Development of a Theoretical Monitoring System Design for a HLW Repository Based on the "MoDeRn Monitoring Workflow" (A Case Study) - 12044

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ABSTRACT

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

INTRODUCTION

Monitoring involves continuous or periodic observations of parameters to help evaluate the behaviour of the disposal system. Preliminary guidance on monitoring, in particular the high-level principles on which monitoring should be based on, have been developed by the International Atomic Energy Agency (IAEA) [1,2], and within a European Commission Thematic Network study [3]. These principles include the requirements that monitoring should not reduce the overall level of repository post-closure safety, and that post-closure safety is provided by means of engineered and geological barriers; it does not depend on monitoring.

However, the general guidance provided by the IAEA and the EC does not provide a reference framework for developing, designing and implementing monitoring programs. An on-going EC Seventh Framework Program Project entitled *Monitoring Developments for safe Repository operation and staged closure* (*MoDeRn*) is building on previous international efforts to provide such a framework.

Within the MoDeRn project, a structured approach – the *MoDeRn* Monitoring Workflow - was elaborated to provide a generic methodology for the development and implementation of a monitoring programme that takes into account specific national boundary conditions [4]. The workflow allows the linking of high-level monitoring objectives to the detailed selection of monitoring technologies and sensor placements. The MoDeRn Monitoring Workflow is illustrated in Figure 1, and contains the following steps:

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

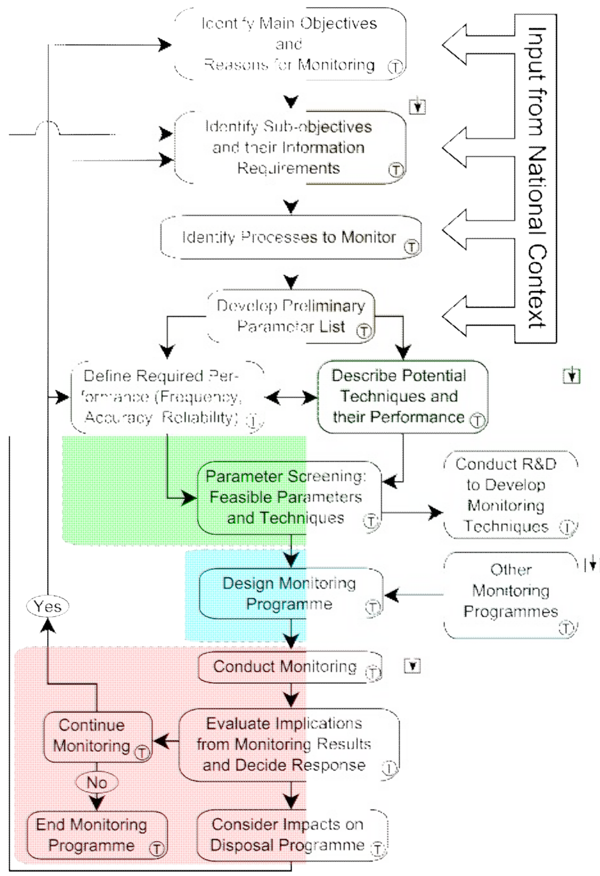

Fig. 1: The *MoDeRn* Monitoring Workflow

In the case study, a modular-based principle monitoring system for a generic German disposal concept in rock salt is discussed based on the approach provided by the *MoDeRn* Monitoring Workflow. The objective is to illustrate the application of the *MoDeRn* Monitoring Workflow, and identify further issues that need to be addressed prior to implementation of repository monitoring systems.

DESCRIPTION OF THE SAFETY CONCEPT

The generic disposal concept considered in the salt rock case study is based on the recent ISIBEL-study [5]; a systematic review of the tools and instruments available to assess the safety of a radioactive waste repository in a salt formation. The objective of the ISIBEL study was to determine if, and to what extent, the technical feasibility and the safety of a final repository can be demonstrated. The study focused on the systematic demonstration of the safe long-term confinement of the waste by demonstrating the integrity of the geotechnical barriers and of the geological main barrier. The safety concept is designed for a reference site model of Gorleben and is based on an improved technical concept. In the concept considered in this study, an emplacement of the HLW waste in vertical boreholes is foreseen.

One main component of the demonstration of safe *confinement* of the waste is the demonstration of the integrity of the individual barriers. If suitably designed, the diversified positioning of engineered barriers together with the convergence properties of the host rock will guarantee that no relevant amounts of radionuclides will be released into the biosphere, even in case one of the engineered barriers may fail. The repository layout is designed in such a way that the geomechanical integrity of the geological main barrier, i.e. the main salt of the Staßfurt layer, can be demonstrated. In order to comply with dilatancy and brine pressure criteria [6], the emplacement cavities are located at sufficient depth and at a suitable distance away from putative fault zones or strata boundaries. The emplacement cavities are spatially arranged in a way that the temperature criterion in rock salt (< 200°C) will not be exceeded.

Furthermore, the disposal concept foresees that the entire void volume of all underground workings in the repository will be backfilled with crushed salt: when all boreholes in a drift are filled with waste containers, they are equipped with a borehole seal, and the drift is backfilled with crushed salt. When the last drift in an emplacement field is backfilled with crushed salt, the corresponding part of the main drift will be backfilled with crushed salt as well, in line with regulatory requirements [7]. Due to compaction by convergence of the salt dome, the porosity and permeability of the crushed salt will decrease following emplacement and, in the long-term, will exhibit the same barrier properties as rock salt.

In the safety concept enshrined in the disposal concept [8, 9], safety objectives have been defined that can be divided into conventional (non-radiological) and radiological safety objectives. The safety objectives are:

- Protection of the earth’s surface (conventional safety objective)
- Protection of groundwater against hazardous contaminants (conventional safety objective)
- Protection of the biosphere against radionuclides (radiological safety objective)
- Criticality safety (radiological safety objective)

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

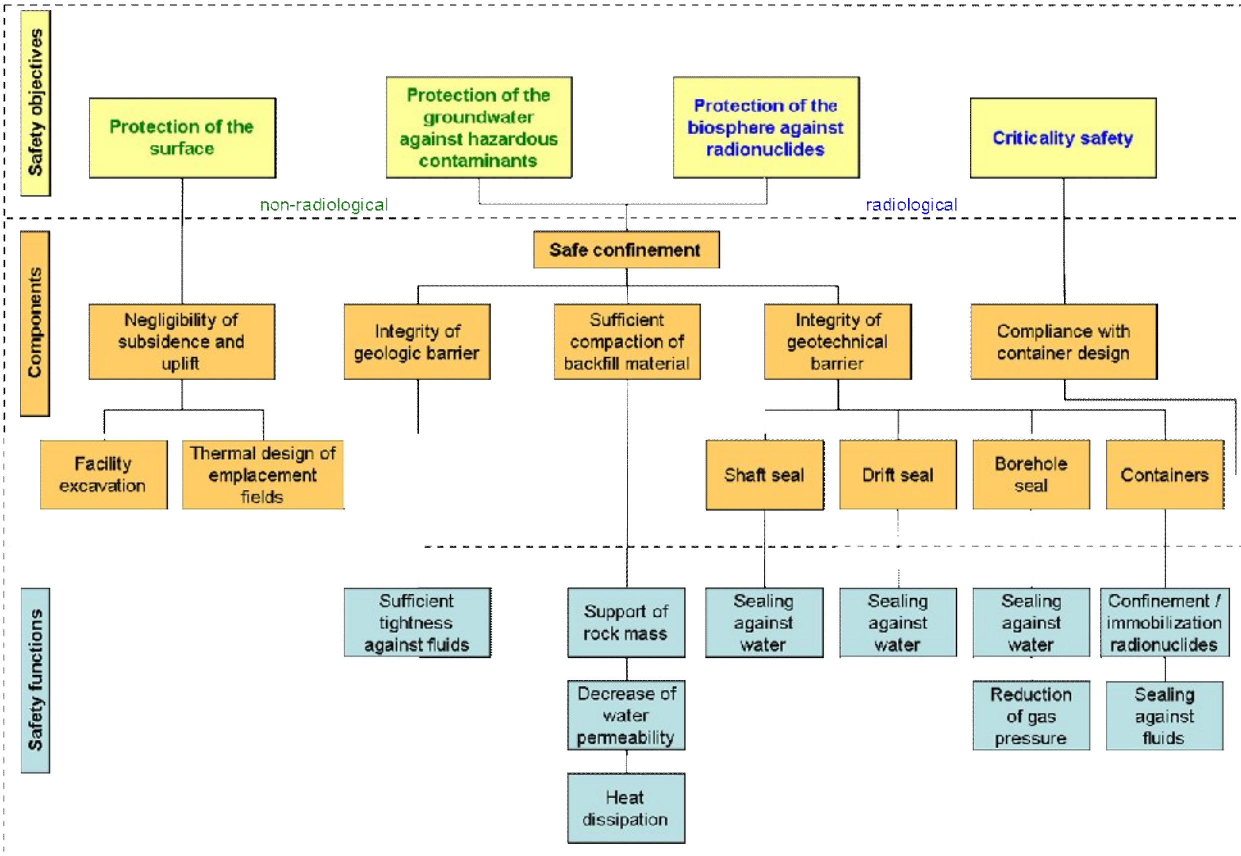

Fig. 2: Relationship between safety objectives, safety assessment components, and safety functions for the salt rock HLW disposal concept

IDENTIFICATION OF PARAMETERS RELEVANT TO MONITORING

When based on the safety functions that can attributed to the individual components, monitoring can support the safety strategy of a disposal concept by providing meaningful data acquired under full-scale in-situ conditions. To do so, the *MoDeRn* Monitoring Workflow foresees in a first step to identify the parameters suitable to demonstrate compliance with the safety functions. The safety functions of the assessment components given in Figure 2 can be related to physical and chemical processes taking place in a repository. These processes are described in a site-specific catalogue of features, events and processes (FEPs) [10]. The FEP catalogue can be used to identify those processes that could significantly affect the safety functions of a component. In order to be able to define a proper monitoring strategy for a process identified by this method, the parameters relevant for the process need to be identified. When performing this analysis for each of the safety functions in Figure 2, a list of all parameters relevant to monitoring can be generated (a more detailed description of the identification process can be found in [11]).

MONITORING LOCATIONS AND FEASIBILITY SCREENING

As a next step, locations for the monitoring devices need to be identified. Furthermore, suitable monitoring techniques and equipment have to be selected.

For the general placement strategy, it is assumed that it is advantageous to implement monitoring systems in one representative emplacement field and not scattered over the entire repository. In [1], the use of a pilot facility is considered to be a possibility to monitor relevant parameters in a representative environment and – at the same time – to gain insight into the behaviour of the waste emplaced without compromising the operation of the actual repository. Following this line of reasoning, in this case study the monitoring activities are envisaged only for one part of the generic disposal facility, the so-called field "East 1" (Figure 3). East 1 is selected, because it will be the first to be filled with waste containers. While emplacement continues in the other emplacement fields, it would be possible to gather data from this representative, sealed "monitoring field". Thus, the evolution of an entire field could be monitored during the operating phase of the repository.

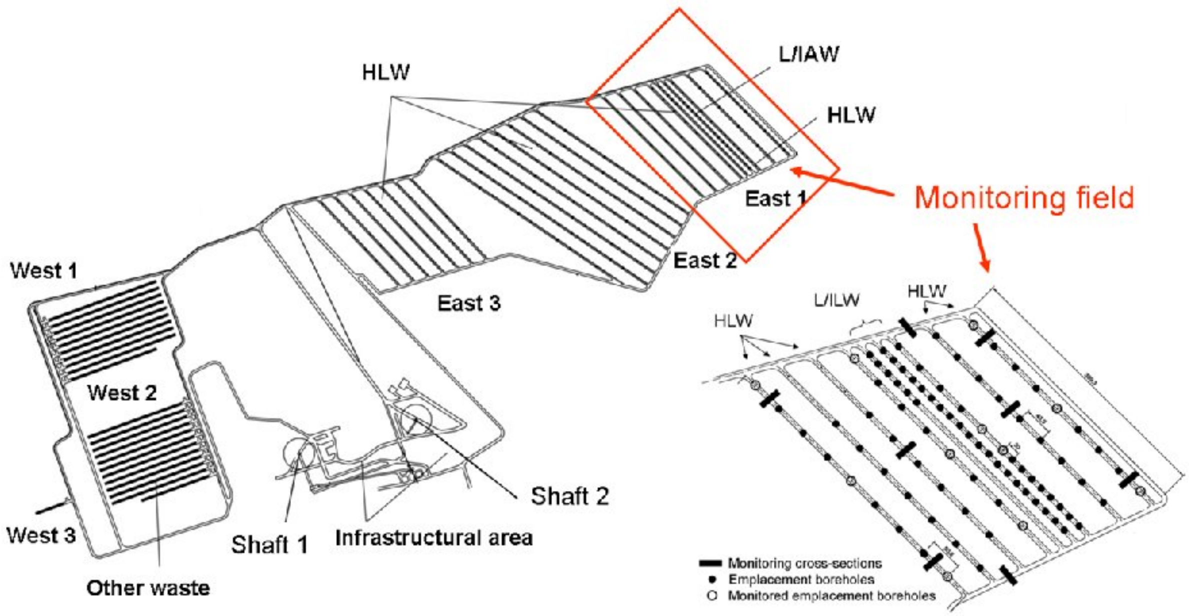

Fig. 3: Draft of the emplacement fields for the vertical borehole disposal option. Status: January 2011.This draft was prepared within the scope of the Preliminary Safety Analysis Gorleben (VSG) and will be further refined as the VSG continues [12] (slightly modified).

Figure 3 (right) shows an enlargement of field East 1. This field is designed for high-level waste (HLW) as well as low-level waste (LLW) and intermediate-level waste (ILW). The black dots indicate emplacement boreholes. The emplacement boreholes indicated with a circle are selected in this study as potential locations for monitoring. These boreholes are either located in the centre of the field so that they are exposed to the highest possible heat development or in the edge of the field so that they are exposed to the highest inhomogeneities of the thermo-mechanical development of the monitoring field.

The exact placement of monitoring equipment within the limited space of the emplacement boreholes is a relevant question. As discussed above, the placement of monitoring equipment within a seal is not considered, because this could potentially impair the safety function of the seal. Instead, the placement of monitoring equipment, including power supply, data acquisition systems and sensors, in a dummy canister at the top of an emplacement borehole is foreseen, directly below the borehole seal (Figure 4). Equipped with sensors on the outside of the canister to measure temperature, moisture, pore pressure, and total pressure, this canister would monitor the conditions at the bottom of the borehole seal. As the gap between the canister and the borehole wall is only a few millimetres, any fluid flows through the seal would be detected, especially if several sensors will be placed on the circumference of the canister. The monitoring data will be transmitted via wireless transmission system (see next section) to the borehole cellar at the top of the borehole (Figure 4). The borehole cellar is used to store the power supply, data recording, and transmitting devices. In the current disposal concept, there are no special requirements on the backfilling of the borehole cellar, so this may be a suitable site for placing monitoring equipment. There will be a need, however, to demonstrate that degradation of the monitoring equipment in the long-term will not affect long-term safety. Additional sensors can be placed at the interface between borehole cellar and borehole plug.

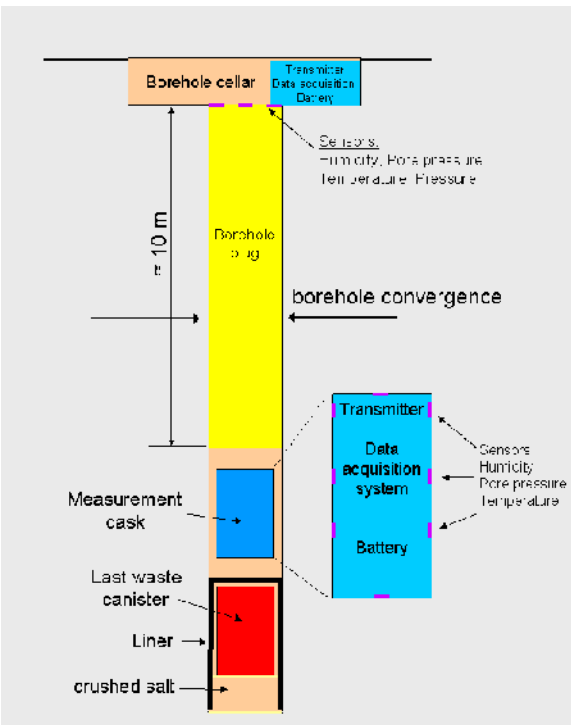

Fig. 4: Schematic diagram for monitoring the borehole seal

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

A feasibility screening for the example case yields that most of the parameters identified to characterize safety-relevant processes can be measured with monitoring equipment currently commercially available [11]. Some parameters have been screened out because placing of monitoring equipment may impair important barrier functions. For instance, measuring the radial rock displacement is not a technical problem, but an emplacement borehole at the location of the plug it is not allowed because no holes should be drilled into the host rock at barrier locations. However, as discussed in the next section, one of the main challenges for setting up a monitoring programme is not on the level of sensors or data acquisition systems but on the ability to transmit the monitoring data wirelessly and to provide an autonomous power supply for the monitoring equipment for several decades. Thus, part of the feasibility screening is to investigate the possibilities of data transmission and power supply and will be discussed in the next sections.

DATA TRANSMISSION

When thinking about monitoring of processes within the underground facilities of a final repository for high-level radioactive waste, especially after its closure, an important aspect to consider is the transmission of monitoring data out of the monitoring field or up to the earth's surface.
In 2001, IAEA [1] emphasized that when developing a monitoring concept, the benefits from having dispose of monitoring data need to be balanced against potential detriments resulting from the process of monitoring. This is especially important when monitoring in the vicinity of geotechnical barriers, where installation of monitoring equipment (i.e. instruments and cables) may result in potential pathways for radionuclide migration. This leads to the requirement that all monitoring activities must be implemented in such a way that they are not detrimental to long-term safety [3]. For the generic German concept in rock salt, the following principles apply when implementing technical measuring and/or monitoring systems:

- *No installation of sensor systems within geotechnical barriers*
- *No cables running through the geotechnical barriers*
- *No cables running along access drifts backfilled with compacting crushed salt*[1]
- *No cable connection from the repository to the surface*

During the past years some institutions and companies have started to develop wireless data transmission systems with the intention to send data through geotechnical barriers and host rock. Corresponding tests are currently running at different underground research laboratories [4]. In addition, a few systems are existing world wide able to send data out of underground excavations, mainly mines, to the earth's surface. In several cases, transmission distances up to several hundred meters have been claimed. The maximum transmission distance depends on the rock through which the signal is being transmitted and can thus only be seen as an indicative value. Table 1 gives an overview of some of the available systems. In case of our generic concept, the depth level of the repository is assumed to be 870 m. By comparing this depth with the operating distances shown in Table I, it is obvious that the development of a wireless connection to the earth's surface will be a challenging task

Table I: Long-distance battery-driven wireless through-the-earth transmission systems

Company	Frequency-range	Operating distance	Name
Kajima Corporation, Japan	1–10 kHz (VLF)	100 – 150 m	unknown
Mine Site Technologies, Australia	ULF	> 100 m	unknown
WFS, Ireland	LF	unknown	Terratext
Transtek, USA	4 kHz (VLF)	300 m	TeleMag
Stolarhorizon, USA	20 kHz	up to 600 m	RadCAT
Vital Alert, Canada	2–8 kHz (VLF)	180m	Canary™Talk
Lockheed Martin, USA	unknown	470 m	MagneLink MCS

[1] Note that crushed salt which is used as backfill material is also considered to act as a barrier although it is not explicitly considered to be a geotechnical barrier

In above ground applications wireless transmission systems containing several relays stations have successfully proven their ability to transmit monitoring data over long distances by data hopping from relay station to relay station [13]. In principle, such a system is conceivable for underground through-the-earth systems as well. Data recorded within the monitoring field would be transmitted along a chain of relay stations to the shaft and up to the surface in several stages. In a closed and sealed shaft the installation of relay stations requires a careful location of the stations between different sealing elements within the shaft.

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

SELF-SUFFICIENT POWER SUPPLY

In the generic disposal concept, a minimum operating period of 25 years is assumed. Furthermore, monitoring is intended to continue during an institutional control period after repository closure of 100 years. Systems for monitoring, data-acquisition and wireless data transmission in backfilled or sealed areas must therefore have a long-term self-sufficient power supply. Such a long-term self-sufficient power supply can be achieved by using radionuclide batteries [14, 15] or betavoltaic batteries [16]. Radionuclide batteries convert heat into electric current and they are autonomous, maintenance-free, and can continue to release energy for long periods of time. The performance of radionuclide batteries have been proven during several space missions (e.g. the Cassini-Huygens space probe). The durability of betavoltaic batteries depends on the half-life of the radioisotope used to provide the energy source. Betavoltaic batteries work similar to solar cells but instead of using photons they use beta particles from the radioactive decay to directly produce electrical current. Tritium-based prototypes of betavoltaic batteries have already been developed and successfully tested, whereas prototypes using nickel isotopes, which could provide a usable half-life of approximately 100 years, are still to be developed. Betavoltaic batteries are rather simple and robust and can be used in rough and high temperature environments where normal chemical batteries can hardly be used. This type of batteries is thus a promising technology to realize self-sufficient power supply of monitoring systems supposed to run over several decades.

DISCUSSION

Based on both regulatory requirements as well as for reasons of public acceptance, monitoring of a geologic repository is not limited to just the operational phase but may continues after closure of the facility. There is a broad international consensus that the development of a monitoring concept for a repository particularly for the post-closure phase needs to carefully weigh the benefits obtained from collected data against potential negative impacts associated with collection of the data [1, 3, 4]. In this context the following aspect has been shown to be relevant for the case study performed:

- To ensure that the integrity of a geotechnical barrier, i.e. sealed boreholes, shafts, and drifts, does not impact the long-term safety function of the barrier, monitoring systems should not be installed within the barrier. However, this has shown not to be a relevant limitation, because it is not the barrier itself but its functional performance as a sealing system that needs to be monitored.

- The same is true for disposal canisters: for reasons of waste handling and radiological safety, monitoring systems should not be installed directly on the outer surface or integrated into the disposal canister as such installations could result in points of weakness and thus affect barrier integrity. As consequence, monitoring should be conducted through observations of the area surrounding the disposal canister.

- The establishment of a dedicated monitoring network initiated at the earliest practicable time will lead for the considered case to a monitoring period of at least 25 years. Subsequently, a post-closure monitoring period of 100 years is assumed. Because repairs or replacement of defect components is not possible during the post-closure case, system robustness is a relevant design criteria in order to meet the monitoring performance objectives. Sensors used in construction monitoring have demonstrated reliable performance over several decades: Bordes & Debreuille [17] analyzed the long-term performance of nearly 7,000 sensors over a wide range of applications. Their analysis showed that malfunctions preferentially occurred during the initial period of use with a significant decrease in failure rates over time. In other words once a sensor is properly functioning it will likely continue to function properly. Despite these reliable performance indicators for purposes of repository performance monitoring the sensors used must provide both a redundant and diversified capability to offset potential system failures to the greatest extent possible. In the case of a large borehole disposal as considered in this paper, not every borehole can be monitored, because such a system would be logistically difficult to implement and disproportionately vulnerable to potential failures. Therefore a representative subset of emplacement boreholes should be considered for performance monitoring.

- In many cases, monitoring data collected during both the operational and post-closure periods need to be transmitted using wireless systems. Although several systems exist around the world, specifically those used in mining to establish communication with trapped miners, the signal transmission ranges of the current known systems is significantly limited, especially in rock formations (see Table 1). Several tests are currently underway to study the transmission of such signals in Belgium, Sweden, and in Switzerland [4]. Similar studies designed to estimate the potential for success are also needed in the German case.

- Battery technologies are available that allows an autonomous power supply operating over several decades. In order to determine which battery concept is best suited for the outlined monitoring concept, the electrical power requirements for each individual component of the monitoring system needs to be determined. This requires early-on development and consideration of the monitoring concept and associated equipment requirements.

- In order to be able to collect data on the performance of repository emplacement areas in the operational and post-closure phase, appropriate monitoring systems must be installed already at the start of emplacement activities. Therefore decisions regarding post-closure monitoring must be made early-on in the development of a repository.

The discussion also leads to several areas where further work is required with regard to the findings of the reported case. These include:

- Development of approaches to respond to unexpected monitoring data
- Analysis of the numerical uncertainties with respect to the evolution of the repository system, in order to understand the sensitivity required for the monitoring system, and to develop ranges of expected design-based system behaviours, against which trigger values/performance measures can be specified.
- Further development and long-term testing of power supplies for sensors and signal relays.

In conclusion, our case study has shown that monitoring of safety relevant processes in a geologic repository does not represent an insurmountable task. However there are still many technological open questions that need to be addressed. These open questions do not only relate to the wireless transmission of data through salt rock over larger distances but also with the development and testing of appropriate monitoring system components that can reliably function in a autonomous and maintenance-free manner continuously under aggressive environmental conditions [18], and consideration of how monitoring data would be used to inform decision making.

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