Monitoring Developments for Safe Repository Operation and staged Closure – The International *MoDeRn* Project - 12040

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ABSTRACT

The main goal of the collaborative, European Commission 7th Framework MoDeRn project is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during the staged approach of the disposal process. To achieve this goal, 18 partners representing 12 countries and including 8 Waste Management Organizations joined their efforts since 2009, and aim at developing a reference framework for repository monitoring by 2013. Achieving this goal includes analysis of whether the implementation of a realistic monitoring programme is likely to address expert and lay stakeholder expectations (objectives), to provide an understanding of monitoring activities and available technologies that can be implemented in a repository context (feasibility), and to provide recommendations for related, future stakeholder engagement activities (social acceptance). Monitoring programs should describe activities likely to verify – with the aim of confirming and possibly enhancing the prior license basis for safety and pre-closure management options – expected repository system evolutions (i.e. natural environment and engineered system evolutions) during a progressive construction, operation and closure phase that may last on the order of a century.

INTRODUCTION

Spent nuclear fuel and long-lived radioactive waste must be contained and isolated for very long periods, and current schemes for its long-term management involve disposal in deep geological repositories. The successful implementation of a repository program for radioactive waste relies on both the technical aspects of a sound safety strategy and scientific and engineering excellence as well as on societal aspects such as stakeholder acceptance and confidence. Monitoring is considered key in serving both ends. It underpins the technical safety strategy and quality of the engineering, and can be an important tool for public communication, contributing to public understanding of and confidence in repository behavior.

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

This increased interest has translated into efforts within several national programs and through international cooperation to develop a better understanding of why, what and how to monitor. International cooperation is reported in the International Atomic Energy Agency (IAEA) Technical Document on monitoring of geological repositories [9] and by the European Commission (EC) within a Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste [10]. In addition, the IAEA has recently requested a review by Member States on its draft safety guide DS357 on Monitoring and Surveillance of Waste Disposal facilities [11]. A fairly comprehensive overview of the current developments on monitoring within individual national programs is provided in [12] and [13].

To further build upon these prior and parallel developments, the European Commission has decided to include the Topic *Strategies and technologies for repository monitoring* in its 7th Framework Program to request corresponding proposals. A Grant (Agreement n°232598) was awarded to the collaborative MoDeRn project, whose main goal is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during the staged approach of the disposal process.

18 partners representing 12 countries and including 8 Waste Management Organizations joined their efforts since 2009, and aim at developing a “roadmap to repository monitoring” by 2013, which addresses these issues. The partners represent organizations responsible for radioactive waste management in the EU, Switzerland, the US and Japan as well as organizations having relevant monitoring expertise. Other partners offer substantial experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organizations, industry) in highly technical issues.

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

The term *Monitoring* refers to a generic activity and the need is felt to provide a concise definition of what is referred to as *Monitoring* in the context of performance verification and confirmation. The overarching motivations for this activity are to enhance confidence of implementer, expert and lay stakeholders during construction, operation and closure of the repository, and to assist the decisions that must be taken during this stepwise disposal process. Project partners have thus decided to remain close to prior definitions as proposed in [9] and in [10], adding the reference to these overarching motivations:

> Monitoring refers to continuous or periodic observations and measurements of engineering, environmental, radiological or other parameters and indicators/characteristics, to help evaluate the behavior of components of the repository system, or the impacts of the repository and its operation on the environment - and thus to support decision making during the disposal process and to enhance confidence in the disposal process.

The project proposed to analyze whether the implementation of a realistic monitoring programme is likely to address expert and lay stakeholder expectations (objectives), to provide an understanding of monitoring activities and available technologies that can be implemented in a repository context (feasibility), and to provide recommendations for related, future stakeholder engagement activities (social acceptance). MoDeRn has progressed on both the associated *Process* issues – why to monitor, how to develop a program, and how to use monitoring results – and *Technology* issues – technical requirements and constraints, technology state-of-the-art, and focused R&D and *in situ* demonstrators.

Subsequent section develop how the project has addressed these questions, first addressing *Process* issues including understanding key factors likely to influence decisions on monitoring and special considerations of stakeholder expectations; and the development of a structured approach to develop and implement a monitoring program, with at its heart considerations of realistic technical feasibility. The approach is tested within the project by means of several *Case Studies*. All of the above are developed in greater detail in companion project papers on Monitoring technology, on the Case Studies and on the overarching socio-technical considerations that may provide the foundation for making monitoring a successful endeavour in enhancing stakeholder confidence.

Factors likely to influence decisions on monitoring

The project has taken the position that there are a variety of factors that influence the decisions each waste management organization will take with regards to monitoring. They are introduced here and are regarded as “boundary conditions” which condition such decisions on monitoring. Some of these “boundary conditions” are related to the general state of knowledge and commonality in practices, consistent with the recommendations, guidelines or requirements of international organizations such as the IAEA, OECD-NEA, or EC. Therefore, certain choices and approaches to monitoring will evidently be shared.

Nonetheless, national differences do exist, leading to differences in strategic, upstream decisions on repository monitoring and even more so after the development of a detailed monitoring program. These “boundary conditions” at the national level, we refer as a “National Monitoring Context”. Understanding these national contexts is important in order to provide a solid basis for further project developments on monitoring objectives and to develop an overall framework that works in different contexts.

To that purpose, initial emphasis was placed on analyzing the existing and varying experiences gained within project partners’ countries. A distinction is made between societal boundary conditions and physical boundary conditions. The former address the way society may influence decisions on monitoring. The latter address conditions, needs and constraints for monitoring related to the physical environment of the repository and of the waste itself.

Societal boundary conditions to monitoring decisions can be interpreted very broadly, including for example also elements such as a country’s social geography. Covering an exhaustive list of such conditions was not assumed of relevance for the purpose of this project. In this report, we therefore focus on the following two categories: (i) the legal and regulatory framework, (ii) stakeholders’ expectations.

When looking at the **legal and regulatory frameworks** described in the national context overviews [12], the levels of detail in which monitoring requirements and approaches are specified vary considerably.

Even though some of these national frameworks provide a basis for what needs to be included in the monitoring program, this tends to be described in relatively general terms, without too much (if any) specification on how the act of monitoring is defined. Mention may be made of a stepwise implementation process, but no details are available on how decisions at each step should be taken. Some regulations may include specific requirements for implementation strategies, e.g. the Swiss regulator calls for monitoring to be conducted in a pilot facility [14]. The French guidelines [15] also address monitoring to inform reversible disposal management.

A special case is post-closure monitoring. Several regulations or guidelines make explicit mention of this, but do not specify whether that should be a form of environmental surface monitoring, or a form of below surface repository monitoring; whether it is about monitoring the construction, or the possible migration of radionuclides from the facility; whether at this stage access control ("no excavations") for nuclear safeguards and large scale evolutions such as indicated by surface subsistence would respond to potential monitoring expectations.

Stakeholders' expectations translate into monitoring objectives and are motivated by the needs of three main stakeholder groups:

- The implementer
- Expert stakeholders, including safety authorities and national review boards
- Concerned citizens and any committees (both at a national and local level) established to represent and inform them –referred to here as lay stakeholders[1]

When referring to stakeholders' expectations, we are particularly looking at the latter two categories. Stakeholder engagement is an important part of the MoDeRn project. To further enhance our knowledge basis on what may be expected from monitoring, the project has furthermore conducted a workshop with expert stakeholders [16]. It has also conducted an analysis of what the implementer thinks a lay stakeholder may expect, and how the implementer views the main purpose and added value provided by monitoring [17]. Finally, to probe further for expectations among a specific group of concerned citizens, a number of exploratory engagement exercises will be initiated with potential local stakeholders in the last stage of the project.

The national context analysis [12] illustrates the point that safety authorities and other **expert stakeholders** such as national review boards are gradually placing greater emphasis on monitoring. At this stage, it does not appear, however, that detailed expectations are expressed. A number of general considerations can be identified, e.g. related to the longevity of some of the possible monitoring and thus the need to address related technological difficulties, and related to the preservation of safety functions in a monitored repository. There seems to be agreement that in-situ monitoring offers some added value and possibly reassurance for the long term safety, which is a pre-requisite to obtaining an authorization to close the repository.

Furthermore, a workshop involving expert stakeholders was held in Oxford (United Kingdom) to obtain feedback on the scope of the work, considering both the process of developing a monitoring program and the associated technology issues [16]. Participants knowledgeable about radioactive waste

[1] We have opted to use the term lay stakeholders (as opposed to expert stakeholders), although we are aware that concerned citizens are not a homogenous group and may well incorporate people with a very particular expertise in relation to the issue at hand.

management[2] attended the meeting. During the workshop, a number of key recommendations were made for consideration in the forward work program of MoDeRn:

- There is a need to clearly explain the relationship of the monitoring program to the safety case and to engineering design.
- There is a need to clearly communicate assumptions about why monitoring is undertaken.
- There is a need to define acceptable ranges (tolerances) for monitoring results, and to have a clear plan in place to respond to any results collected that fall outside these ranges.
- The Preliminary MoDeRn Monitoring Workflow diagram provides a valuable overview of what must be considered when developing a monitoring program.
- There is a need for a flexible, adaptable monitoring program to support decision making and to respond to future changes in monitoring requirements/technology developments.
- There may be benefit in considering the issue of post-closure monitoring further within the MoDeRn Project.
- There is a need to acknowledge the benefits of independent scrutiny of monitoring programmes, and monitoring results in particular, in order to build the trust of the public.
- There should be a clear strategy, from the outset of implementing a monitoring program, on when and how to communicate with lay stakeholders on monitoring.
- There is a need to identify what monitoring technologies need to be developed or might be available in the future.

The monitoring context analysis [12] made clear that thus far, relatively few countries have engaged with **lay stakeholders** specifically on the subject of monitoring. A range of initiatives to engage with lay stakeholders on broader issues of radioactive waste management in different MoDeRn Partner countries have nevertheless identified some key views and expectations that may influence decisions on repository monitoring:

- Monitoring to provide assurance: i.e. to demonstrate good practice and to verify the adequacy of the basis for the long-term safety case;
- Monitoring to aid decision making in a stepwise process and to provide transparency; and through this;
- Potential for sharing knowledge and make (to some extent) visible what is happening below the surface and thus almost literally opening the “black box”;
- Raise the potential for independent oversight: Availability of data creates opportunity for ‘checks and balances’ and for independent expert judgment.

Since lay stakeholder expectations of monitoring, have mainly been expressed indirectly and at quite a high level to-date, current understanding of lay stakeholder opinions could not be directly used to guide the selection of specific monitoring parameters, because available information is not sufficiently detailed.

Further on to the initial “national context” analysis, the projects Social Science experts have explored expert – mainly implementer - views on repository monitoring as well as reviewed what the social

[2] From the following organisations: Regulatory organisations (in Belgium, Finland, Switzerland and the UK), advisory bodies in the UK, a public stakeholder group in Germany, and the Belgian agency for radioactive waste and enriched fissile materials (ONDRAF/NIRAS).

science research literature tells us about the expectations and motivations that are likely to influence lay stakeholders' attitudes towards monitoring [17].

What became clear from this analysis is that issues of (re)assurance and confidence building are among the main drivers for monitoring. This confirms previous observations that the vital question is how to organize monitoring in such a way that it answers different stakeholders' expectations, thus contributing to raising their confidence in repository performing to the promised standards of safety.

Given the long timeframes involved in implementing a geological disposal facility and its staged closure, techniques and expectations may (and will) evolve. Therefore issues of (re)assurance and confidence building cannot be expected to be settled here and now for the full length of the disposal process. In that light, monitoring programs should be designed so that they remain flexible enough to cater to changing social and regulatory expectations placed among them. To continue building confidence, both the product and process of monitoring will have to continue meeting different stakeholders' expectations, while staying within the limits of what is scientifically sound and both technically and financially feasible.

Furthermore, if monitoring is to contribute to confidence building, then the process of monitoring should be made transparent and open for public and expert scrutiny. This is not done by merely producing data and arguing how these corroborate experts' claims and models. What is as important is to produce these data in such a way that others have access to them and are able to control how they came about. This is not an issue of monitoring alone, but will have to be built in the institutional context through which roles and responsibilities for long-term radioactive waste management are organized.

The findings of this social sciences analysis are reported on more extensively in a companion paper.

Physical boundary conditions refer to key elements of the repository system, i.e. the inventories describing quantity, content and conditioning of the waste, the natural environment and the engineered system. Any monitoring activities that may be developed will need to be adapted to the expected behaviour after construction, waste emplacement... of these physical boundary conditions, consider the specific functions they are expected to contribute to (e.g. safety functions, provisions for pre-closure management options) and the specific constraints under which such monitoring would need to be done.

The properties and quantity of waste inventories, often conditioned in a primary waste matrix such as borosilicate glass and in a primary waste package, condition the search and design for a suitable natural and engineered environment for the repository system. Monitoring prerogatives need to consider their influence on evolutions, such as from heat generation, potential to release radioactive gas or to produce hydrogen. They also need to consider interactions between the waste environment and the potential influence on expected waste form performances.

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

The overall engineered system includes considerations of overall layout, thermal management, as well as specific barrier performances to contribute to the basis of the safety case and of operations. It is first worth noting that repository layout and envisioned construction, operation and partial closure, may induce greater or lesser technical challenges to conduct monitoring. This is mostly related to the ability to access to the vicinity of the monitored component and/or its near-field, and the duration for which such access is possible.

To a greater or lesser extent, currently envisioned repository monitoring programs consider monitoring to be limited to a set of representative structures. These need to be identified and positioned within the overall repository layout. They may e.g. be termed a pilot facility and be positioned on the edge of the main disposal field, ensuring access to its vicinity and relative ease for monitoring during the entire pre-closure phase. They may also be spread throughout the actual disposal modules.

Monitoring objectives for waste disposal packages (WDP) most likely address their capacity to isolate waste forms for a required duration. These are typically measured with respect to water tightness in response to long term safety requirements and mechanical stability in response to both long term safety and operational/retrievability requirements. Monitoring prerogatives would address such expected performances, making use either of representative long term tests, on prior quality assurance and monitoring in a transfer store, and/or on in-situ monitoring.

The specific design of a disposal unit, i.e. cavern, drift, long or short borehole disposal, associated with a given buffer, plug and/or structural component, may create specific technical challenges for monitoring. Monitoring implementation strategies, in particular pertaining to disposal unit monitoring, need to be adapted to construction procedures, to environmental conditions and levels of accessibility of these units. Detailed technical solutions for instrumentation are still under development. Of particular importance is the need to preserve safety function performances. Upon closure of the disposal unit, this may call for the use of wireless transmissions.

The repository sealing system, which may include disposal unit plugs or seals, gallery seals and access shaft/ramp seals, is emplaced to restrict water flow and radionuclide transport through the repository. Monitoring activities may consider the mechanical and hydraulic properties of such seals and possibly confirm an adequate chemical environment consistent with expected seal material swelling. Detailed considerations need to take into account the timescales at which natural seal resaturation may operate.

A structured approach to develop and implement monitoring

An obvious conclusion from the National Context analysis is that any technical specifics of a monitoring program must be tailored to and developed within its national context. The overall process, however, to conduct such developments proceed along common steps. An important question to ask of monitoring is: How to ensure that the implementer and other stakeholders will have confidence in monitoring results? This is in part addressed by a clear framework to develop and implement a monitoring program, and traceable decisions and justifications at each step of this framework.

Within a general framework, several key issues must be addressed. First: identifying relevant monitoring objectives, as they derive from stakeholder expectations and implementer's analysis. Second: the capacity to provide some information to meet those objectives. Third: the use of monitoring within the disposal process. In addition, the iterative update of these and the corresponding evolution of monitoring objectives also need to be considered.

The summary flowchart (Fig 1) provides an overview of key steps to consider when developing a monitoring program.

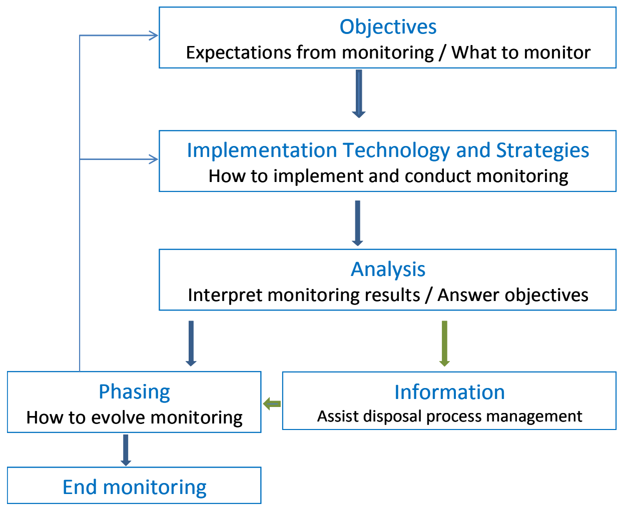

Fig 1. Summary flowchart of key steps in developing and using a monitoring program

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

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

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

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

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

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

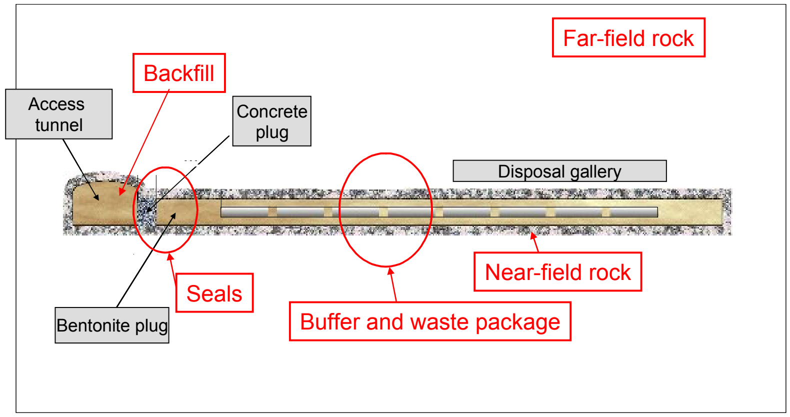

Fig 2. Typical engineered and natural repository components subject to monitoring

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

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

Analysis of these in a given context will provide a basis to provide a realistic assessment to what extent monitoring might provide further support to the disposal process, and also what specific aspects cannot be answered directly through monitoring. Presenting this in a transparent manner will prevent making exaggerated claims, which might in the future discredit the value of monitoring.

Some processes operate at typical **timescales** which are substantially higher than a century. They will thus not be accessible to direct confirmatory monitoring. This consideration could be addressed in previous experiments, by providing for artificially accelerated transients (e.g. forced resaturation). Assuming that in-situ repository evolutions will not be subjected to any artificial acceleration, monitoring of very slow natural evolutions would at best provide information limited to detecting initial evolutions, which might in certain cases provide confirmation that adequate process models were selected, or to confirming the absence of significant evolution. This is the case e.g. for far field responses in host rocks having very small transmissivity. It is also the case for near field and engineered barrier evolution to their long term, post closure configuration (e.g. very slow seal resaturation and swelling).

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

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

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

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

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

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

Monitoring is limited by available technology. A realistic development of a monitoring program must thus consider **available monitoring technology and strategies** to implement the monitoring program. In particular, environmental conditions and the requirement to monitor over extended periods of time impose specific technical requirements on monitoring systems [18]. Analysis should highlight technological shortcomings that may still represent an obstacle in meeting monitoring objectives, and propose improvements by conducting several focused RTDs. In a repository, these may also address the need to avoid detrimental impact of monitoring on pre-closure/post-closure performances.

An overview of available state-of-the-art of suitable monitoring technology is currently being developed. This state-of-the art overview benefits from the combined expertise of project partners and has also solicited further input from additional experts. To this end, in 2010 the project organized and hosted a Monitoring Technologies Workshop at Troyes [19], which brought together 55 experts from a range of organizations, including oil and gas, mining and civil engineering, radioactive waste management organizations and research institutes, to discuss monitoring technology issues related to:

- Overview of Applications and Technologies.
- Geotechnical and Hydrogeological Monitoring.
- Sensor Networks and Fibre Optic Sensors.
- Air-based and Satellite-based Monitoring Technology.
- Non-intrusive Monitoring and Wireless Transmission.

The workshop concluded that a range of technologies were available although some of these had recognized limitations. With a focus on durability of monitoring systems and the benefits of monitoring without disturbing the wastes through the application of non-intrusive techniques, the MoDeRn programme of research, development and demonstration [20] is based on further developments to add to and/or adapt available state-of-the-art in monitoring technologies. These activities include:

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

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

Developments pertaining to technology will be presented in greater detail in a companion project paper.

All monitoring is conducted to inform the **decision process** by providing relevant data, e.g. to enhance the science basis used to develop predictive models, or to verify in-situ evolutions are consistent with the assessment basis. Three major decision points in a disposal process are acknowledged:

- Decision to focus on a specific site to prepare a license application
- Granting of license for construction and operation
- Authorization to bring the repository into a post-closure configuration

In addition, most programs acknowledge a stepwise approach to construction, operation and partial closure, prior to closing the repository. These may give rise to opportunities for additional decision points in the management of the disposal process.

The major decision points for site selection and license application are reasonably well understood. Some national contexts have identified legal provisions governing the process of authorizing closure, which would include review by safety authorities and possibly call for a dedicated “repository closure” law. There seems to be at present, however, no guideline or clear understanding available on how decision points between granting of a license and closing the repository would be addressed, although it is acknowledged that a periodic re-evaluation of the safety basis will be conducted. In particular, there is no clear understanding on the relative weight monitoring data would carry to informing these decisions, although it is assumed that monitoring results obtained in-situ or from associated long term science activities will provide a significant basis for decisions on further disposal process management.

Case studies to test the proposed approach

Above developments focus on the general approach to developing a monitoring program. Such developments cannot, however, be done at an abstract level and therefore must rely on work conducted with specific examples, as provided by the national contexts and further developed in specific case studies. These tackle all relevant monitoring aspects by considering a system design based on different monitoring concepts and adapted to different specific host rocks and engineered barriers.

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

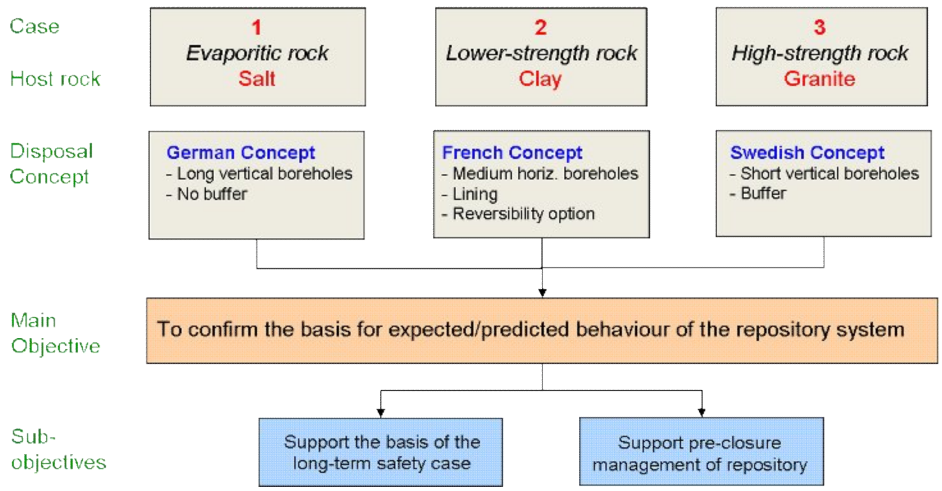

Fig 3. Case studies developed within MoDeRn

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

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

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

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

These case studies will be presented in more detail a companion project paper.

CONCLUSION

Collectively, these activities will form the basis for a 'roadmap for repository monitoring', and consolidated project results aim at providing a shared international view on how monitoring programs may be developed to respond to specific national needs at the various steps in the disposal process. This intends to synthesize our current, collective understanding of how monitoring can contribute to verify safety and inform pre-closure management, and this may contribute to confidence in and acceptance of the disposal process. A **website (www.modern-fp7.eu)** provides updated information about progress as well as access to relevant publications.

It seems important, though, that any statements on monitoring remain cautious and realistic as to the perceived added value it is expected to aid decision-making and the success of the disposal process. Indeed, a certain number of limitations of monitoring can be recognized. This should be understood as a recommendation both to pursue efforts in reducing such limitations, to evaluating whether or not they are acceptable, and most of all to provide transparent communication on them. These limitations are primarily related to five considerations:

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

For all of these, it is important to achieve a balance between the added value monitoring can bring to a transparent and informed management of the disposal process, and the potential risk to operational activities and to long term safety. The above identified limitations should be further developed within a national context, recorded and recognized. Nevertheless, a monitoring program contributes substantial added value to the disposal process. Reconsidering the list of limitations above – where *limitations* is understood relative to an idealized, and impossible perfect confirmation of repository long term evolutions – it can readily be seen that in-situ monitoring provides further, complementary opportunities to enhance the basis for evaluating long term safety.

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

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

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

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

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

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