work, it uses the museum exhibition as an ‘index’ to reference objects located and buried, collectively produced and dispersed around the world, connecting local, international and planetary scales of engagement. Following the ‘Perpetual Uncertainty’ exhibition, a *Pazugoo Index*

(2018) has been acquired by the Malmö Konstmuseum collection for future preservation and scholarship. Examples of its distributed iterations include a clay burial ritual at a event marking time and toxicity in Amsterdam,[7] and its custodianship with local guides at the Maralinga site in Australia.[8]

4.2 Thomson & Craighead

Artists Jon Thomson & Alison Craighead investigate understanding of geological and planetary time through the relationship between live data and the material world. Their artwork *temporary index* is an array of decorative counters that mark sites of nuclear waste storage across the world. Each counter is a kind of totem marking the time in seconds that remains before these sites of entombed nuclear waste become safe again for humans. These timeframes range from as little as forty years or as much as one million years. A booklet accompanies the collection of counters, which describes each site in more detail, and providing contextual information about the human legacy of nuclear waste and what we as a species have done so far to deal with it.

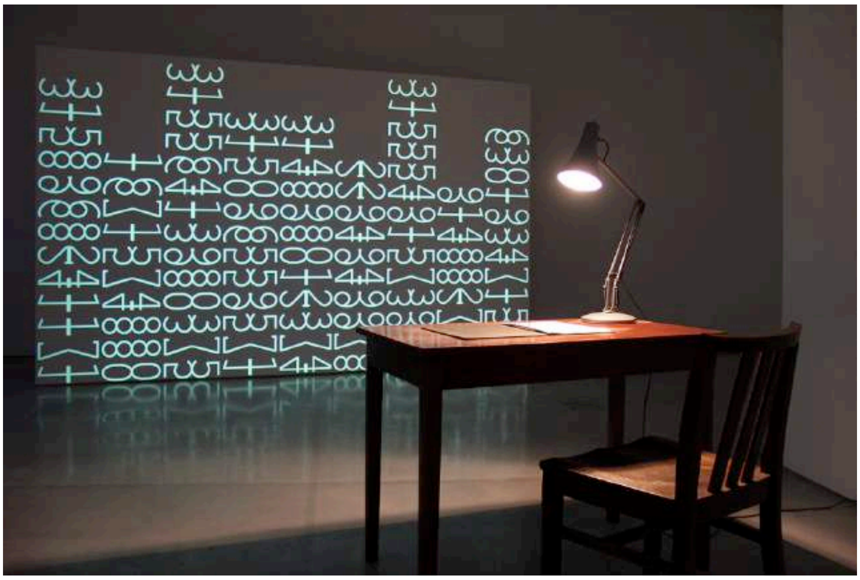

Figure 6: Temporary index, Thomson & Craighead, 2016

At the core of the *temporary index* artwork is a database which drives an array of numeric counters which countdown the probabilistic decay of radioactive materials in seconds. The numbers at the bottom of each column count down in seconds. The counters can be presented as a full array or single totem, embedded in specific sites, syndicated online, presented in an art gallery, included in nuclear archives, and preserved in museum collections. These animated objects of contemplation are representations of time that far outstrip the human life cycle and provide us with a glimpse into the vast time scales that define the universe in which we live in, but which also represent a future limit of humanity's temporal sphere of influence. The design of the counter demonstrates how human measurement of time is a process of linguistic and pictorial language.

Temporary index has been exhibited as a full array of counters at Carroll Fletcher Gallery, London (Fig 6), and the Malmö Konstmuseum in Sweden in 2018. In the Perpetual Uncertainty exhibition at Bildmuseet a single totem operates as a signpost, mapping the distance between the museum and the Chernobyl entombed reactor, tracing the downwind path of radiation that contaminated lichen in northern Sweden, and led to the culling of thousands of reindeer (Fig 7).

Figure 7: Thomson & Craighead, Temporary Index, Chernobyl Reactor #4, Ukraine. Bildmuseet, Umeå University, Sweden, 2016.

At Z33 House of Contemporary Art in Hasselt, 2017, the projected totem counted down the waste waiting to be entombed in the Low Level Waste site at Dessel, just a few miles from the art gallery. In 2019 the artists are creating a totem counter for the Nucleus archive at Wick, Scotland, commissioned by Highland Highlife and the Nuclear Decommissioning Agency (NDA).

We are now developing relationships with radioactive waste storage sites across Europe to build a series of live decay-rate counters, markers of time as well as place. Research for the project has included site visits to the LLW Ltd at Drigg, UK; Horonobe URL, Hokkaido, Japan; Nucleus Archive, Wick, Scotland, and HADES in Mol, Belgium.

5. Discussion

The Nuclear Culture project and the *Pazugoo* and *temporary index* artworks raise many important considerations for future partnerships between the visual arts and RK&M projects as they shift towards the public domain of archives and collections, and informal creative cultural practices.

The visual arts can introduce new conceptual and organisational frameworks for rethinking long-term communication challenges. Artists work between institutional and informal cultural practices that value culture on its own terms, address the limits of institutions. The visual arts can address over-arching and holistic concerns within the nuclear economy, and are not specific to one area of scientific specialism. The tendency for over-reliance on patriarchal closed knowledge management, needs to be addressed to develop distributed more resilient knowledge networks for RK&M. The RWM sector already faces problems with passing on knowledge as people retire, new cultural forms are needed that engage younger generations in nuclear culture.

Visual art addresses the RK&M "dual track" approach to future transmission as each generation of artists builds on the knowledge and practices of their predecessors. Artworks are the focus of gallery and museum education programmes to engage children and young people with complex ideas. The relay of intergenerational culture is also the focus of many socially engaged art practices. Whilst future communications are found in art objects preserved within collections, and public art commissioning processes.

Art can create informal spaces for dialogue that is reflexive, poetic, political and discursive without having to solve problems or comply with specific agendas. Alongside exhibitions, the Nuclear Culture project always organizes an interdisciplinary roundtable discussions to bring citizen stakeholders into discussion with artists, philosophers, architects, sociologists, anthropologists as well as scientists and engineers working in the nuclear field. The roundtable involves presentations from stakeholders, artists and scientists, followed by roundtable discussions in small groups so that everyone has a chance to share their knowledge and experience. In addition to the artists field research, exchange visits enable people to learn about new perspectives on radiation and the nuclear, often moving outside their comfort zone. For example Z33 in Hasselt organised regular tours of the Perpetual Uncertainty exhibition for residents of Mol and Dessel. Whilst in Malmo, museum staff were taken on a tour of their local nuclear power plant.

Museums also function as memory institutions, preserving contemporary objects in perpetuity for scholarship and public display. This includes visual arts objects, research based artworks and documentation of social processes. To achieve this artworks have to be recognised as having a cultural significance within the time in which they are made, so that they continue to reflect their contemporaneity. However, it should be noted that art museum collections tend not to include unrealised public art and architectural proposals. Markers of sites can aim to be permanent or temporary. Temporary public works may have a huge cultural impact which can be recorded and archived, whilst permanent works can be ignored or buried. So the only way to understand visual art as future cultural heritage is to work with its curators.

International mechanisms for contemporary nuclear artworks are both formal and informal. Artists such as Thomson and Craighead are interested in shared server protocols, and distributed artworks which can exist in many different forms as markers of time as well as site. Andy Weir's *Pazugoo* figure as a spiritual marker of radioactive waste to be located at the entrance to URL's and waste sites, buried in waste containers and placed in art galleries and museum collections. These ‘networked’ projects provide an opportunity to include the RK&M Key Information File (KIF) in their archival documentation, connecting museum collections with specific burial sites.

6. Conclusion

The visual arts can only offer methodologies for creative organisation, connecting institutional and public culture through a mix of closed and open source networks, strategic and tactical modes of operation, combining long-term vision with short term relevance.

Working with other disciplines can help to broadened the horizons of the context in which we work, giving people permission to think differently, and speak about concerns that the normative culture of their field doesn’t allow space for. It can help to articulate things people already know but don’t have the language or support to describe. The arts and humanities can think holistically, they don’t need to compartmentalize research-processes and knowledge in the same way as science and engineering. At the same time these disciplines are not homogenous, there are many arts and many sciences. But industry/ research or art/science partnerships often have expectations that art might articulate what is already visible and known, whilst artists might interrogate the interplay of visibility and invisibility both materially and politically in unexpected ways.

Care needs to be given to the methodologies of creative production and distribution. The RWM industry is commissioning artists proposals, but how is that work impacting on the visual arts? How is the work being critiqued, referenced, archived within visual culture?

Several centuries of curatorial work is needed for the nuclear archives to move into the public domain, and to be able to include art and politics. The first step is to establish a curatorial context for the commissioning, production and dissemination of these contemporary artworks within multiple discourses, to find new ways of embedding the complexity of radioactive waste management in our past, present and future cultures.

Acknowledgements

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Andy Weir is an artist, Senior Lecturer in Fine Art at Arts University Bournemouth and PhD researcher at Goldsmiths, University of London.

Jon Thomson is an artist and Professor of Fine Art at the Slade, UCL, London; Alison Craighead is an artist and Reader in Contemporary Art and Visual Culture at the University of Westminster, Lecturer in Art at Goldsmiths University of London.

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[7] Project by Anna Volkmar and Jacob Warren,’(In)human Time: Artistic Responses to Radiotoxicity’, May 2018.

[8] Project by Jacob Warren. Maralinga, Australia, is the site of British nuclear tests between 1956 and 1963, and part of land currently proposed as low to intermediate level radioactive waste storage site.

D.c – Session on Post Closure Safety Cases and Monitoring Strategies

Screening Of Monitoring Parameters For The Dutch OPERA Disposal Concept

Jaap Hart, Ecaterina Rosca-Bocancea, Thomas J. Schröder[1]

[1] Nuclear Research and consultancy Group (NRG), The Netherlands

1. Summary

This paper describes a case study using the Modern2020 methodology to identify engineered barrier system- (EBS) and host-rock-related monitoring parameters. The case study make use of the outcome of the Dutch national programme OPERA[19] on the conceptual radioactive waste disposal facility in Boom Clay host rock.

The OPERA disposal concept is described as well as the safety functions attributed to the various barriers of the envisaged facility. For testing the Modern2020 screening methodology, the focus was on the OPERA Supercontainer and processes potentially affecting its safety functions.

The screening exercise identified several options to improve the clarity in the descriptions of the various steps of the screening methodology. Modifications of the Modern2020 flowchart were suggested, and an overview of the modified workflow was communicated to the partners involved.

2. Introduction

The project Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal (Modern2020) aims to provide the means for developing and implementing an effective and practical repository monitoring programme. Hereby, requirements of specific national programmes on geological disposal are taken into account. The main focus of the project is monitoring of the repository near-field during the operational period to support decision making and to build further confidence in the post-closure safety case.

Within Task 2.2 of the Modern2020 project, “Screening Test Cases”, NRG performed a systematic, stepwise procedure to identify parameters as candidates for monitoring processes which potentially may compromise the safety functions of the Dutch OPERA concept for the geological disposal of radioactive waste in Boom Clay [1]. The focus of this research was to:

- Test the methodologies to identify engineered barrier system- (EBS) and host-rock-related monitoring parameters for the Dutch national disposal programme as developed in Task 2.1 of the Modern2020 project, “Decision making requirements, monitoring strategies and approaches to screening the preliminary parameter list” [2].
- Further enhance the understanding of EBS and host rock evolutions in the Dutch OPERA concept for the geological disposal of radioactive waste to substantiate the future prospect of developing a monitoring programme in the Netherlands.

[19] OPERA: Onderzoeks Programma Eindberging Radioactief Afval - Research Programme for the Geological Disposal of Radioactive Waste

The Modern2020 screening methodology is depicted in Figure 1. The methodology is based on the philosophy that monitoring in geological disposal is a framework of three interlinked levels:

- Processes are evaluated which have a potential relevance with respect to the post-closure safety case;
- Parameters are identified which are representative for these processes and which are considered to be both relevant and valuable;
- Technologies are identified which can be deployed and which are feasible and sufficiently reliable to monitor the identified parameters.

The Methodology also includes cross-comparison of monitoring parameters to check for completeness and appropriate redundancy, and to ensure that an integrated monitoring programme is developed.

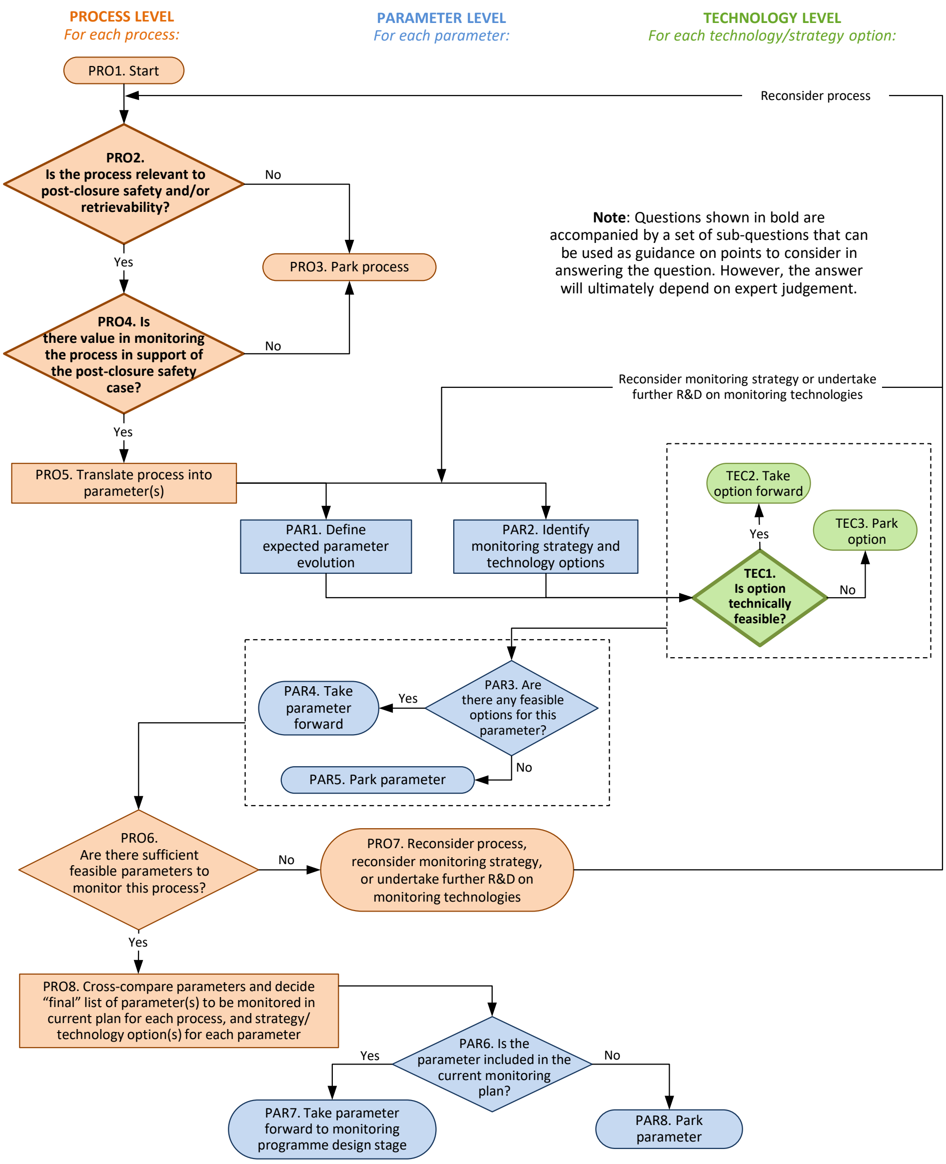

Figure 1: The Modern2020 Screening Methodology

The following sections elucidate on the OPERA disposal concept and its safety functions, the features, events, and processes (FEPs) potentially affecting the safety functions, and the selection of processes and parameters applying the proposed Modern2020 screening methodology.

3. OPERA disposal concept

3.1. Context

Already in the 1980's the Netherlands decided for a policy of long-term interim surface storage of radioactive waste with the start of actual geological disposal currently not foreseen before the next century [3]. In addition the Dutch government issued a policy directive in 1993 stating that underground disposal of highly toxic waste (including radioactive waste) was permissible in the Netherlands, provided that it remains retrievable over the long term [4].

The nuclear programme of the Netherlands is comparably small, with currently one nuclear power plant, resulting in relatively small amounts of radioactive waste intended for disposal. The extended period of surface interim storage of radioactive waste provides an opportunity to perform research and development on the potential and possibilities of geological disposal, either in a national repository or as part of a multi-national facility.

Despite that the policy of long-term interim storage favours a certain "wait-and-see" attitude, during the last 40 years many efforts have been devoted in the Netherlands to investigating geologic disposal of radioactive waste ([5], [6], [7], [8]). The main focus of the earlier programmes was on disposal in rock salt and included both performance assessments and detailed analyses on generic repository designs. The research interest in Boom Clay is more recent, reaching to the end of last century.

In June 2011 the six-year research programme for the geological disposal of radioactive waste, OPERA, started [9]. The objective of the OPERA research programme was to provide a first, preliminary safety case for a disposal concept in Boom Clay. The OPERA program was structured in 7 work packages comprising 43 Tasks, each addressing an aspect relevant for building a Safety Case for deep geological disposal in the Netherlands. These work packages provides the necessary input to enable a safety assessment of the OPERA disposal concept in Boom Clay [10].

An important motivation of monitoring R&D in the Netherlands is the Dutch requirement of retrievability after closure of the repository. Consequently, monitoring of processes relevant for the post-closure safety can serve as input for a possible decision of waste retrieval.

3.2. OPERA reference concept

The generic OPERA reference concept for the disposal of radioactive waste in Boom Clay host rock is shown Figure 2.

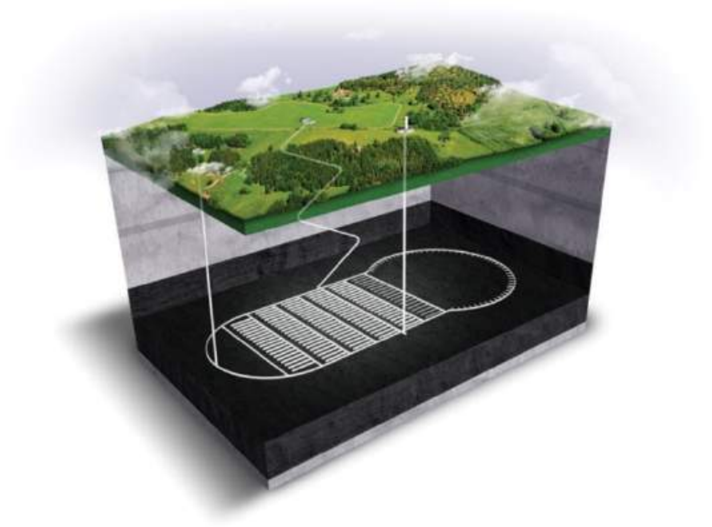

Figure 2: OPERA concept for the disposal of radioactive waste in Boom Clay.

The facility contains four waste disposal sections for (1) vitrified high-level waste (HLW), (2) spent fuel from research reactors, (3) non-heat generating HLW and (4) intermediate/low level waste (ILW/LLW) and depleted uranium. The disposal tunnels are supported by concrete wedge-shaped blocks. After the emplacement of the waste packages, the disposal drifts are backfilled with grout and hydraulically sealed off using a plug.

Figure 3: General layout of the HLW (left) and LILW (right) waste sections, and the OPERA Supercontainer

To allow for an efficient storage and disposal, standardised waste packages are used. The LILW is conditioned with concrete, whereas the depleted uranium is disposed of in Konrad type II steel containers. A Supercontainer with uniform outer dimensions is used for the heat-generating HLW, for spent fuel from research reactors as well as for the non-heat generating HLW. Figure 3 shows an artist impression of the OPERA Supercontainer for heat-generating HLW.

3.3. OPERA safety functions

In the OPERA concept the safety functions as defined by the Belgian waste management organisation ONDRAF/NIRAS [11] have been adopted. Safety functions are defined as the functions that a disposal system should fulfil to achieve its fundamental objective of providing long-term safety through a concentration and confinement strategy, while limiting the burden placed on future

generations. Figure 4 gives a graphical presentation of the safety functions attributed to the OPERA disposal system in Boom Clay for HLW.
Note in this figure the assumption that the engineered containment phase applies to the supercontainer only. After the loss of integrity of the supercontainer any release of radionuclides is assumed to be delayed and attenuated by the remaining (engineered) barriers as well as the Boom Clay host rock.

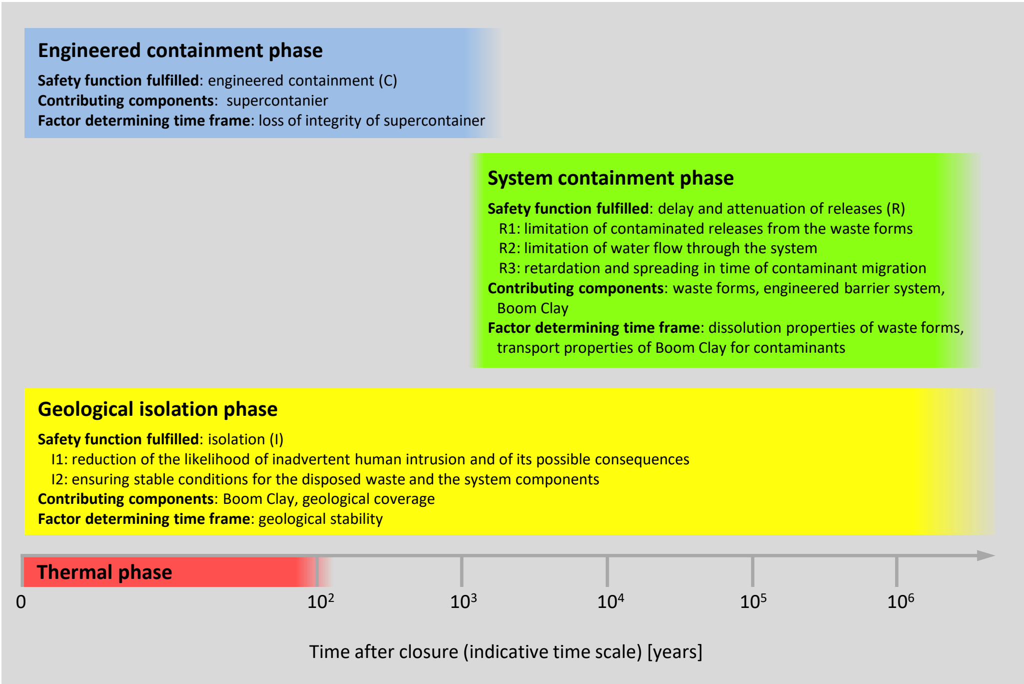

Figure 4: Safety functions provided by the main components of the OPERA disposal system in Boom Clay and its geological coverage. The timescale applies to HLW.

An overview of the objectives of the safety functions and the barriers and compartments of the OPERA disposal system are shown in Table 1 (based on [**Erreur ! Signet non défini.**]: Table 1).

Table 1: Overview of safety functions, objectives, components and barriers

Period	**Safety function**	**Objectives**	**Component/barrier**
Engineered containment phase	(C) Engineered containment	Prevent the release of contaminants from the waste disposal packages	Waste package
System containment phase	(R1) Limitation of contaminant releases	Delay and spread the RN release from the waste forms	Waste form
	(R2) Limitation of water flow	Prevent and/or limit advective transport of groundwater	Engineered barrier system Host rock (Boom Clay)
	(R3) Retardation of contaminant migration	Delay RN transport and dilute RN concentrations	Host rock (Boom Clay)
Geological isolation phase	(I1) Reduction of the likelihood of inadvertent human intrusion	Limit the likelihood and impact of human intrusion	Host rock (Boom Clay) Geological coverage
	(I2) Ensuring stable conditions	Limit the likelihood and impact of erosion exposing the wastes	Host rock (Boom Clay) Geological coverage (long term)

The safety functions play a crucial role in the Modern2020 screening procedure for establishing processes and parameters considered relevant for monitoring.

3.4. OPERA FEPs and scenarios

In OPERA a FEP screening process has been undertaken in order to identify potential threats to the OPERA safety functions and to derive scenarios considered relevant to the long-term safety. The FEP screening process performed as part of the present study uses the OPERA FEP database developed in the OPERA project OSCAR [12]. The FEP database has been used to check for completeness of the processes and events which may be relevant for the functioning of (a component of) the OPERA disposal system and which may be a candidate for monitoring.
The relevant scenarios identified for further analysis as part of the OPERA safety assessment are summarised in [13]. A total of 24 scenarios and assessment cases were identified, including the Normal Evolution Scenario (NES), representing the most likely evolution of the disposal system.

For testing of the Modern2020 screening procedure, the NES has been considered, as well as a number of Alternative Evolution Scenarios, in case these were considered as relatively 'short-term', i.e. potentially occurring within a time-frame practical for monitoring:

- Abandonment of the facility
- Poor Sealing scenario
- Excessive early containment failure scenario
- Excessive gas generation scenario
- Criticality event

4. Modern2020 screening approach

4.1 General approach

Considering that the geological disposal programme in the Netherlands is presently in a conceptual stage, NRG has adopted the following approach to derive processes and parameters as candidates for the monitoring in a future Dutch geological disposal facility:

- The Dutch OPERA concept for radioactive waste disposal and the related OPERA safety functions have been described and the roles of the EBS and host rock have been elucidated;
- Features, events, and processes (FEPs) have been identified which potentially can affect the various components of the EBS and host-rock functionalities;
- The expected evolutions of the most relevant processes occurring in the disposal system during the foreseen monitoring period have been described and time scales have been assigned to the representative processes;
- A preliminary list of parameters has been identified which are considered representative for EBS and host-rock processes potentially affecting the safety of the disposal system;
- The preliminary list of parameters has been used to test and evaluate the Modern2020 screening methodology; and proposals for modifications of the Modern2020 workflow have been elucidated.

4.2. Selection for testing the Modern2020 procedure

In order to perform the Modern2020 screening, FEPs and scenarios considered described in the previous sections, were rearranged in order to structure the existing information in a more coherent manner: the information obtained from analysing the safety functions and related FEPs was organized for each of the OPERA disposal components:

- Waste form,
- Waste container,
- Backfill,
- Disposal cell plug,
- Gallery lining,
- Near-field of the host rock,
- Far-field of the host rock, and
- Shaft seal

For each of these barriers of the OPERA disposal concept the information was reconsidered as follows:

- Identification of safety function(s) for each barrier;
- Identification of the most relevant processes potentially affecting the safety functions or other functions;
- Identification of parameters which were judged characteristic for the identified processes.

The tables generated for each of the engineered barriers altogether present the preliminary process and parameter lists. These tables were the basis of further screening of the Modern2020 methodology.

The actual testing of the screening methodology was not performed for all barriers of the OPERA disposal system, but focused on the processes and parameters of a single example case: the OPERA Supercontainer. The list of processes and parameters which were identified as candidates for monitoring of processes relevant to the OPERA Supercontainer are summarized in Table 2.

Table 2: Supercontainer (SC) processes considered for further screening

Notation	**Process**
	Carbon steel overpack
SC-1	Mechanical disturbance of carbon steel overpack as a result of corrosion (stress corrosion cracking, cold cracking, welding)
SC-2	Steel corrosion following water ingress, resaturation
	Concrete buffer
SC-3	Thermal evolution
SC-4	Water ingress – resaturation, flooding
SC-5	Geochemical evolution due to pore water/concrete interaction
SC-6	Mechanical load evolution due to external forces
SC-7	Mechanical load evolution due thermal processes (expansion)
SC-8	Corrosion induced cracking of concrete buffer
	Steel envelope
SC-9	Steel corrosion due to interaction with Boom Clay pore water
SC-10	Mechanical load evolution as a result of external forces
	Supercontainer
SC-11	Release of radiation

4.3. Result of the screening process

The processes considered in Table 2 as potential threat to the supercontainer's safety functions were assessed and parameters representative for these processes were identified. In addition, an evaluation of the evolution in time of these processes was performed in order to assess the practical feasibility of monitoring the parameters at hand. In the end, this lead to the list of processes and parameters for the OPERA Supercontainer as potential candidates for monitoring. Hereby it has been assumed that a time frame for monitoring of a process beyond several hundred years would not be practical or feasible.

Table 3: Supercontainer processes and parameters considered for monitoring

Process	**Representative Parameter**	**Time Scale [a]**
Carbon steel overpack		
SC-1 - Mechanical disturbance	Pressure Displacement	0 – 100's
SC-2 - Steel corrosion	Redox potential H_2 presence	10's – 100's
Concrete buffer		
SC-5 - Geochemical evolution	pH Redox potential Pore water chemistry	10's – 100's
SC-6 – Mechanical load (external forces)	Pressure Displacement	0 – 100's
Steel envelope		
SC-9 - Steel corrosion	Redox potential H_2 presence	0 – 100's
SC-10 - Mechanical load	Pressure Displacement	0 – 100's

A note to be made to the list above is that only limited information is available concerning the alternative evolution scenarios (AES) of the OPERA disposal system, since a qualitative assessment of these scenarios has not yet been performed.

In addition, no quantitative design criteria for the barriers of the OPERA disposal concept have yet been established. As a consequence, the testing of the Modern2020 screening methodology could only be performed with sufficient adequacy up to the identification of available techniques to measure the identified parameters.

5. Conclusion

A case study has been performed of the proposed Modern2020 methodology to identify engineered barrier system- (EBS) and host-rock-related monitoring parameters for the Dutch national OPERA programme on the conceptual radioactive waste disposal facility in Boom Clay host rock.

Basis of the procedure are the safety functions attributed to the various barriers of the OPERA concept. Executing and documenting the various steps of the Modern2020 screening methodology in a structured and reproducible way appeared to be a labour-intensive effort. For testing the Modern2020 screening methodology, the focus was on the OPERA Supercontainer and processes potentially affecting the safety functions of this engineered barrier.

The screening exercise identified several options to improve the clarity in the descriptions of the various steps of the screening methodology. Modifications of the Modern2020 flowchart were suggested, and an overview of the modified workflow was communicated to the partners involved.

The application of the screening exercise to the OPERA disposal concept was found a useful exercise. The Modern2020 workflow contains a comprehensive and detailed collection of relevant questions, which help focussing on what kind of knowledge is necessary to support evidence for safety, and what aspects need to be considered when further refining design criteria. The lessons learned may serve as a basis to further evolve the OPERA disposal concept and to develop a future monitoring plan in the Netherlands.

Acknowledgements

This study has been carried out as a part of Modern2020 Task 2.2. The Modern2020 project is co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Horizon 2020 Framework Programme and by COVRA.

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Qualification of diameter change monitoring system of inaccessible steel tube

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1 Summary

Monitoring the diameter change of tubes inserted in boreholes constructed as disposal cells for High Level radioactive Waste (HLW), over a time period of several decades, is very challenging. This paper describes the qualification steps performed from controlled conditions to representative conditions, without radiation, of ovalization monitoring by distributed optical fiber sensors (OFS) glued at the external face of the tubes.
First results obtained are promising. Indeed, during grouting of the casing of the second in situ cell demonstrator, raw data indicate clear observation of the filling of the volume between the casing and the surrounding rock. In addition, raw data fit well with the expected load shape, which has been observed for several in situ demonstrators and under controlled test either with numerical modelling. These in situ tests prepare another test plan mid-2019 where an 80 m borehole will be instrumented in order to prove Andra's capacity to monitor future disposal cells in Cigéo, planned to be 80 m in length in the Pilot phase.

2. Introduction

The French National Radioactive Waste Management Agency (Andra) is responsible of the Cigéo project (Industrial underground radioactive waste disposal). Cigéo is dedicated to the disposal of intermediate and high level, long lived radioactive waste in a deep geological disposal facility. The monitoring of the facility includes several phases of the project, from construction to post closure phase. In addition, the monitoring system has to provide information to support the reversibility, as "the capability of future generations either to continue building and operating consecutive phases of a disposal facility or to review the decisions made in the past and modify the management solutions". In order to support the reversibility of Cigéo, an R&D program has been acted by Andra in order to evaluate monitoring system and techniques dedicated to the surveillance of high-level waste (HLW) disposal cells with respect to retrievability conditions.

The HLW disposal cell consists of horizontal micro-tunnels, about 0.92 m in diameter and 80 m length, equipped with metallic casing in order to allow emplacement and retrieval of disposal packages during retrievability phase. The annular gap between this casing and the host clay rock is filled with cement-based material that imposes corrosion-limiting environmental conditions. One of the key parameters to monitor, in order to assess possible HLW retrieval operations, is the evolution of the casing's diameter (ovalization). In fact, the gap between waste package and metallic liner is designed to keep enough space to handle them, if needed, during operational period, at least a century.

3. Ovalization monitoring system qualification

In order to monitor the remaining gap inside a casing to handle waste packages, several measuring techniques exist. Optical fiber sensors (OFS) are one of the fastest growing and most promising researched areas for the long-term health assessment of engineered structures. This is due to their features of durability, stability, dimensions (small diameter, long length) and insensitivity to external electromagnetic perturbations. What's more, OFS are distributed, which means one fiber optic cable is thousands of sensing points, according to the selected technique (Rayleigh or/and Brillouin techniques), enable mapping of strain distributions in two or even three dimensions. Thus, real distributed measurements can be used to reveal the global behavior of a structure rather than extrapolation from local point measurements.
This paper presents the results of the qualification of a monitoring approach of ovalization assessment based on distributed OFS. Firstly, a design has been tested at small scale [1] in the laboratory, in order to determine sensing technique and sensors' fixation method. Results obtained have been used in the one-to-one scale test, where one sleeve element, about 2 m long, has been instrumented and subjected to controlled charge loading (see Fig. 2). The test validated the final design planned to be installed in situ.

The design of the monitoring by OFS cable has been determined by Neubrex co. Ltd, based on their feedback of pipeline monitoring. As Neubrex is the supplier of the OFS interrogator, based on combined Brillouin and Rayleigh techniques able to separate strains and temperatures acquired in only one optical fiber [2], the design has taken into account the instrument's advantage of centimeter spatial resolution. Indeed, OFS cable has been glued at the external surface of the sleeve in 5 spirals spaced by 0.28 m (see Fig. 1). Acquisition system has been configured to provide a measurement each 5 cm (sampling interval), with an average of 10 cm (spatial resolution). The test included displacement sensors, placed at the external and internal part of the tube, as a reference for OFS measurements. This test confirmed that the design could provide radial displacements (named ovalization in the paper) from circumferential strain measurements, which however requires the knowledge of the global shape of the mechanical loading, applied on the tube.

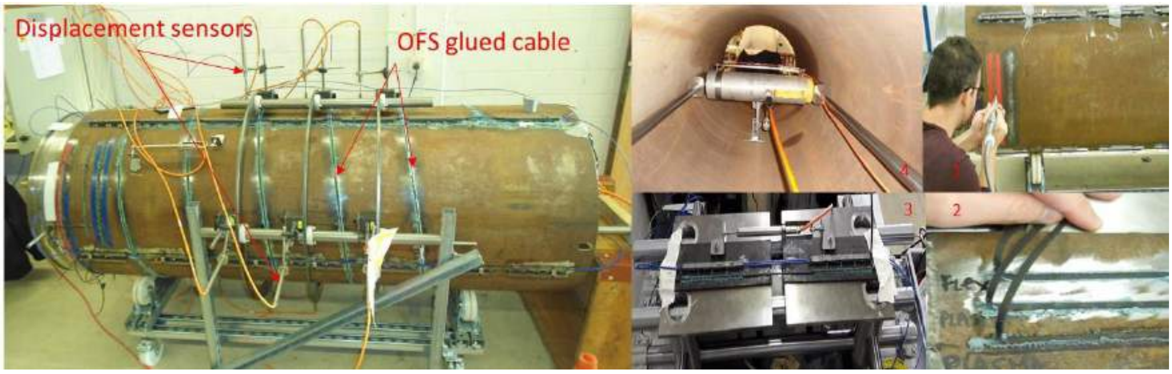

Figure 2: Photos of the sleeve equipped with OFS cables, the Sleeve equipped with (outside) classical sensors and OFS cables spiraled and (inside) hydraulic jack used to apply the radial loading (left) and the different steps of the laboratory test (1) surface preparation, (2) glue test, (3) axial strains up to break, (4) load test, and (right).

Several demonstrators were instrumented to monitor ovalization of the casing, according to the method tested in the laboratory, in Andra's underground research laboratory (URL) in Bure.

4. In situ AHA1604 demonstrator

This first demonstrator is the "AHA1604" experiment with a 112 m long excavated borehole in 2017. One sleeve element of the casing has been instrumented for ovalization assessment. In addition, three longitudinal OFS cables, dedicated to temperature and axial strain measurements, have been installed at the external face of the casing along 15 m (see. Fig. 3) in three positions around the outside of the sleeve.
Results obtained in the framework of this demonstrator allowed improving installation design of OFS longitudinal cables and optimization of acquisition parameters for grout injection monitoring of the gap between the casing and the host rock (see. Fig. 5).

Figure 3: Photos of the OFS cables installation in AHA1604, gluing longitudinal cables during sleeve insertion (left), OFS cables management before ovalization sleeve insertion (middle) and OFS cable loop management at the top of the casing for ALC1605 (right).

5. In situ ALC1605 demonstrator

The second demonstrator is "ALC1605" with about 30 m of excavated borehole in 2018. The same configuration has been installed for ovalization monitoring with, for this second test, two sleeve elements similar to the one instrumented in AHA1604. In addition, three longitudinal OFS cables, in three positions around the outside of the sleeve, were installed with optimization of OFS cables protections, taking advantage of the design evolution. Indeed, it has been added runners to center the casing in the borehole, which allow easier and safer emplacement of OFS cables at the external face of the casing. Although, all cables were protected, steel half shells used for AHA1604, which are no more necessary for the new design of ALC1605, were kept for the top cables only.
As this second demonstrator is dedicated to heating test (heaters will be placed inside the casing to simulate thermal load of HLW) a new OFS cable has been developed to resist to 90°C (maximum temperature expected at the outer face of the casing). Additional tests on specimens are planned, in controlled thermomechanical conditions, for OFS cable performance assessment.

Several measurements were analyzed and first results are promising. For instance, real-time strain and temperature measurements were obtained during grouting phase for ALC1605, as monitoring of AHA1604 allowed determination of the best parameters for grout monitoring. Indeed, Fig. 4 shows first results of ALC1605 injection monitoring where it indicates clear observation of the filling of the gap between the liner and the surrounding rock.

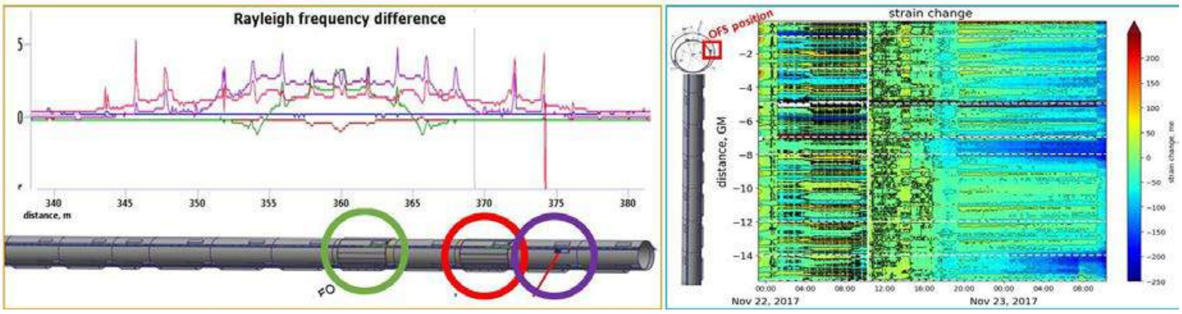

Figure 4: Raw data during grouting of the gap between the casing and the host rock, measured in OFS cable placed at the external surface, right side, along the casing for ALC1605 (left) and strain change for AHA1604 (right) measured by OFS cable at the same position. The circles indicate location of grout and the color indicate the curve's color in the Rayleigh frequency difference.

In order to assess possible handling of waste packages placed in the casing, the monitoring of casing ovalization is tested by OFS. Several tests were performed in order to, firstly, determine the best technique to assess ovalization, secondly, the possible relationship between circumferential strain distribution around the ovalization section are analysed using 2D model.

The obtained data in Fig. 4 will be converted to radial displacements, thanks to coefficients determined during laboratory load tests and 2D modelling. These data will be compared to measurements obtained by displacement sensors placed inside the sleeve at the same location. From raw data, we can already observe the expected load shape at each spiral by compressive strains in vertical locations (top and bottom) and tensile strains in horizontal locations (right and left) as expected for a bending loading.

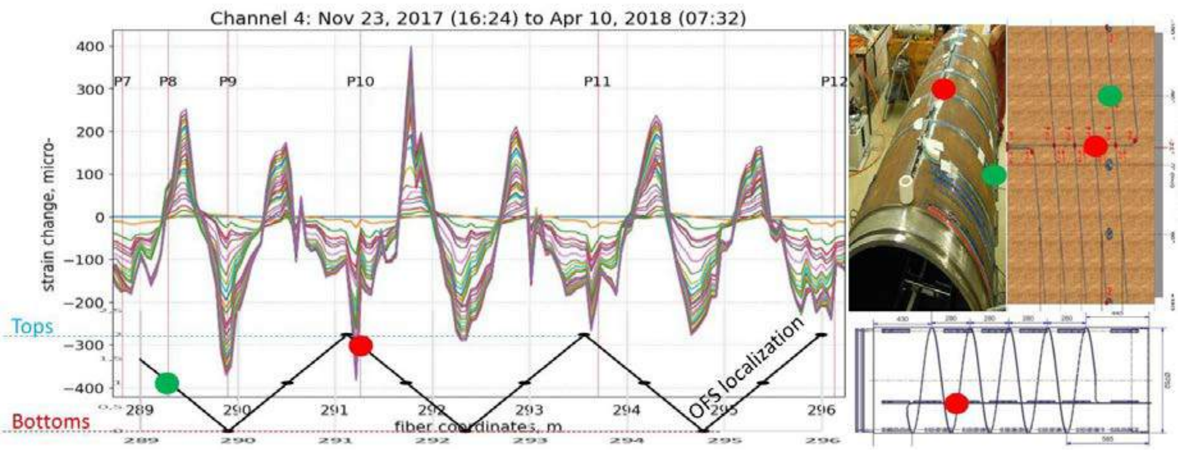

Fig. 5: Fingerprinting of the OFS cable spiraled around the sleeve with, schematic view, photo and specific localizations of the fiber. Red circle for P10 (21° left to the top) and green one for P8 (right side), and obtained circumferential strains (left) with black line in the bottom indicating localization of tops, sides and bottoms of the sleeve along the OFS cable.

The data will be acquired for several years in order to assess behavior over time, especially when the heaters have been placed inside the casing. The thermal effects on strains and ovalization will be determined in order to be account of them. This will allow better understanding of the casing's behavior.

6. Conclusions

All OFS sensors have seen successfully installed without any damage (100% survival rate) for both demonstrators AHA1604 and ALC1605. Success concerned all ovalization sleeves (3 in total) and longitudinal OFS cables (three orientations for each demonstrator). Four different installation methods, with optimizations of the cable protection system, were tested for the three different longitudinal OFS cables.

Results obtained are analysed in order to determine the ovalization of the casing in situ. Calculation method and analytical parameters are tested and will be validated thanks to direct measurements of diameter change inside the casing by classical displacement sensors.

The next step is the instrumentation of the AHA1605 demonstrator, mid-2019, where all tested method will be applied in order to provide a representative monitoring system of the HLW cells planned for Pilot phase in Cigéo. The expected length of excavated borehole is 80 m and the monitoring system is planned to provide thermomechanical and chemical characterization of the cell (casing, cement material surrounding the casing and internal atmosphere).

Acknowledgements

The authors wish to acknowledge the support of the European Commission via the project MODERN2020 ‘Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal’.

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D.d – Session on Long-term Integrated Monitoring Programmes

Hydrogeological Monitoring in Long and Deep Tunnel Projects – A Perspective of Austrian Base Tunnels

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1. Summary

Underground works influence hydrogeological regimes and – vice versa – are affected by groundwater in excavation and operation stages. Hydrogeological monitoring is an inevitable measure for the perpetuation of knowledge of any underground structure. In parallel, by monitoring, important data for generation of the hydrogeological model is recorded.
For underground works, it is recommended to start monitoring as soon as possible and – wherever technically feasible – continuously. Apart from quantitative parameters like runoff or head it is recommended to monitor in situ parameters (continuously, as well), stable isotopes (monthly) and a small hydrochemical parameter set e.g. ion balance (quarterly). Investigation of groundwater fauna is still not state of art but it is recommended to apply it systematically in future investigations.
The application of continuously measuring monitoring devices on the one hand provides data in periods when the monitoring point is not accessible (snow cover, avalanche risk…) and, on the other hand, they are the only possibility to capture extreme values (both flood and drought) and drought hydrographs.
Modern developments in monitoring are new inventions or creative usage of existing methods. An autonomous sampler with multiparameter sondes and data logger shall be applied in wells, caves, mines and power plants. The small amount of collected water is limited to stable isotope analysis or for tracer tests. In Austrian karst environment, a combination of a common pressure sonde with data logger, wire and remote transmission units allows a continuous observation of the head without construction of an observation well. With time lapse cameras periodic springs are monitored.
As future possibilities, it is recommended to develop the existing INSAR technology for the purpose of monitoring groundwater fluctuation and to integrate systematically groundwater fauna in every hydrogeology project for underground works.

2. Introduction

Acquisition of hydrogeological data during design, construction, maintenance and closure of underground works has two main purposes:

(1) Collection of base data for the hydrogeological model.
(2) Perpetuation of knowledge.

Underground works are influenced by groundwater and – vice versa – possibly affect the groundwater regime. The excavation works may change flow paths and directions, and discharge regions could be turned to recharge zones. The hydraulic conductivity around the opening usually is raised by order of magnitudes but can be lowered, dependent on the geological setting and the support measures. In direct consequence, dewatering of the rock mass can lead to surface settlements. The physical and chemical properties of the groundwater are changed by the new flow conditions and by interaction with the excavation [1].

Therefore, during the design stage of underground works the geologist is confronted with four main questions:

(1) Which underground and surface flow systems will be affected by the excavation?
(2) Is there an influence from dewatering on existing surface or underground structures?
(3) What is the estimated quantity and quality of water at the face during the excavation works?
(4) What is the amount and chemical / physical properties of water to expect during excavation and permanently at the portals?

The Republic of Austria is a largely mountainous country and around 62 % of the total area (ca. 84.000 km²) belongs to the Eastern Alps. Due to the distinct morphology there is a large history in tunnelling for railways (since 1840) and motorways (since the 1960's). In 2019, in Austria three railway base tunnels are in the excavation stage. In parallel for many deep motorway tunnels a second tube will be built – currently such works are in the realization stage. Deep tunnels or caverns for HEPPs (hydroelectric power plants) are in design or excavation stage. Other underground works were realized for gas pipelines, water conductance or mining purpose.

Based on the experience in the 1950's and 60's , when dewatering by underground works caused springs and creeks to run dry and caused long lasting judicial proceedings [7], subsequent intensive monitoring programs were established well before the tentative start of any excavation work.

During the decades the methods of monitoring changed. Given the fact that many meteorological phenomena will hardly be captured by monthly manual measurements, automatic data loggers were introduced. Driven by environmental restrictions of emissions of "contaminated" drainage water, the set of parameters to be investigated has increased significantly. In addition to standard hydrochemical analysis (ion balance), heavy metals and POP – *persistent organic pollutants* – today are monitored and state of art. The use of stable isotopes and tritium is a well-distributed method for natural tracers of the groundwater. The monitoring of groundwater fauna however still is not state of the art.

The number of monitoring points depends on the project and the sensitivity of its environment. For big tunnel projects more than 2.000 monitoring points are common, consisting of springs, creeks, production wells, monitoring wells, drainages, artificial ponds, weather stations and underground points of water access in existing underground structures or along the growing tunnel. The duration of these programs exceeds 25 years for the long base tunnels and HEPP's but even rises up to around one decade for the smaller motorway tunnels.

Monitoring programs are biased by different types of obstacles:

- Limitations of the feasibility of the quantification of a spring or soil wetness.
- Seasonal restrictions of access to monitoring points.
- Capture of extreme values (high and low) of runoff or other parameters.
- Periodic activity of creeks and springs.
- Initially low quality of civil works of the spring tapping.
- In wells: Problems with instabilities of the borehole, hydrogeological reliability of a single borehole, reliability of the origin of the tested water etc.
- Alteration of the monitoring points (by nature, animals, vandalism…).

3. Methodology

3.1. Monitoring points

The most typical points of monitoring are springs, production wells, monitoring wells and surface waters (creeks, rivers). Additionally there are monitored rainwater in weather stations, fishponds, water influx in underground structures, water treatment plants etc.

3.2. Devices

The choice of the monitoring devices depends mostly on the defined monitoring frequency. Despite the given fact - that monthly measurements neither capture extreme values nor depict representatively the response of spring and groundwater to precipitation events - monthly monitoring is still state of art and used at every tunnel site. Continuous monitoring only is applied at monitoring points with strategic relevance.

Typical devices for monthly measurements are of very basic nature like plumb-lines, buckets and clocks etc. The equipment contains multi parameter sondes (typically temperature, pH value, electrical conductivity, oxygen saturation) either as a hand-held set or in combination with the tape measure. Continuous monitoring devices are pressure cells with data loggers, mostly including temperature and electrical conductivity. Other parameters like pH value or turbidity are monitored continuously in special cases, only.

For pressure measurements two possibilities of the consideration of the air pressure are used: Open tube equilibrium or measurement of atmospheric pressure with a second device. The open tube equilibrium needs warranty that the monitoring point is never flooded and ideal for wells. The arrangement with two devices is used with difficult geometric conditions or very high groundwater fluctuations (Fig. 1).

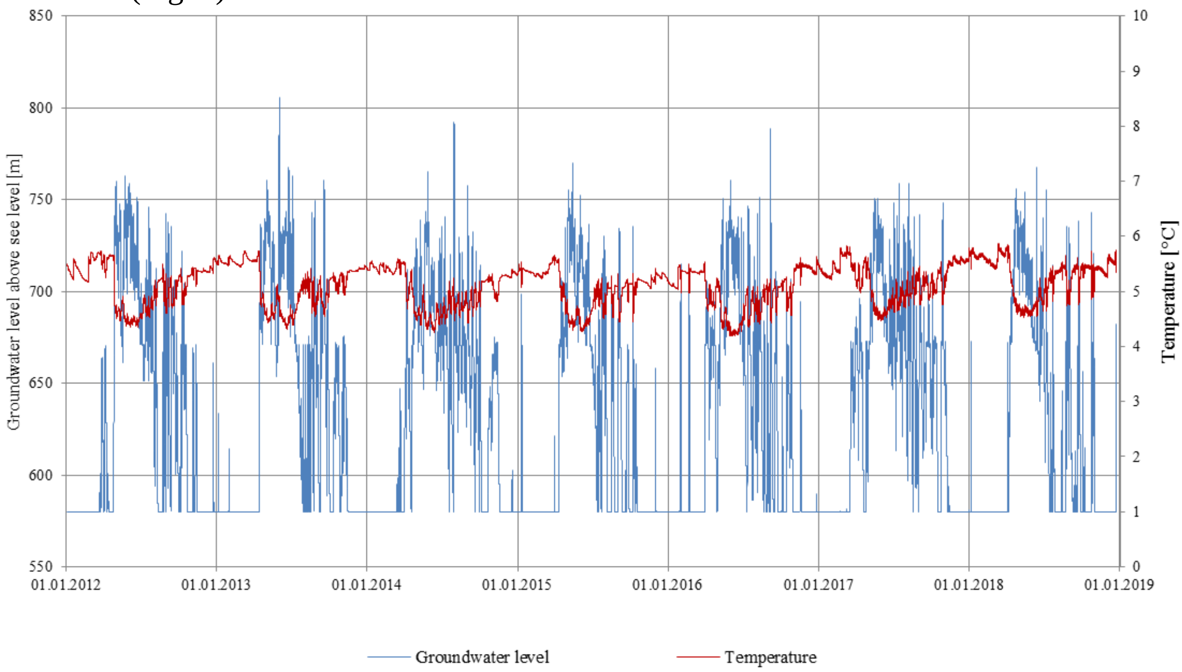

Figure 1: Continuous observation of groundwater fluctuations of more than 200 m in karst needs two independent devices: One for total pressure, one for barometric pressure. In the diagram, already the calculated difference is plotted.

At the water treatment plants of all tunnelling sites, autosamplers are installed. The samplers commonly are dimensioned for taking 24 samples of the treated water – one per hour in 24 hours – in a refrigerator.

3.3. Parameters

Common in situ parameters are temperature, electrical conductivity, pH and Eh values and oxygen saturation as objective and organoleptic properties as subjective parameters. In laboratory, hydrochemical and bacteriological analyses are undertaken, according to the national drinking water guidelines derived from EC guidelines (98/83/EC). However, the hydrogeologist needs a complete ion balance and every chemical analysis shall contain the 8 most important ions (Na^+, K^+, Ca^{2+}, Mg^{2+}; HCO_3^-, Cl^-, NO_3^-, SO_4^{2-}) in oxygen bearing water and 4 additional ions (Fe^{2+}, Mn^{2+}, NH_4^+, NO_2^-) in water free of oxygen. These very basic analytes are complemented by case-specific parameters of very different nature, like strontium, boron, antimony, uranium etc.

For both source of groundwater and groundwater dynamics, analysis of stable isotopes like $\delta^{18}O$, δ^2H and tritium are state of the art. Isotopes present in samples such as $\delta^{34}S$, $^{13}C/^{12}C$, $\delta^{18}O$ in sulphate, ^{35}Cl, $^{87}Sr/^{86}Sr$ are used for special purposes only. Isotopes such as $\delta^{17}O$ (Fig. 2) or radioactive isotopes other than tritium are used in special cases only.

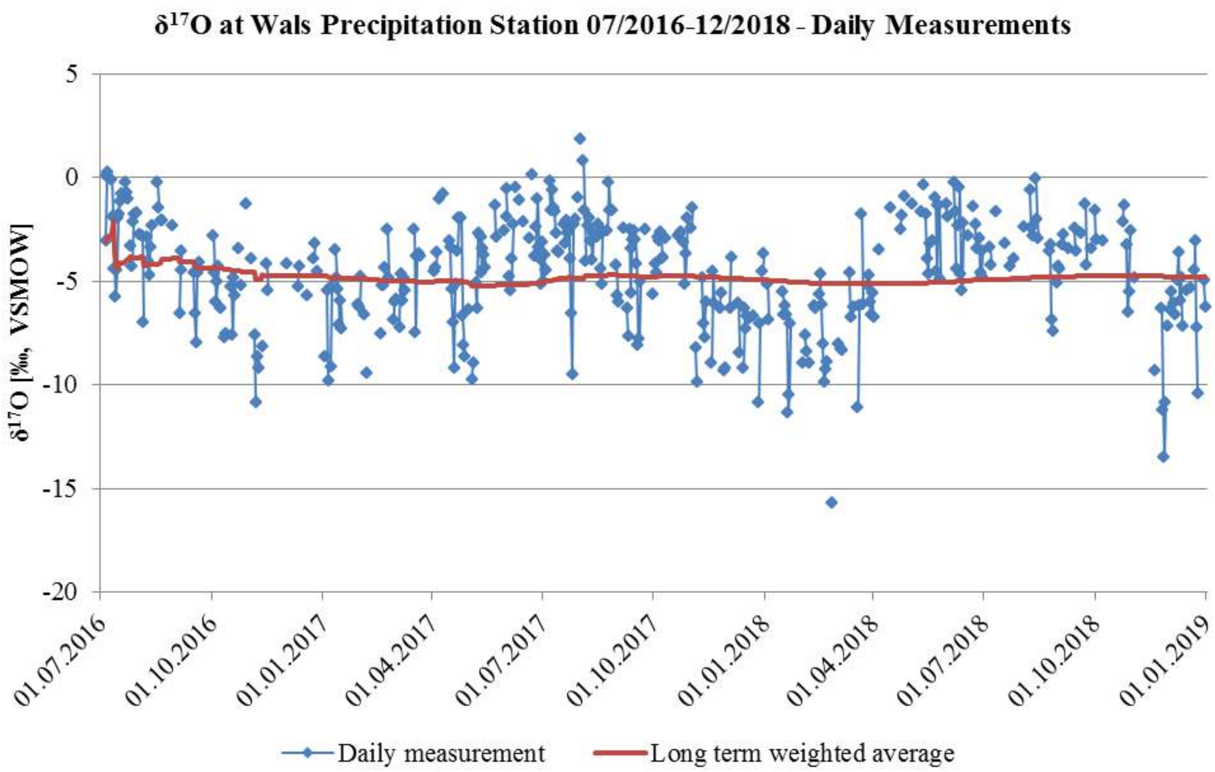

Figure 2: For the interpretation of isotopes of groundwater, an extensive data base of precipitation values is needed as input data. At Isolab Salzburg laboratory in Wals, Austria, the observation of stable isotopes are based on daily measurements. As example, in the diagram, single measurements of oxygen 17 and the long term weighted average are plotted for 30 months' observation time.

A very recent development is the systematic introduction of POP, *persistent organic pollutants*, on the basis of Stockholm Convention on Persistent Organic Pollutants [6] in water monitoring programs.

For perpetuation of knowledge, as well as for the purpose of hydrogeological interpretation, groundwater fauna needs to be monitored. However, the associated technology is still not state of art, and the systematic investigation of groundwater fauna is still not applied at Austrian tunnels.

In comparison to groundwater fauna, the use of microbiology is very common. It usually involves the technical conditions of the spring-tapping civil structure only, and doesn't consider / record deeper hydrogeological information. Therefore, the purpose is primarily to ensure the perpetuation of the knowledge base.

3.4. Creative and innovative solutions

The technical and logistic challenges encountered within these monitoring campaigns motivate the hydrogeologists to develop new methods, and invent new or modify existing equipment. These ideas can be categorized into established methods, methods in development and in a testing phase, and methods at the conceptual stage.

The developments for challenging these obstacles are of different nature. Apart from simple home-made technical devices, modern developments include:

- Remotely controlled data loggers.
- Autonomous sampling and monitoring devices.
- Continuous monitoring of stable isotopes.
- Use of time lapse cameras.
- Application of citizen science.
- Use of satellite based radar interferometry.

One of the most frequent challenges in the alpine monitoring campaigns is the access for measurement and maintenance during winter season. Access in snow takes more time and needs improved security measures. For big monitoring campaigns *avalanche risk management plans* are established and carried with properly-engaged avalanche experts. The execution of these plans causes interruptions in the monthly monitoring at affected points. The corresponding points – often springs – shall be monitored automatically, if possible. The possibility is given where spring tapping structures permit installation of measurement devices and data loggers. If information about the head is relevant for risk management, commonly piezometer sensors in monitoring wells are connected with data remote transfer devices. In one case – where boreholes are not possible at all – a natural cave is used for installation of a wire transfer from an extended underground lake to the portal and from there wireless via GSM signal to a server. For power supply, batteries and solar panels are common.

Only with continuous monitoring devices, combined with data loggers, extreme values can be captured. For extensive hydrogeological modelling, the stable isotopes of the groundwater samples shall be analysed at extreme values or other triggering parameters. As the continuous monitoring of oxygen-18 and deuterium is technically feasible only at places where simple laboratory conditions can be applied (e.g. civil structure at spring tapping or container with permanent power supply), Pucher et al [4] are developing devices which permit triggered sampling of small amounts of water.

The idea is to combine qualitative monitoring with sampling devices and trigger the sampling; the small amount of water limits the usage for stable isotope analysis or tracer tests.

Data loggers for temperature, pressure and other parameters are applied at almost every monitoring campaign. In karst regions, however, there are certain limits for the application of data loggers at sites where the activity of springs is periodic. Höfer-Öllinger et al. [3] demonstrate the use of time lapse cameras for spring monitoring. Due to the usage of infrared flash in darkness, the use of these cameras is reduced to a distance of around 20 m of a water course. As well as information about spring activity, other information, like snow cover, can be obtained. The images can be interpreted manually or automated by software and videos can be created.

4. Results

The introduction of creative and/or innovative methods in monitoring programs allows:

- Obtainment of data in remote area and harsh environment.
- Remote control of monitoring or sampling devices.
- Capture of extreme values and drought hydrographs.
- Embedding of hydrogeological events in risk management.

5. Discussion

A good understanding of hydrogeological processes is only possible if corresponding data is available. By comparison of long lasting continuous monitoring programs with monthly or weekly measurements – of the same monitoring points – any differences in essential information for hydrogeological interpretation become evident.

There are still further possibilities in monitoring which are still not state of art or in development. One of the technologies shall be citizen science where amateurs or local habitants are trained and involved for measurements. Nowadays applied only with the maintenance of weather stations, this method in the future shall be applied systematically for observation of hydraulic phenomena of periodic springs, wetlands, flood events, snow cover etc.

The drawdown of groundwater, caused by underground operations, induces surface settlement ([1] and references herein). The amount of drawdown depends mostly on the ground conditions. Extremely exact measurements of differential settlements by satellite-based Interferometric Synthetic Aperture Radar (INSAR) technology are used for observation of these excavation works [1]. Theoretically, this method shall allow natural groundwater fluctuations to be obtained by use of satellites.

The fact that groundwater fauna still is not used systematically with every hydrogeological project related to underground works could indicate that there is still a broad lack of understanding. Groundwater fauna investigations are still not state of the art and therefore aren't typically applied consistently. It is strongly recommended to change this habit and close this knowledge gap.

6. Conclusions

On the one hand, the development of devices for monitoring runs in parallel with technological inventions. On the other hand, good inventions are created by the intelligent combination of existing methods.

Relatively cheap methods providing information of high value are:

- Use of continuous monitoring.
- Long term stable isotope monitoring.
- Long term monitoring of the most important analytes (ion balance).

These methods shall be applied wherever technically and as soon as possible. Other technologies are important, as well, but more expensive and shall be applied as part of a well-defined questionnaire.

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Multi-Parametric Devices with Innovative Solid Electrodes for Long-Term Monitoring of pH and Redox-Potential of the actual pore water of COx formation in a future Nuclear Waste Repository

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1. Summary

We present innovative electrochemical probes for the monitoring of pH and redox potential in pore water in near-field rocks of a future deep geological radioactive waste repository at 500 m depth within the clayey Callovian-Oxfordian (COx) formation. The conceived experimental set-up assembles two multi-parameter probes (MPPs), used together throughout two series of several months duration measurements *in situ* into the underground research laboratory of Andra at Bure, France. The two MPPs, connected in series, were up-flow fed with actual pore water of COx formation during several with a very low flowrate. Each MPP is composed of different individual probes containing the following: two monocrystalline antimony electrodes for pH sensing; eight AgCl/Ag-based reference or Cl^- selective electrodes; four Ag_2S/Ag-based reference or S^{2-} selective electrodes; eight platinum electrodes; two gold electrodes; two glassy-carbon electrodes; two ruthenium and two inox 316 electrodes, for redox potential measurements. The Open Circuit Potential (OCP) measurements of the developed sensors under different conditions and in quasi-actual conditions were compared to conventional reference electrode and pH electrodes in terms of performance, reliability and robustness and allowed to create calibration curves. Conductivity measurements, carried out along MPPs, will not be presented here. Overall, the conceived bundle of electrodes as designed works reliably during a timescale that is promising for monitoring the COx formation during its envisaged use for hosting a nuclear waste repository.

2. Introduction

2.1. Context

Near-neutral pH and low redox potential (Eh) are considered to be favourable conditions for nuclear waste disposal in clay formations, because most radionuclides, including actinides, have a low solubility under such conditions [1]. Radioactive waste-management programmes today mainly focus on deep geological storage, as this is currently the most appropriate strategy for ensuring the long-term safety of people and environment. “Cigeo” is the name of a future deep geological disposal facility for high-level and intermediate-level long-lived radioactive waste, to be built in France, at

500 m depth within the clayey COx formation. The COx formation is a 130 m thick clay-rich rock, dating back to 160 million years ago and lying at a depth of 400 to 600 m. It is a water-saturated environment with extremely low permeability, porosity and hydraulic conductivity. The temperature, pH and CO_2 partial pressure of the COx pore-water solution are constant at 21-22 °C, 7.2 (±0.2) and 8.10^{-3} atm, respectively. Anoxic conditions prevail in the COx formation. Within the mineralogical assemblage [2], geochemical models predict Eh values ranging from -180 to -200 mV, corresponding to an equilibrium between pyrite and pore-water sulphate [S(+VI)] concentrations, and iron-bearing phases such as Fe-bearing carbonates or nanogoethite [3–5].

2.2. Objectives

pH and redox potential are thus key parameters for monitoring the evolution of pore water in the above COx formation [6]. The objective was to choose the appropriate materiel for electrodes and to design, create and optimize a robust multi-parameter probe for reliable on-site monitoring of pH (±1 pH unit) and redox potential (±100 mV) in order to ensure the long-term safety of the operation.

3. Materials and methods

To achieve our objective, various types of electrodes made of different sensitive solid materials were studied and the electrochemical measurements (mainly OCP) of the developed sensors under quasi-actual conditions were examined in terms of performance, reliability and robustness. Each MPP is composed of different individual probes containing the following: two monocrystalline antimony electrodes for pH sensing; eight AgCl/Ag-based reference or Cl^- selective electrodes; four Ag_2S/Ag-based reference or S^{2-} selective electrodes; eight platinum electrodes; two gold electrodes; two glassy-carbon electrodes; two ruthenium and two inox 316 electrodes, for redox potential measurements. Several among these electrodes will be used for conductivity measurements, carried out along MPPs, but the results will not be presented here. We built up an innovative multi-parameter probe device, carrying up to 20 electrodes for such long-term monitoring, directly placed at 490 m depth into a gallery the Meuse/Haute Marne Underground Research Laboratory (URL) of Andra at Bure, France. The conceived experimental set-up assembles two multi- MPPs, connected in series, which receive the seepage water extracted from the borehole EPT1201. Preserved from air contact, the water feeds up the two MPPs during several months, with a low flowrate of 1-2 mL/h. The MPPs were down fed to avoid bubble formation and thus two-phase flow. Two series of measurements were carried out, which both lasted several months. The difference between the two series resides in the progressive appearance or not, of highly sulphate-reductive conditions in the water passed through the MPPs. In the case of progressive arrival of highly sulphate-reductive conditions, the reason for sulphide production is the organic content of conventional pH electrodes used for comparison with the monocrystalline antimony Sb_2O_3/Sb electrode. These two series were rich in results, and they allow the comparative electrochemical behaviour of all the electrodes (the OCP of solid electrodes versus reference electrodes) for pH and redox potential, during several months of immersion, as well as in the absence and the presence of hydrogen sulphide (H_2S, HS^-, S^{2-}).

4. Results and discussion

In the absence of sulphide, all the electrodes behave (left part of Fig. 1A) as predicted by the calibration lines obtained in glovebox (GB) conditions in laboratory [6]. The calibration lines for Sb_2O_3/Sb electrode allowed the conversion and monitoring of pH as presented in Fig. 1B, where the pH measurements are coherent with those obtained by a pH conventional electrode over 8 months duration. **The calibration lines in the presence of sulphide,** obtained also in glovebox conditions in laboratory [6] from OCP measurements of all the electrodes (see Fig. 1C for Sb_2O_3/Sb electrode), enable us to deduce the pH under these *in situ* conditions.

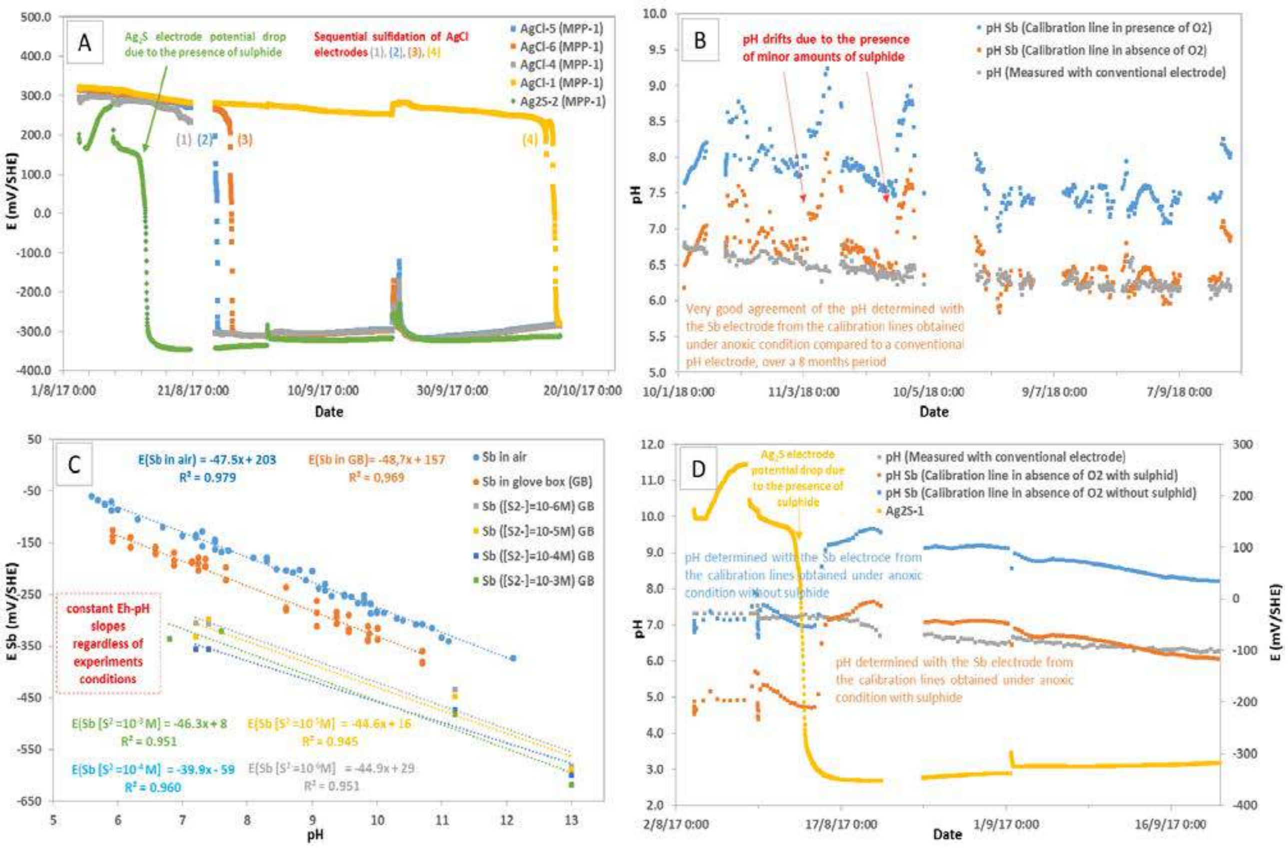

Figure 1: A: OCP of four AgCl/Ag and one Ag2S/Ag electrodes versus time during exposition in situ, with progressive sulphidisation of water. B: pH versus time from conventional pH electrode and from Sb2O3/Sb electrode using calibration curves obtained in glovebox (GB) conditions (absence and presence of O2). C: Calibration curves (OCP of Sb2O3/Sb electrode versus pH from conventional pH electrode) obtained in glovebox (GB) conditions using various sulphide concentrations. D: pH versus time from conventional pH electrode and from Sb2O3/Sb electrode using calibration curves obtained in glovebox conditions (absence of O2 and presence of sulphide); and simultaneous OCP monitoring of Ag2S/Ag electrode versus time.

The OCP of Ag_2S/Ag electrode, initially close to those of AgCl/Ag, detects the progressive appearance of sulphide in the pore water passed through the MPPs, as its potential progressively decrease and stabilise approximatively at the value of -350 mV versus AgCl/Ag conventional reference electrode (Fig 1A). In addition, all the four AgCl/Ag electrodes (Fig 1A), progressively behave as Ag_2S/Ag electrodes as their surface was covered by a thin layer of Ag_2S. The progressive replacement of the Cl^- in the surface of AgCl/Ag electrodes by S^{2-}, according to the reaction AgCl↓ + S^{2-} → Cl^-+Ag_2S↓, is one of the reasons why the AgCl/Ag electrodes, progressively became

Ag_2S/Ag electrodes. The speed of this conversion is governed by the preparation conditions of solid AgCl/Ag electrodes (see Fig. 1A right, the last converted AgCl/Ag electrode in yellow).
Figure 1D presents the pH measured by Sb_2O_3/Sb electrode by using calibration curves obtained in GB conditions without sulphide. These measurements are coherent with the pH measured by the conventional electrode, as long as there is no sulphide. Once the presence of sulphide underlined with the Ag_2S/Ag electrode (Fig. 1D yellow curve), one sees that the pH isn't coherent anymore with the pH measured by the conventional pH electrode. This is the reason why further calibration lines were established at the laboratory (see Fig. 1C) to characterize the behavior of Sb_2O_3/Sb electrode according to the pH, in the presence of various sulphide concentrations. Figure 1C illustrates that the sensitivity of Sb_2O_3/Sb electrode is constant and does not depend on the conditions of the medium such as the presence/absence of O_2 or the presence of sulphide. On the other hand, these parameters have an influence on the standard potential. Thus, by using the calibration lines in the presence of sulphide presented in Figure 1C, the pH measured by the Sb_2O_3/Sb electrode is coherent with the one measured by the conventional pH electrode (Figure 1D).

5. Conclusion

Innovative electrochemical probes for the monitoring of pH and Eh have been implemented on site and allowed two series of measurements to be made on the seepage water extracted from a borehole in the COx clay-rich rock. Overall, the conceived bundle of electrodes, as designed, worked reliably during a timescale that is promising for monitoring the evolution of the pore water composition in the COx formation during its envisaged use for hosting a nuclear waste repository. Further work is ongoing to develop calibration lines for a more accurate calibration of some new probes. Experiments, for estimating corrosion rates of the new electrode materials in reconstituted COx solution are planned. After these developments, it could be possible to envisage their use during the operational period of Cigeo, on the decade timescale.

Acknowledgements

This work was funded by a BRGM-Andra partnership (CAPTANDRA project, 2016–2018).

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3D Overarching Scientific Information System for the FE experiment

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1. Summary

Comprehensive monitoring programs include numerous sensors using both standard fixed point "static" sensors and newer technology sensors such as fiber-optic distributed temperature sensing (DTS). Management and overview of the hardware, installation, operation and monitoring becomes challenging in larger experiments. Monitoring often continues for years and measurements can be recorded frequently. Over time, billions of measurements can be recorded making the data processing for review, evaluation and analysis both labour intensive and time consuming.

Nagra implemented the Full-Scale Emplacement (FE) experiment at the Mont Terri rock laboratory to demonstrate as realistically as possible the construction, waste emplacement and backfilling processes for a spent fuel / high level waste disposal tunnel according to the Swiss repository concept at a 1:1 scale. The FE experiment is a long-term heating experiment currently 4 years in operation and monitoring is foreseen for more than 10 years.

With more than 1 million measurements recorded each day the FE experiment data quickly overwhelmed standard desktop software. We developed the OASIS – Overarching Scientific Information System to manage all the FE information (construction details, monitoring data, geophysical logs, chemistry data and documentation). The system consists of a high-speed client server database and web app that runs on any computer with a modern internet browser. Review, evaluation, plotting, reporting and data export are fast even with the nearly 2 billion measurements recorded to date. Nagra refers to the OASIS system for the FE experiment as the FE Information System (FEIS).

The DTS system records measurements related to a fiber optic cable length. FEIS calculates the physical 3D position of the measurements along the cable within the FE experiment on-the-fly at run time. Temperature measurement accuracy from the DTS system was greatly improved by deriving values using the DTS raw Raman backscatter measurements (Stokes and anti-Stokes) with coefficients determined using a comprehensive calibration system.

Centralizing the project information promotes transparency, consistency and accountability. Relating data together allows investigators to correct inconsistencies so more spatially and temporally accurate information are available. The system also improves findability, accessibility, interpretability, and reuse of the digital assets. Archives of the database and monitoring system data files collected by the data-pipeline are automatically produced, improving long-term care of the valuable digital assets. Relating data together within the database is a benefit to the experiment. The web browse app allows password-controlled access to the project data and documentation for all stakeholders.

2. Introduction

Large scale experiments in underground rock laboratories, e.g. experiments on coupled thermal-hydraulic-mechanic processes, include comprehensive monitoring programs with many sensors using both standard fixed point "static" and newer technology sensors such as fiber-optic distributed temperature sensing (DTS) for temperature measurements and time-domain reflectometry (TDR) for water content measurements. Management and overview of the hardware, installation, operation and monitoring becomes challenging in larger experiments. Monitoring often continues for years and measurements can be recorded frequently. Over time, billions of measurements can be recorded making review, evaluation and analysis of the data challenging and time consuming.

The Full-Scale Emplacement (FE) experiment at the Mont Terri rock laboratory [1] was implemented to demonstrate as realistically as possible the construction, waste emplacement and backfilling processes for a spent fuel / high level waste disposal tunnel according to the Swiss repository concept at a 1:1 scale (Fig. 1). Three electrical heaters were installed on bentonite blocks in the tunnel to simulate the heat output of nuclear waste canisters. After installation the tunnel was backfilled with granulated bentonite material. The 2.7m (diameter inside shotcrete) x 50m tunnel and surrounding rock (Opalinus Clay) are instrumented with more than 1800 static sensors, 2.4 km of fiber optic cables for DTS, TDR sensors and monitored boreholes. The sensors are distributed in boreholes, in the tunnel lining, in the bentonite buffer surrounding the three electrical heaters as well as in and on the heaters themselves.

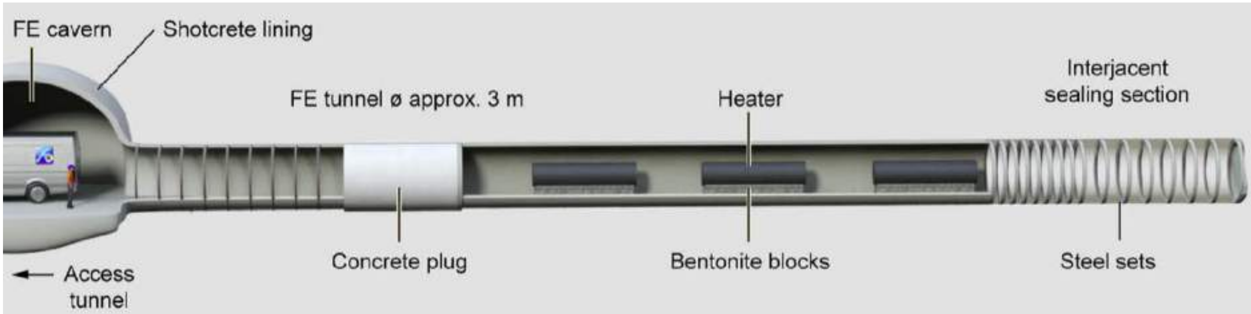

Figure 1: Visualisation of the general layout of the FE experiment and the 50 m long FE tunnel at the Mont Terri Rock Laboratory; sensors, bentonite backfill and rock bolts are not shown. Figure taken from [1].

The FE experiment is a long-term heating experiment currently 4 years in operation and monitoring is foreseen for more than 10 years. Long-term monitoring of boreholes started in 2011 and long-term monitoring of the complete experiment started in 2014. The heating phase of the FE experiment was initiated at the end of 2014. The measurement intervals of the different sensors vary between every 5 mins to every 4 hours. In addition, manual measurements and chemical analyses are periodically made.

The more than 1 million measurements recorded each day at the FE experiment quickly overwhelmed standard desktop software. We developed the OASIS – Overarching Scientific Information System to manage all the FE information (construction details, monitoring data, geophysical logs, chemistry data and documentation). The system consists of a high-speed client server database and web app that runs on computer with a modern internet browser. Review, evaluation, plotting, reporting and data export are fast even with the nearly 2 billion measurements recorded to date. The OASIS system is called the FE Information System (FEIS) in the FE experiment [2].

3. FEIS design

FEIS joins data sets from across different data acquisition systems allowing access to the data from all monitoring platforms. The system is “overarching” because it centralizes all information (data and documents) in one location.

FEIS consists of 3 main components:

1) Data-pipeline: Transforms the raw data coming into actionable and meaningful information. Automatically collects monitoring data from multiple contractors with different file formats and recording rates. Verifies and evaluates the data, assigns rich meta-data to the measurements, sends alarms when measurements exceed limits or go missing and makes the data available just minutes after being collected.

2) Database: Open source object relational PostgreSQL database with PostGIS and statistical R language extensions. The database extends GIS by modeling the project in 3D space. The statistical R language extension allows high-level statistical analyses to be done directly within the database. The database also includes a document content management system with complex and complete document search functionality, with keyword and full text searches that are independent of grammatical structure.

3) Web browser app: Charts and tables are fast, dynamic and interactive. Plots can be zoomed and scrolled, tables searched and sorted. Charts, tables and even drawings are created dynamically on-the-fly so any change in the project is immediately seen when the web page is refreshed.

FEIS represents the FE experiment in a virtual 3D space (Fig. 2) using custom spatial operators developed with the power of advanced PostgreSQL features such as operator overloading (these operations cannot be done so easily in other databases). The database uses geometric objects and custom linear algebra operators to work with the data and calculate spatial relationships between objects. Users can easily change between 2 sets of local coordinates (gallery meter, FE coordinates) and the official Swiss grid because the database translates coordinate systems. These features separate FEIS from conventional Graphical Information System (GIS) database systems which are primarily based on 2D mapped data.

Determining spatial relationships using a standard information database would involve complex mathematics and complex database queries. The project 3D model with custom spatial operators allow simple database queries which help to avoid errors. There is no need to store information like “sensor A is in borehole B” in FEIS. Instead FEIS simply calculates that sensor A is within borehole B. This makes FEIS very dynamic. When there is a change in the project (for example a sensor is moved) only the sensor coordinates need to be updated. FEIS calculates all spatial relationships at run time (on the fly). As a result, calculations, table data, plots and even drawings are automatically updated.

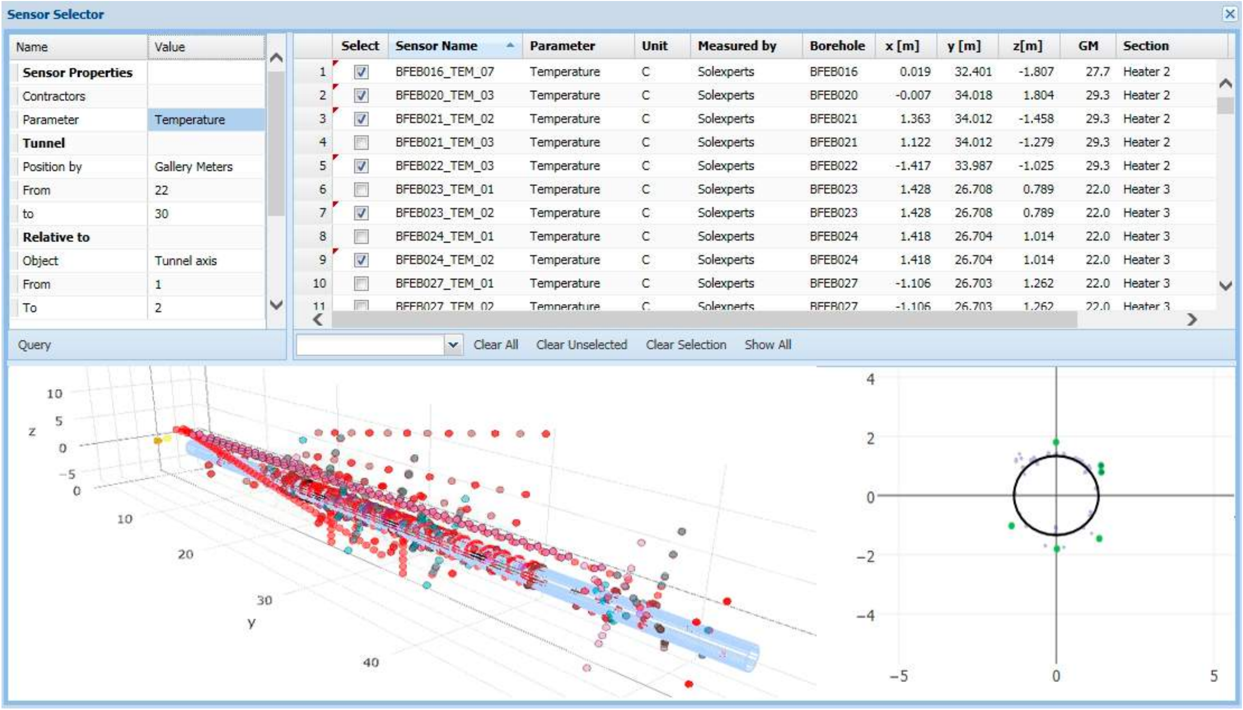

Figure 2: Sensor selection window showing spatial and non-spatial selection fields with a sensor selection table with sortable columns.

The web browser app is a single page Internet browser application providing easy, fast and efficient review, analysis and reporting. It runs in any modern internet browser. Manual measurements can be entered, chemical analysis spreadsheets uploaded and users can define mathematical expressions (calculations, functions and statistics) using sensor measurements as variables. Data are associated with rich meta-data making it easy to plot, report and calculate with only representative data. No data is deleted – the meta-data are simply marked as not valid. If the data are later determined to be representative then their meta-data is changed.

4. Data management with increased quality

Centralizing the project information promotes transparency, consistency and accountability. Problems of multiple versions, out-of-date documentation and data, inconsistent nomenclature, difficult to find documentation, etc. are significantly reduced.

Discrepancies in construction, nomenclature and monitoring details can easily be overlooked when data are stored in spreadsheets or multiple reports. Data quality can be difficult to evaluate. Relating data together allows investigators to correct inconsistencies so more spatially and temporally accurate information are available.

Spatially relating the 3D position of sensors, boreholes and other project components together corrects errors in survey coordinates easily missed by reviewing rows of coordinate values. The database brings structure and consistency to the project and normalizes monitoring and testing activities, which results in improved data management and stewardship. The system also improves findability, accessibility, interpretability, and reuse of the digital assets. Archives of the database and monitoring system data files collected by the data-pipeline are automatically produced, improving long-term care of the project's valuable digital assets. Relating data together is a benefit to the experiment. The web browser app allows password-controlled access to the project data documentation for all stakeholders.

5. 3D model and DTS measurements

The FE experiment's comprehensive monitoring program includes innovative DTS technologies. The DTS method provides a continuous temperature profile along several fiber optic cables that are routed in boreholes and along and round the tunnel wall. DTS has the advantage in long-term monitoring over conventional electrical "point-type" temperature because the temperature sensing involves only glass fiber and not delicate electronics. The DTS measurement unit (containing a laser and detection electronics) is outside of the sealed tunnel and can easily be replaced in case of defect.

The DTS system records measurements related to a fiber optic cable length. Using a process referred to as fingerprinting (heating the cable locally at know locations and noting the measured cable lengths where the responses are observed) the relationship between the DTS system cable length measurements and FE experiment coordinate system are determined.

FEIS calculates the physical 3D position within the FE experiment on-the-fly at run time using the project 3D model, custom spatial operators and the cable fingerprints. A large volume of DTS data is produced because several measurements are performed per day with sampling data recorded at intervals 0.05 – 1.0 m. FEIS stores the measurements in advanced data structures making it possible to report the DTS measurements with charts and tables within seconds.

FEIS reports the DTS measurements from three perspectives: as a profile showing temperatures within the tunnel at a given time; as a time-series showing the change in temperatures at a given point over-time; or as temperatures along the cable at a given time. Being able to view the DTS measurements from all three perspectives results in unique, detailed insights into the temporal and spatial variations of the temperature field in and around the heated FE tunnel.

The DTS measurements can be shown in FEIS as a 2D thermal map as well as a 3D thermal map spatially oriented around a cylinder representing the FE tunnel. Figure 3, below, shows a more detailed prototype 3D view of the experiment with a semi-transparent thermal map wrapped around the tunnel and static temperature sensors. Because the drawing is created by the database system the drawing is dynamically updated when data change.

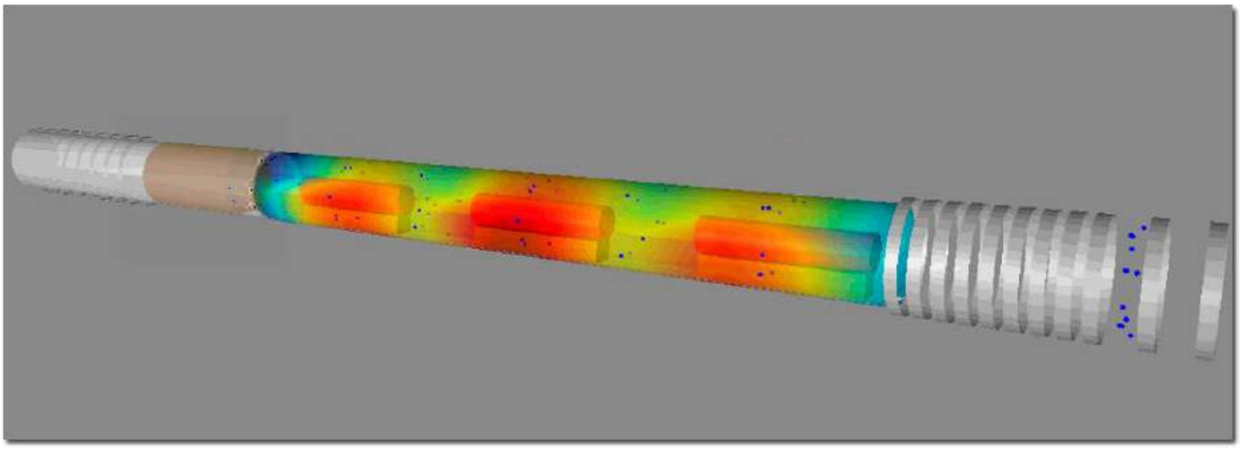

Figure 3. FEIS generated spatially correct 3D drawing of the FE tunnel with a semi-transparent thermal map and static temperature sensors (blue dots).

6. Improved DTS accuracy

Temperature measurement accuracies from DTS system were greatly improved by deriving values using the DTS raw Raman backscatter measurements (Stokes and anti-Stokes) with coefficients determined using a comprehensive calibration system. Two water baths covering the expected experiment temperature range were permanently installed near the FE tunnel and the fiber optic cables were routed through the baths. Conventional high precision temperature sensors automatically measure bath temperatures and the acquired data are collected and appended to FEIS by the FE data-pipeline allowing for calibration of the DTS system [3].

The location of step losses (abrupt decreases in light signal strength along each cable due to cable damage, splices or sharp cable bends) were determined using optical time domain reflectometry (OTDR). FEIS compensates the raw DTS measurements for step losses and determines bath temperatures corresponding to the time of each DTS measurement. Then, with the equations described by [4], FEIS calculates “dynamic” calibration coefficients for each cable measurement using the raw DTS measurements taken along the cable segments within the baths and the bath temperatures.

FEIS calculates temperatures on-the-fly using the raw DTS measurements and the dynamic coefficients each time the users request the data. The system is dynamic – if a new equation is used or parameters are changed then the temperature values are simply recalculated the next time the data are requested. The calculated temperatures are traceable because all parameters used to derive the values are stored with the measurement in the database. The process is based on optimized SQL procedures and is extremely fast. The resulting temperatures have an average measurement accuracy of 0.1 - 0.3°C depending on fiber optic cable type and DTS unit, Fig 4.

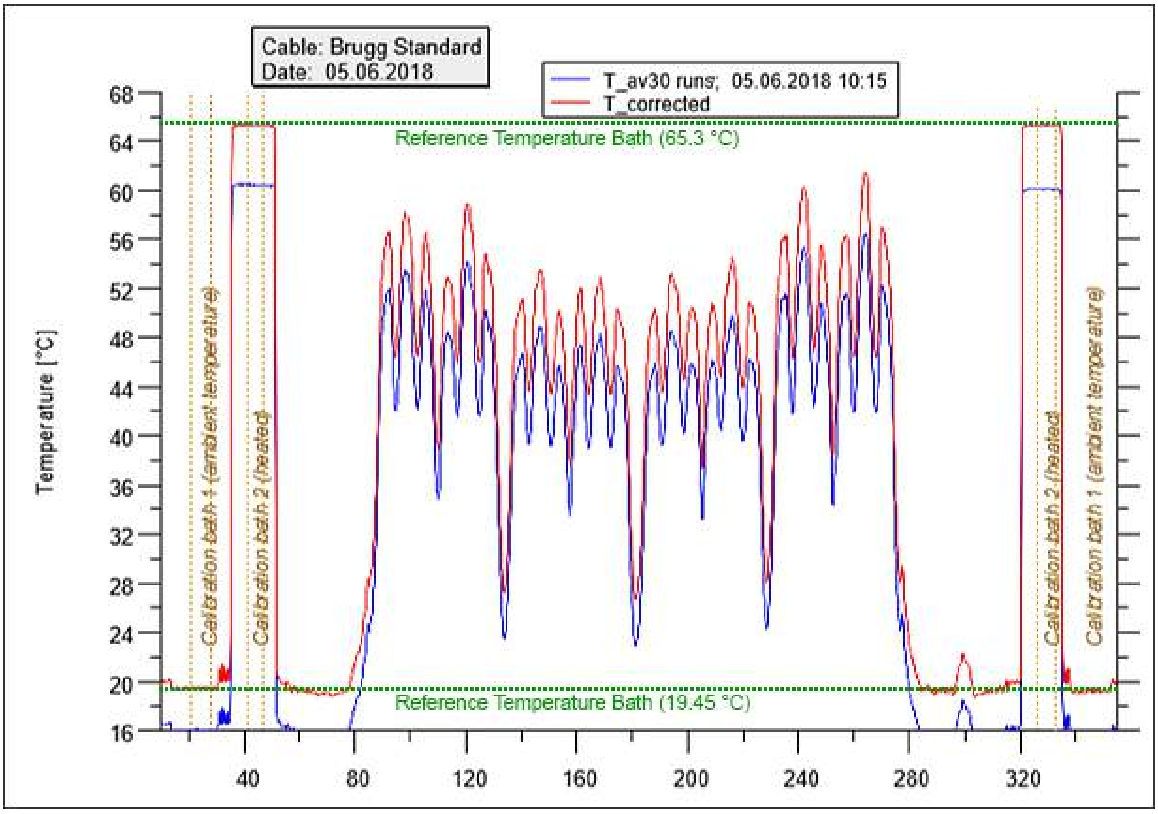

Figure 4. DTS temperatures vs temperatures derived from the DTS raw Raman backscatter measurements (Stokes and anti-Stokes) with dynamic coefficients.

7. Conclusion

Monitoring the FE experiment with more than 1 million measurements recorded daily led to the development of OASIS – Overarching Scientific Information System to manage all the FE information (construction details, monitoring data, geophysical logs, chemistry data and documentation). The FE experiment refers to the OASIS system as the FE Information System (FEIS). FEIS provides fast review, evaluation, plotting, reporting and data export, even with the nearly 2 billion measurements recorded to date.

FEIS represents the FE experiment in a virtual 3D space extending the system beyond conventional Graphical Information System (GIS) database systems which are primarily based on 2D mapped data. The DTS system records measurements related to a fiber optic cable length. FEIS calculates the physical 3D position on the measurements along the cable within the FE experiment on-the-fly at run time. Temperature measurement accuracies from DTS system were greatly improved by deriving values using the DTS raw Raman backscatter measurements (Stokes and anti-Stokes) with coefficients determined using a comprehensive calibration system.

Centralizing the project information promotes transparency, consistency and accountability. Relating data together allows investigators to correct inconsistencies so more spatially and temporally accurate information are available. The system improves findability, accessibility, interpretability, and reuse of the digital assets. Relating data together within the database is a benefit for the experiment. The web browser app allows password-controlled access to the project data and documentation for all stakeholders.

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Appendix E. Short Abstracts – Poster Presentations

E.a – Session on Monitoring Technologies

Distributed pore pressure monitoring with a DOFS-system – Prototype test

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Abstract

Distributed Pore Pressure (DPP) monitoring will provide a powerful opportunity and solution to the monitoring scheme of deep geological disposal facilities (GDF). This project was promoted by Nagra and Neubrex since 2016 and comes to the stage of field tests.

The prototype of DPP is based on the distributed FO sensing (DFOS) technology. In the first stage with laboratory tests a pore pressure sensing system was developed and successfully tested achieving all target requests. As part of the system the newly developed instrument reached stability and precision of laser frequency control good enough for a pressure level less than 1 psi.

In the second stage the industrial production of DPP cable is completed for 0.5 km length, which consists out of a holed spiral FIMT with embedded so-called pressure isolation blocks (PIB). The PIB's are responsible for the separation of the different measurement section along the cable to provide the specific point measurements along the cable.

Further laboratory evaluation results will be reported, and a description of the whole measurement system ready for the field test will be given.

Polymer optical fibre Bragg gratings for nuclear waste repositories

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Abstract

Polymer fibres have been present for a similar length of time as silica fibres, though the more favourable attenuation of silica fibre led to greater attention being focused upon the former and not the latter. Since the demonstration of the first polymer optical fibre Bragg grating (POFBG), the interest in and uptake of polymer fibre has steadily increased along the entire fabrication, inscription and implementation supply chain. While silica offers low loss and sensitivity, polymer offers entire step changes in the level of sensitivity to given measurands. While long distance polymer optical fibres have been largely abandoned, sensors in polymer fibre are seeing increasing use. Using silica fibres to cover connection distances allows low transmission losses and a more sensitive FBG in a short length of polymer fibre at the detection location. Polymer fibres have been shown to deliver higher sensitivity to strain, temperature, pressure and refractive index change. While silica based sensors will remain more advantageous for some applications such as high temperature sensing, polymers have already found applications in an ever growing number of domains. These domains are becoming increasingly complex, as polymer fibres become more robust and stable, permitting researchers to move past fundamental measures such as strain and temperature.

An inscribed FBG is a periodic modulation of the refractive index of the fibre core. This modulation produces a stop band in the transmission spectrum around a central wavelength, known as the Bragg wavelength. FBG sensing is typically done in a reflection configuration, where the grating produces a pass band around the Bragg wavelength, whose shape and power depend upon the characteristics of the grating inscription parameters. The Bragg wavelength will undergo a positive or negative change in wavelength dependent on the parameter and the fibre type. All FBG changes originate in the properties of the fibre that contains them, offering a variety of results with careful fibre selection and even accurate compensation of unwanted variables. For instance, the negative thermo-optic coefficients of polymer fibres allow interesting contrast to silica fibres, where strain and temperature detection in silica fibre can be isolated effectively using a polymer reference line.

The need for sensors capable of accurate and reliable operation under continual radiation spans multiple sectors of industry. Radiation parameters significantly vary between these applications, leading to a range of techniques and sensing modalities that are best optimised for each environment, delivering reliable performance and an appropriate level of radiation hardness. Many optical fibre sensors for radiative environments have been developed for applications such as dosimetry and temperature sensing. Distributed sensing using FBGs under radiative conditions has been studied for applications such as radioactive waste disposal monitoring, where it is important to maintain sensor capabilities while mitigating the impact of the ambient gamma radiation. The effect of gamma radiation on silica fibres is well documented, where the degradation of colour centres within the fibre causes a marked increase in optical attenuation. Polymer optical fibres (POF) are an alternative that have only recently been under consideration for these applications. In radiative environments, polymer fibres need extensive research to demonstrate their performance, especially with FBGs under said conditions.

This work analyses polymer fibre Bragg gratings under gamma radiation with the intention of bringing their unique attributes to the monitoring of radioactive waste repositories. Tests were conducted at SCK•CEN using the RITA irradiator over a two-week period, with online measurements conducted. We present the resultant profile changes and draw conclusions as to the sensitivity of said fibres with respect to silica, along with expectations of sensor life span within a repository context. Our work is the first examination of these details for polymer fibre Bragg gratings, examining the problem from the perspective of a practical study. A preliminary results set is under examination and the current progress shown in the below figure.

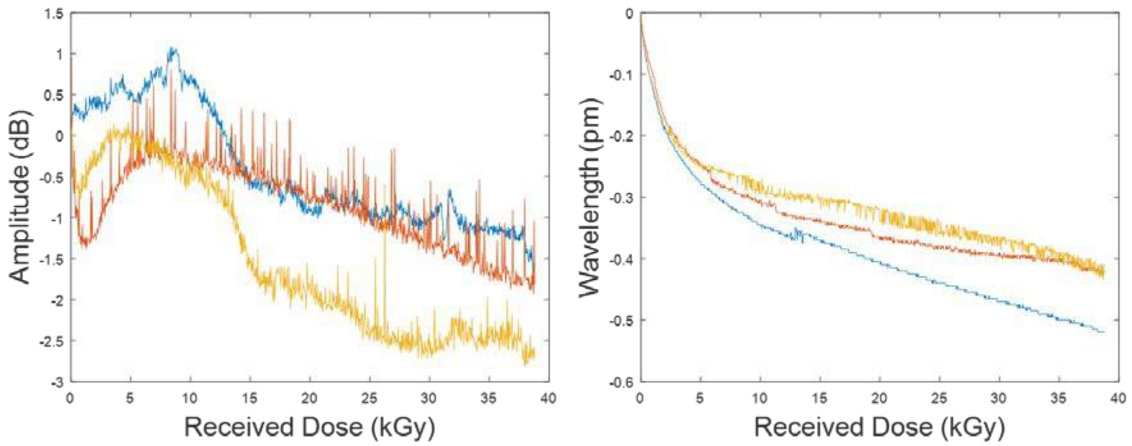

Figure 1: Femtosecond inscribed FBGs within PMMA mPOF fibres under gamma radiation. Amplitude response (L) and Bragg wavelength response (R).

Proposed Project SealWasteSafe: Materials Technology, Quality Assurance and Monitoring Techniques for Safe Sealing Systems in Underground Repositories

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Abstract

The proposed BAM project SealWasteSafe will advance the state of the art for the construction and monitoring of safe sealing systems for underground repositories of radioactive or toxic waste. During this project, a novel salt concrete exhibiting neither significant cracking nor shrinkage will be optimized for use in the sealing systems. The composition of this material will be based on alkali-activated materials, which are characterized by particularly small thermal deformations during the hardening reaction. Quality assurance and continuous monitoring systems developed during this project will be demonstrated not only for high reliability, but also for resistance to highly alkaline environments and to water intrusion along cables or at sensor locations. A variety of sensors will be used in combination with wireless Radio Frequency Identification (RFID) technology to record moisture, temperature, and, if necessary, corrosion activity within the sealing system. Distributed Fibre Optic Sensor (FOS) technology will also be used for strain, temperature, and moisture content measurement. Ultrasound-based measuring methods will be utilized for the detection of cracks and delaminations. Additionally, digital image correlation and acoustic emission analysis will be used for deformation measurements and crack detection. A novel borehole probe and advanced ultrasound imaging techniques will be further developed to track cracks and delaminations within the host rock in 3D. The surface-based Large Aperture Ultrasound System (LAUS) will also be utilized to detect cracks and delaminations deep below the exterior surface of the sealing system. Although the focus of this project will be on the host rock salt, the resulting technologies will be intentionally developed in a way that facilitates their adaptation to other host rocks.

E.b – Session on Post Closure Safety Cases and Monitoring Strategies

Monitoring Concept Development for a HLW Repository in Germany in Close Relation to the Safety Case

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Abstract

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. It underpins the technical safety strategy and quality of the engineering, and can be an important tool for contributing to public understanding of and confidence in repository behaviour.

In that sense, as part of the MODERN2020 project, a monitoring concept has been developed for a high-level waste repository in a clay formation in Germany. This concept development is based on both, the (inter-)national guidelines and German regulatory framework on the one hand and the recent outcomes of the MODERN and MODERN2020 projects on the other hand.

This presentation briefly describes the philosophy of developing a monitoring programme in close relation to the safety case. The monitoring concept is related to the German ANSICHT project within which, as part of the safety case, a safety assessment concept has been developed. Recognizing that the work focus in MODERN2020 is set to the engineered barrier system (EBS), the monitoring concept development is explained and illustrated using specific seals as an example.

Starting with the safety case and its corresponding sealing concept, the way of how to come to a monitoring concept is given, making explicitly use of the new developed *MODERN2020 Screening Methodology*. Safety function and performance targets are given and it is explained how monitoring may help evaluating the achievability of the performance targets. Finally, an illustrating overview of the monitoring concept, which is developed not as a rigid but as a so-called "learning concept", is presented.

Anomaly detection algorithms as a support for the geophysical monitoring of high-level radioactive waste repositories

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Abstract

The presented algorithm focuses to the fast processing of the data obtained by the non-invasive geophysical monitoring of the deep geological repository. The robust inverse techniques such as geophysical tomography often require extensive data analyses and substantial computer resources to give the full model of the monitored area. Therefore we proposed an additional data processing tool.

The anomaly detection algorithm is based on image processing and classification techniques with supervised learning. In the case of the repository monitoring, the computer vision or machine learning techniques can be applied to detect significant abnormal structures in the acquired data. The physical conditions in the repository such as water saturation or temperature should either remain unchanged or they should change in a known manner. Atypical changes in the acquired data stream may alarm a problem in the repository – for example the surrounding barrier may be corrupted and safety of the repository can be endangered.

The main purpose of our algorithm is to be a supplementary method for the full waveform inversion of the seismic data with ability to automatically extract temporal changes in the data and with the ability to propose an explanation why the data may have changed. Such a detection can never replace any of full waveform inversion techniques, but it may be useful during the repository monitoring to set the alarm when the reservoir condition is modified and to help to find the origin of the problem.

The repository itself is strictly defined – it is a structure with defined and well known geometry, with the stable quasi-homogeneous surrounding. This fact can be very helpful for the supervised learning – the normal operating conditions can be sampled and used as the initial training data set. The synthetic data used in our experiment were created with 11 selected levels of water saturation in the area (from 0 to 100 %). The abnormal configuration which is to be detected is low water saturation.

The heart of the algorithm is the pre-trained classifier, which is able to distinguish the predefined normal and abnormal repository configurations. The original input seismic data are normalized, thresholded and converted into sets of black and white images. In the next step the set of the images is converted into a feature vector used as the input of the classifier. The feature vector combines the information describing the typical shapes detected in the image. The data are classified as “dry” or “wet”, according to the selected level of water saturation.

The paper presents both the algorithm structure and training methodology as well as the results obtained with the synthetic and field data.
The pre-processing algorithm was developed using the MATLAB environment, which was also used to test and select the most suitable classifier structure. The final implementation of the selected classifiers is done in Python with the support of Scikit-Learn a XGBoost. All the work was covered by the Modern2020 project.

E.c – Session on Decision making and response planning

Learning from other cases for nuclear waste siting: comparing nuclear and hazardous waste in terms of regulation and public perception

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Abstract

The political, societal, and regulatory processes of waste management differ for different waste types. Nuclear and hazardous waste is dealt with fairly differently in many countries. The question may arise if one can learn from one process for another. For instance, in countries such as Switzerland or the USA, the disposal of nuclear waste has received immense attention, whereas the case for hazardous waste is less obvious. Since the social perception of different waste systems is an important factor as it also influences public discourse, we conducted a two part study in Switzerland comparing nuclear and hazardous waste in terms of both regulation and public perception.

As shown in the present study, there is a partial discrepancy between the technical analysis of both types of waste and their perception by the survey participants. According to technical perspectives, hazardous waste compared to radioactive waste is more difficult to assess in terms of long-term storage, risk assessment, storage conception, regulation of stakeholders and procedures. Nonetheless, radioactive waste is perceived by the survey participants as more negative, more dangerous, less controllable and more persistent. These concerns are relevant for any plan to monitor – be it the disposal processes or the post closure phase.

Considering the mistakes made in the past dealing with both nuclear and hazardous waste, learning processes should be visible for both types of waste. A clear regulation of the requirements and the responsibilities of the stakeholders is crucial, also for hazardous waste. At least for Switzerland, this is less the case than with radioactive waste. As the technical investigation of the two waste systems has shown, there is actually a need for follow-up in process and process questions, especially in the case of hazardous waste.

One can ask, whether the current special treatment of the radioactive waste case in Switzerland is appropriate. Then, it could serve as a model for dealing with hazardous waste. Or, is it rather a comparatively generous approach to the process for a nuclear storage? Then, one could probably learn from the less clearly regulated hazardous waste case.

In addition, the question arises whether the population's high sensitivity to radioactive waste has led to a different, more explicit and comprehensive scientific and political debate with them. Then the public discourse would still have to do this for hazardous waste. However, some facts complicate establishing such a discourse. Given the number and heterogeneity and power of involved actors and the different origins and composition of hazardous waste, it seems difficult to form a generally valid process. The initial situation is more complex than with radioactive waste. The question, therefore, is how and whether it is at all possible to plan hazardous waste repositories (or landfills) by analogy to the radioactive waste siting process. This would require social pressure, political framework

conditions and an economic concept. A start could be made on adequate information on hazardous waste. Public discourse could also link to the finding that study participants felt more responsible for hazardous waste than for nuclear waste. This could be a tie to personal responsibility for potentially toxic materials and substances in products.

Hence, one can conclude that it is more likely that learning goes the direction from nuclear waste to hazardous waste management, rather than the other way round.

E.d – Session on Long-term Integrated Monitoring Programmes

Long-term monitoring of the EDZ in the Callovo-Oxfordian Clay using 4-D numerical well analysis and hydraulic tomography approaches

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Abstract (1500 word)

The Meuse / Haute Marne Underground Research Laboratory (URL) provides the location for a long-term experiment designed to investigate the induced fracture network around open or sealed drifts. The aim of this experiment, called the CDZ-experiment (Compression of the Damaged Zone), is to monitor the effects of mechanical loading and unloading on the mechanical and hydraulic properties of the EDZ (Excavation Damaged Zone). In the context of this experiment, a large number of hydraulic tests were performed between six closely spaced wells prior to and after the mechanical loading of the EDZ. The tests allow for the long-term monitoring and quantification of the effect of the mechanical loading on the hydraulic and mechanical properties of the EDZ.

The hydraulic tests were first analyzed using the numerical borehole simulator Multisim, which was developed by AF-Consult Switzerland Ltd. The borehole simulator Multisim is particularly suited for the analysis of hydraulic tests performed in low permeability media and allows for a rigorous uncertainty analysis, which comprises a residual analysis, estimation of joint confidence regions of the fitting parameters, a perturbation analysis to appraise the accuracy of the estimated fitting parameters, and a sampling analysis to quantify the influence of the non-fitted parameter.
In a second step, the cross-hole pressure responses of the hydraulic tests were analyzed with a travel time based tomographic approach. The inversion is based on the transformation of the transient groundwater flow equation into the eikonal equation using an asymptotic approach. The eikonal equation can be solved with ray tracing techniques or particle tracking methods, which allows the inversion of large data sets in a short time with relatively low computational effort (common PC). The main feature of this procedure is a travel time integral relating the square root of the peak travel time, assuming a Dirac point source at the origin, to the inverse square root of the hydraulic diffusivity.

The reconstructed three-dimensional hydraulic diffusivity distribution displays the different zones of the EDZ with a high level of detail and provides important information about the spatial distribution of hydraulic parameters within the EDZ. The comparison of the reconstructed tomograms with the results of the -borehole test analysis performed with Multisim shows a reasonable agreement. The time-lapse pressure tomography results describing the hydraulic tomographic results prior and after the mechanical loading allow for monitoring the change in hydraulic properties caused by mechanical loading with a spatial resolution not possible with conventional test analysis techniques. It could be shown that the long-term effect of the mechanical loading on the spatial distribution of the hydraulic properties is in good agreement with the predicted induced stress field.