nagra

Arbeitsbericht NAB 21-11

Pilot Repository Monitoring: First Concept Report

December 2021

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for the Disposal of
Radioactive Waste

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KEYWORDS
Pilot repository, monitoring, EP21, parameter selection, interpretation, transferability

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

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List of Acronyms

Acronym	Definition
AGNEB	Arbeitsgruppe des Bundes für die nukleare Entsorgung (Federal Workgroup for Nuclear Waste Disposal)
EBS	Engineered barrier system
EC	European Commission
EDZ	Excavation damage zone
ENSI	Swiss Federal Nuclear Safety Inspectorate
EURAD	European Joint Programme on Radioactive Waste Management
EUU	Erdwissenschaftliche Untersuchungen untertag (underground geological investigations)
FEP	Features Events and Processes
FDR	Frequency domain reflectometry (measurement technique for water content)
HLW	High-level waste (spent fuel assemblies and high-level waste from reprocessing)
IAEA	International Atomic Energy Agency
L/ILW	Low- and intermediate-level waste
LVDT	Linear variable differential transformer
Nagra	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (National Cooperative for the Disposal of Radioactive Waste)
NAB	Nagra Arbeitsbericht
NEA	Nuclear Energy Agency
NTB	Nagra Technischer Bericht
R&D	Research and development
RTDS	Resistance temperature detector sensor
SEFV	Stilllegungs- und Entsorgungsfondsverordnung
SFI criteria	Safety function indicator criteria
TDR	Time domain reflectometry (measurement technique for water content)
THM	Thermal-hydraulic-mechanical
TRL	Technology readiness level
URL	Underground rock laboratory
ÜUG	Überwachung Umwelt und geologisches Umfeld (surface-based monitoring of the environment and geological surroundings)

1 Introduction

The National Cooperative for the Disposal of Radioactive Waste (Nagra) must submit an overarching monitoring concept for the general license application that covers all realisation phases of the deep geological repository (ENSI 2018). Monitoring of the pilot repository is part of the overarching monitoring concept.

This report has the aim to present the requirements and first concepts related to pilot repository monitoring. In the context of the 2021 Waste Management Programme (Nagra 2021a) this document serves as background report ("Hintergrundbericht") and answers Condition 5.2 (see Appendix) of the Swiss Federal Council attached to the 2021 Waste Management Programme (Bundesrat 2018). In addition, this report forms a basic document for the development of the overarching monitoring concept and the site-specific planning of pilot repository monitoring.

The planning and licensing steps of a deep geological repository are configured to ensure a safe, secure, sustainable, and publicly acceptable construction, operation, and closure. The pilot repository monitoring provides information on the behaviour of the early-stage evolution of the multibarrier system following waste emplacement. Therefore, these monitoring data form the input to the periodic updates of the safety case as well as for a stakeholder dialogue, confidence building, and decision making.

The present report identified the regulatory requirements on the pilot repository and its monitoring, defines the objectives of the pilot repository monitoring as developed by Nagra, and describes the next steps in development of the pilot repository monitoring concept. Moreover, a preliminary methodology for the identification of potential monitoring parameters is presented. Furthermore, ongoing research and development (R&D) and fundamental considerations about data interpretation and transferability to the main repository are discussed. In addition, selected topics of R&D projects on monitoring technology are presented.

The pilot repository

The pilot repository is an independent part of the deep geological repository and is used to monitor the evolution of the multibarrier system by means of a small representative amount of radioactive waste up to the end of the Monitoring Phase (ENSI 2020a). In the current Swiss disposal concept the pilot repository is spatially separated from the main repository (Nagra 2021a). Therefore, the pilot repository will have a certain distance to the main repository to minimize the thermal-hydraulic-mechanical (THM) impact of the main repository. Furthermore, the pilot repository will be placed in geological and hydrogeological conditions that are comparable to the main repository. The design (construction, support, emplacement) will correspond to the main repository.

A possible schematic layout for the different underground facility elements and structures of a combined repository is shown in Fig. 1-1. In the current concept an L-shaped observation drift surrounds the pilot repository on two sides. The observation drift will be used for borehole-based monitoring of the pilot repository. Access to the pilot repository and the observation drift is provided by a short branch from the operational tunnel. In the current concept (Nagra 2021a) the high-level waste (HLW) pilot repository consists of three emplacement drifts and the low- and intermediate-level waste (L/ILW) pilot repository consist of one emplacement cavern.

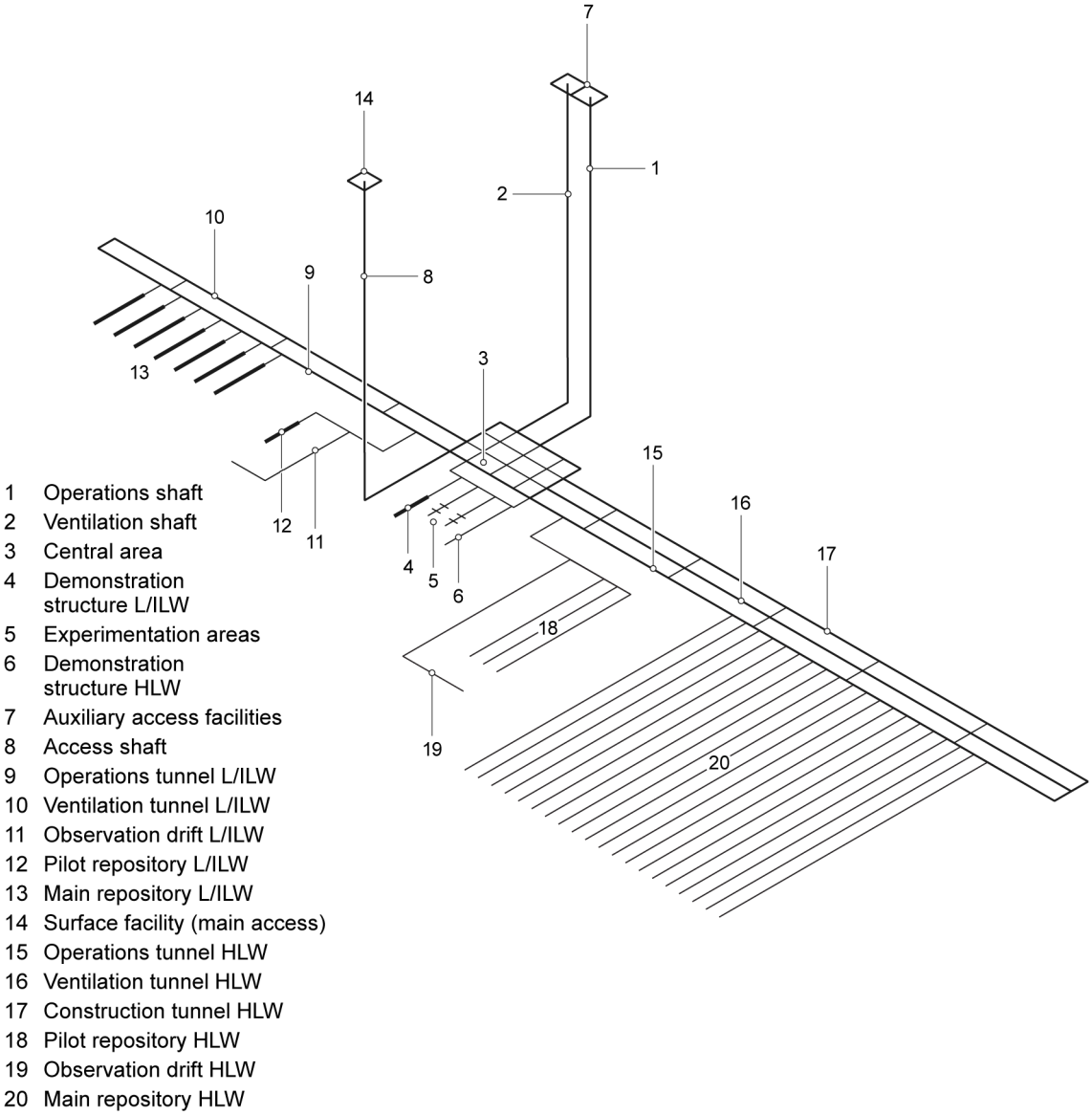

Fig. 1-1: Systematic sketch for the underground facilitiy elements and structures of a combined repository accoring to Nagra (2021a)

After granting the nuclear operation license the phase of emplacement operation starts (Tab. 1-1). Before the emplacement in the main repository a small representative amount of HLW disposal canisters or L/ILW disposal containers will be emplaced in the respective pilot repository and the monitoring of the pilot repository will commence. Therefore, the effective monitoring duration of the pilot repository is at least 10 years longer than the duration of the official Monitoring Phase (Tab. 1-1), which starts not before completion of the emplacement in the main repository. In addition to the pilot repository monitoring, surface-based monitoring of the environment and the geological surroundings (Fanger et al. 2021) as well as monitoring in the remaining open underground structures (Nagra 2021b) and monitoring for operational safety will be undertaken during the Monitoring Phase. The Monitoring Phase is divided in two parts. After part 1 of the Monitoring Phase the access structures to the main repository at disposal level will be backfilled and sealed. However, the observation drift will remain accessible (Fig. 1-2) during part 2 of the Monitoring Phase. At the end of part2 of the Monitoring Phase the entire repository will be closed.

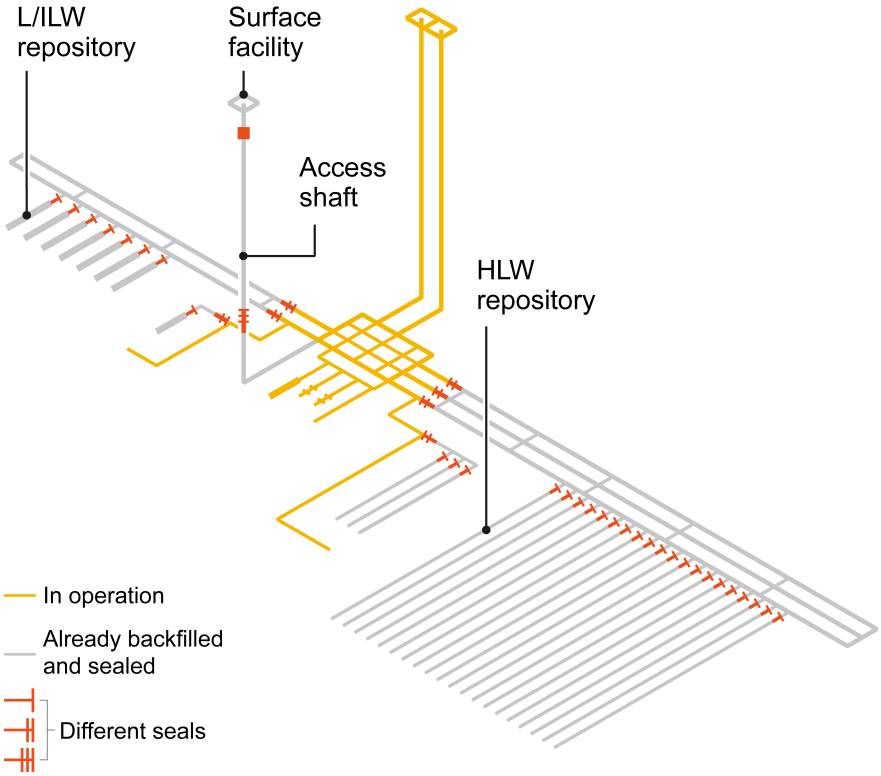

Fig. 1-2: Open underground structures (in yellow) during part 2 of the Monitoring Phase

The current planning assumption is that the duration of the entire Monitoring Phase is 50 years (SEFV 2007). Nagra (2021a) assumes a duration of 10 years for HLW and 10 – 20 years for L/ILW depending on repository type (single vs. combined) for part 1 of the Monitoring Phase and 40 years for the duration of part 2 of the Monitoring Phase (Tab. 1-1). The Monitoring Phase ensures that information is provided on the behaviour of the early-stage evolution of the multibarrier system following emplacement as well as the possibility for waste retrieval. If necessary, the duration of the Monitoring Phase can be adapted. The end of the Monitoring Phase and subsequent closure will be decided by the Federal Council (Art. 39 KEG).

Tab. 1-1: Planned timeline for the phases of repository realisation for the different repository types according to Nagra (2021a)

		Underground geol. investigations	**Repository construction**	**Emplacement operation**	**Monitoring Phase – part 1**	**Closure main repository**	**Monitoring Phase – part 2**	**Closure entire repository**
Single reposit.	L/ILW	2035 – 2044	2045 – 2049	2050 – 2064	2065 – 2074	2075 – 2080	2075 – 2114	2115 – 2118
Combined reposit.		2035 – 2044	2045 – 2049	2050 – 2064	2065 – 2084	2085 – 2090	2085 – 2124	2125 – 2126
	HLW	2035 – 2054	2055 – 2059	2060 – 2074	2075 – 2084	2085 – 2090	2085 – 2124	2125 – 2126
Single reposit.		2035 – 2054	2055 – 2059	2060 – 2074	2075 – 2084	2085 – 2090	2085 – 2124	2125 – 2126

2 Regulatory requirements

In connection with the pilot repository monitoring, the Nuclear Energy Act –"Kernenergiegesetz" (KEG 2003), the Nuclear Energy Ordinance - "Kernenergieverordnung" (KEV 2004), and the Guideline for Swiss Nuclear Installations – "ENSI G03 Richtlinie für die schweizerischen Kernanlagen" (ENSI 2020a+b) are of relevance. The relevant content of these laws, regulations and guidelines are summarized below in Tab. 2-1 to 2-5.

Tab. 2-1: Content of the Nuclear Energy Act (KEG 2003) in relation to pilot repository monitoring

Art. 13	Conditions governing the granting of a general licence 1. A general licence may be granted if the following conditions are met: c. a plan has been submitted for decommissioning, or for the monitoring period and the closure of the installation;
Art. 16	Conditions governing the granting of a construction licence 1. A construction licence is granted if the following conditions are met: e. a plan has been submitted for decommissioning, or a project for the monitoring period and a plan for the closure of the installation.
Art. 39	Monitoring period and closure 1. The owner of a deep geological repository is obliged to submit an updated project for the monitoring period and a project for the eventual closure if: a. the emplacement of radioactive waste has been completed; b. the operating licence has been withdrawn or has expired in accordance with Article 68 paragraph 1 letters a or b, and the Department has ruled that a project must be submitted. 2. Upon expiry of the monitoring period, the Federal Council shall order the closure of the repository, if the permanent protection of humans and the environment is ensured.

Tab. 2-2: Content of the Nuclear Energy Act (KEV 2004) in relation to pilot repository monitoring

Note: KEV (2004) uses pilot installation for pilot repository and main section for main repository.

Art. 23	General Licence Application documents Applications for a general licence must be accompanied by the following documentation: d. concept for decommissioning, or for the monitoring period and closure;
Art. 24	Construction licence Applications 2. They must submit the following documentation: f. decommissioning plan or project for the monitoring period and plan for closure of the installation
Art. 64	Elements of a deep geological repository A deep geological repository comprises a main installation for the emplacement of the radioactive waste, a pilot installation and test areas
Art. 66	Pilot installation 1. In the pilot installation, the behaviour of waste, backfill material and host rock must be monitored until the expiry of the monitoring period. During monitoring, data must be collected in order to confirm long-term safety with a view to closure. 2. The obtained findings must be transferable to the processes going on in the main section. They form the basis for the decision on the closure of the repository. 3. The following principles must be observed in connection with the design of the pilot section: a. The geological and hydro-geological conditions must be comparable to those of the main section. b. The pilot section must be spatially and hydraulically separated from the main section. c. The construction of the pilot section and the emplacement procedure of waste and backfill material must correspond to those of the main section. d. The pilot section must contain a small but representative quantity of waste.
Art. 68	Monitoring period 1. The owner of a deep geological repository must describe in an up-dated project the planned measures for monitoring the repository after emplacement of the waste has been completed. He must also propose a duration for the monitoring period. 2. The Department orders the start of the monitoring period and specifies its duration. It may also extend this period as required.

The guideline G03 and the associated background report (ENSI 2020b) show the current definitions and requirements of ENSI regarding repository monitoring and the pilot repository (Tab. 2-3, Tab. 2-4, Tab. 2-5).

Tab. 2-3: Definitions of monitoring and pilot repository according to ENSI Guideline G03 (ENSI 2020a)

Note: ENSI provides only German definitions in ENSI (2020a).

Überwachung	Überwachung ist die über längere Zeit kontinuierliche oder periodische Beobachtung einer Eigenschaft, die Messung einer Kenngrösse oder die Summe aller solcher Beobachtungen und Messungen.
Pilotlager	Das Pilotlager ist ein eigenständiger, vom Hauptlager abgetrennter Teil des geologischen Tiefenlagers, in dem das Verhalten der Abfälle, der Verfüllung und des Wirtgesteins bis zum Ablauf der Beobachtungsphase überwacht wird.

Tab. 2-4: Extracts of guideline G03 (ENSI 2020a) in relation to pilot repository monitoring

Note: ENSI provides only a German version of ENSI (2020a).

6.1	Überwachung
a.	Für die Bau-, Betriebs- und gegebenenfalls Nachverschlussphase eines geologischen Tiefenlagers ist ein integrales Überwachungsprogramm zu erstellen.
b.	Das integrale Überwachungsprogramm hat mindestens die Überwachung des geologischen Umfelds, die radiologische Umweltüberwachung, die radiologische Überwachung während der Betriebsphase, die Überwachung im Pilotlager sowie die messtechnische Überwachung während Bau und Betrieb zu umfassen.
c.	Der Zusammenhang zwischen den verschiedenen Überwachungsaspekten ist im Überwachungsprogramm aufzuzeigen.
d.	Das Überwachungsprogramm muss von den Entsorgungspflichtigen periodisch sowie zu den Bewilligungsgesuchen des geologischen Tiefenlagers auf seine Eignung hin geprüft, nach Bedarf aktualisiert und dem ENSI eingereicht werden.
e.	Die Überwachung eines geologischen Tiefenlagers muss rechtzeitig und spätestens mit der Rahmenbewilligung aufgenommen und solange fortgeführt werden, bis das geologische Tiefenlager nicht mehr der Kernenergiegesetzgebung untersteht.
f.	Die Überwachung hat die Messungen aus der Standortcharakterisierung zu berücksichtigen.
g.	Der Einfluss der für die Überwachung vorgesehenen Installationen auf die Langzeitsicherheit ist aufzuzeigen und zu minimieren
h.	Die Ergebnisse der Überwachung sind mit der periodischen Berichterstattung zu dokumentieren und dem ENSI einzureichen.
i.	Rückstellproben sind aufzubewahren und den Behörden bei Bedarf zur Verfügung zu stellen.
6.2	Pilotlager
a.	Die Auslegung des Pilotlagers muss ein Überwachungsprogramm zur zeitlichen Entwicklung des Pilotlagers und seines geologischen Umfeldes berücksichtigen.
b.	Störfälle im Pilotlager dürfen die Betriebs- und Langzeitsicherheit des geologischen Tiefenlagers nicht beeinträchtigen und umgekehrt.
c.	Ein Pilotlager ist vor Beginn der Einlagerung der entsprechenden Abfälle in das Hauptlager zu beschicken, zu verfüllen und zu versiegeln.
d.	Eine eventuelle Umlagerung der Abfälle aus dem Pilotlager in einen neu aufgefahrenen Lagerstollen ist bei der Auslegung zu berücksichtigen.

Tab. 2-5: Extracts of the background report to guideline G03 (ENSI 2020b) in relation to pilot repository monitoring

Note: ENSI provides only a German version of ENSI (2020b).

6.1	Zu Kapitel 6.1 Überwachung
	Die Überwachung ist für jeden Überwachungsaspekt stufengerecht an die jeweilige Phase anzupassen. Dabei erfolgt der Übergang vom Überwachungskonzept über das Überwachungsprogramm bis zur Überwachung themenspezifisch, schrittweise und stufengerecht.
	Gemäss Art. 23 KEV muss mit dem Rahmenbewilligungsgesuch ein Konzept für die Beobachtungsphase eingereicht werden. Diese Vorgabe wird in der Richtlinie auf das gesamte geologische Tiefenlager sowie alle Phasen der Realisierung des Lagers erweitert.
	Die Überwachung im Pilotlager respektive der Experimente in den Testbereichen dienen dazu, die Prozesse bezüglich der Abfälle und der Sicherheitsbarrieren vor Ort zu beobachten und Daten zur Erhärtung des Sicherheitsnachweises zu ermitteln (Art. 65 und 66 KEV). Die Resultate dieser Überwachung liefern Grundlagen für den Verschluss des geologischen Tiefenlagers.
6.2	Zu Kapitel 6.2 "Pilotlager"
	In Art. 66 KEV sind Aspekte zur Auslegung des Pilotlagers bereits detailliert geregelt. Für seinen Zweck muss das Pilotlager in der Bauweise und im Inventar repräsentativ für das Hauptlager sein. Im Gegensatz zum Hauptlager muss das Pilotlager mit Überwachungseinrichtungen instrumentiert und entsprechend ausgelegt werden. Dazu kann das Pilotlager aus einer oder mehreren Kavernen beziehungsweise einem oder mehreren Stollenabschnitten bestehen. Im Pilotlager und seiner Umgebung soll die Wirksamkeit des Barrierensystems überwacht werden. Dies soll Schlüsse auf das korrekte Funktionieren des Hauptlagers er-möglichen. Das Pilotlager dient dazu, physikalische und chemische Vorgänge im Hauptlager an einem realistischen Abbild zu beobachten. Es dient auch der Information der Bevölkerung über die Entwicklungen des Hauptlagers während der Beobachtungsphase.
	Die Dauer der Beobachtungsphase in der Schweiz wird anhand aktualisierter Unterlagen nach Abschluss der Einlagerung der Abfälle durch das UVEK festgelegt (Art. 68 KEV). Die Verordnung über den Stilllegungsfonds und den Entsorgungsfonds für Kernanlagen vom 7. Dezember 2017 (SEFV 2017; SR 732.17) geht für die Berechnung der Entsorgungskosten von einer Dauer der Beobachtungsphase von fünfzig Jahren aus. Unter Berücksichtigung der Dauer für Bau, Einlagerungsbetrieb, Beobachtungsphase und Verschluss dürfte die Standfe-stigkeit der unterirdischen Bauwerke auf über hundert Jahre auszurichten sein. Das Projekt für die Beobachtungsphase ist alle zehn Jahre zu überprüfen und nachzuführen (Art. 42 KEV). Eine zu lange Beobachtungsphase kann die Langzeitsicherheit gefährden, zum Bei-spiel durch das verlängerte Offenhalten von Hohlräumen und einen allfälligen Kontrollverlust über das Tiefenlager, ohne dass ein signifikanter Mehrwert an Informationen zu erwarten ist.
	Zu Bst. a: Um die Verhältnisse im Pilotlager zu verfolgen und Anzeichen von ungünstiger Wechselwirkung zwischen Barrieren zu erkennen, können zum Beispiel folgende Aspekte überwacht werden: • zeitliche Entwicklung der Temperaturverteilung • Wasseraufsättigung • Druckverhältnisse (Wasser, Gas, Gebirge) • felsmechanisches Verhalten des Gebirges und Mikroseismizität

Tab. 2-5: Cont.

	• chemische Parameter der Poren- und Kluftwässer • Gasentwicklung aus den Abfallgebinden
	Viele der im Hauptlager erwarteten Prozesse laufen viel zu langsam ab, als dass sie während der Beobachtungsphase im Pilotlager erfasst werden könnten. Es ist daher zu erwarten, Zu Bst. b: Die Anforderung ergänzt die vorgegebene räumliche und hydraulische Trennung gemäss Art. 66 Abs. 3 Bst. b KEV. Zu Bst. c: Um eine möglichst lange Beobachtungsdauer zu erreichen und frühzeitig auf mög-licherweise unerwartete Erkenntnisse aus der Beobachtung des Pilotlagers reagieren zu können, sollen die Beschickung und die Überwachung des Pilotlagers vor dem Beginn der Einlagerung im Hauptlager erfolgen. Zu Bst. d: Die Überwachungseinrichtungen könnten die langfristige Wirkung der Barrieren des Pilotlagers beeinträchtigen und damit dessen Langzeitsicherheit gefährden. Daher ist bei der Auslegung der untertägigen Bauwerke zu berücksichtigen, dass für die Überführung des Pilotlagers in einen langfristig sicheren Zustand eine Umlagerung der Abfälle aus dem Pilot-lager in einen neu aufgefahrenen Lagerstollen notwendig sein kann.

3 Objectives of pilot repository monitoring

One of the basic design principles of a deep geological repository is that long-term safety is provided through passive safety with a multibarrier concept (KEV Art. 11 and ENSI 2020a). The individual elements of the barrier system are the waste matrices, the disposal canisters, the materials used for backfilling and sealing of the underground structures, the host rock and other geological formations that may additionally contribute to the confinement of radioactive materials (confining units). Monitoring should not compromise the performance of these barriers. However, monitoring features prominently in the implementation of a deep geological repository, because it can provide the repository implementer, expert reviewers (e.g. safety authorities) and lay (e.g. public) stakeholders with in situ data of the repository project.

The overarching monitoring concept of Nagra foresees currently four different main monitoring programmes. Surface-based monitoring will be done in the framework of the so-called ÜUG ("Überwachung Umwelt und geologisches Umfeld", Fanger et al. 2021) and has the main objective to provide data for conservation of evidence before, during and after the repository construction, operation and closure. Collection of information from surface-boreholes is included in ÜUG. Underground monitoring, excluding the pilot repository, will be done in the framework of the underground geological investigations, the so-called EUU ("erdwissenschaftliche Untersuchungen untertag", Nagra 2021b). The main objective is to provide site-specific underground monitoring and exploration data for enhanced site characterisation and for long-term safety assessments. A key feature of the EUU are experiments and demonstrations in the experimentation areas and demonstration structures (numbers 4, 5, 6 of Fig. 1-1) to collect site-specific data to strengthen the safety case before the submission of construction and operating licence applications. These in-situ experiments are complemented by laboratory programmes and by generic (non-site-specific) investigations, for example experiments in other underground research laboratories (URL). Monitoring for operational safety (underground and at surface) will be done in the framework of the operating safety programme. The main objective of the fourth monitoring programme, the pilot repository monitoring, is to provide monitoring data in support of the safety case after granting the operating license. A common objective for all monitoring programmes is to contribute to increased stakeholder confidence regarding the disposal system.

The specific aims of the pilot repository monitoring programme are:

- to provide information on the behaviour of the actual emplaced multibarrier system
- to check predictive models of multibarrier system behaviour
- to allow early detection of any unexpected and undesirable system evolution
- to provide input for decisions regarding the closure of the access structures to the main repository, the continuation of monitoring, and the closure of the entire facility.

The opportunities for monitoring the engineered barrier system of the pilot repository and the host rock directly surrounding the pilot repository are limited, because the passive safety may not be compromised. However, repository-induced effects in the far-field rock can be monitored using surface-based observation methods such as boreholes e.g. for hydrological changes in deep aquifers or temperature changes.

4 Development of the pilot repository monitoring programme

Owing to the stepwise planning and implementation of the repository, the development of the pilot repository monitoring programme is a stepwise procedure, too. An important milestone of the development of the overarching monitoring concept incl. pilot repository monitoring is the general license application. According to KEV Art. 23 a concept for the Monitoring Phase must be submitted together with the general license application. ENSI (2020a) extends this monitoring requirement to all phases and all parts of the repository.

The overarching monitoring concept for the general license application will consider site-specific aspects. However, the considerations about pilot repository monitoring will remain at a conceptual level. In this context this report presents a first basic document with generic concepts. Nonetheless, the conceptual parts of this report and of the monitoring documents for the general licence application are designed to be able to implement adjustments in the future, if necessary. The next steps for the further development of the pilot repository monitoring for the general licence application are:

- integration into the overarching monitoring concept
- inclusion of planned updates of the safety case
- re-evaluation of the methodology for selection of monitoring parameters
- refinement of strategy for interpretation and transferability of monitoring data based on results from R&D projects
- refined identification of R&D needs for monitoring technology.

For the nuclear construction license (construction of pilot and main repositories) a project for the monitoring period must be part of the application documents. At this stage the repository design will be presented as part of the application, including specification of the location and number of tunnels, caverns, drifts, branches, and seals in compliance with the legal requirements. The detailed design of the pilot repository monitoring programme will be prepared when the results of the underground geological investigations are available. In addition, new developments in monitoring technology might become available and will be considered at this time. To be able to react early to new technology developments, Nagra continuously reviews the state-of-the-art and undertakes R&D on monitoring technology.

After the emplacement of the waste has been completed, the owner of the repository must describe in an up-dated project the planned measures for monitoring the repository and proposes the duration for the Monitoring Phase (Art. 68 KEV). However, the duration of the Monitoring Phase is determined by the Federal Department of the Environment, Transport, Energy and Communications (DETEC).

5 Preliminary sequence of instrumentation for pilot repository monitoring

Geological surveys undertaken during the construction of the observation drifts (11 and 19 in Fig. 1-1 respectively) are the first step in the sequence of pilot repository monitoring. The observation drift provides first geological, hydrogeological, and geotechnical information about the location of the pilot repository. The observation drift will be used to drill and instrument boreholes for monitoring the entire life cycle of the pilot repository from pre-construction state over effects of construction and ventilation, to emplacement and post-emplacement processes. To cover different directions around the pilot repository, e.g. parallel and perpendicular to the pilot repository, a "L-shape" was chosen for the observation drift in the current planning phase. The distance to the pilot repository must take long-term safety requirements into account, but also allow drilling and instrumentation of boreholes covering the pilot repository area.

During construction of the pilot repositories, geological, hydrogeological, and geotechnical surveys and monitoring will be undertaken to support detailed characterisation of the pilot repositories. Prior to emplacement, the drifts and cavern will be exposed to atmospheric conditions and ventilation resulting in changes of the near-field conditions in the direct vicinity of the pilot repository. Monitoring in and around the drifts and cavern during this period will provide a record of these changes and allow an understanding of boundary conditions to be developed before emplacement.

Before emplacement, temporary monitoring instrumentation will be removed. If any monitoring instrumentation is left in the drifts and cavern for monitoring, some of the instrumentation could be used to also monitor the emplacement and backfilling process. For example, fibre-optic sensors and distributed temperature sensing were used to investigate in situ the dry density of the emplacement granulated bentonite material within the Full-scale Emplacement (FE) experiment at the Mont Terri URL (Sakaki et al. submitted, Sakaki et al. 2018). This investigation method can be used as quality control during emplacement and as monitoring method for heat transport processes after emplacement.

Once emplacement in the pilot repository is completed, monitoring of the pilot repository during the remaining operation phase and the subsequent Monitoring Phase is conducted. After part 1 of the Monitoring Phase, the access to the pilot repository drifts and cavern will be backfilled and sealed (Nagra 2021c) and only access to the observation drift is possible during part 2 of the Monitoring Phase.

The presented sequence is generic and not site specific. During the stepwise development of the actual repository design the monitoring sequence will be refined and can be adapted.

6 R&D projects

Nagra is looking back on comprehensive experience of R&D projects that were related to pilot repository monitoring. The projects have focused on monitoring concepts, strategic aspects and the link to safety analysis, as well as practical work on the development and testing of monitoring techniques and sensors.

On a European level, Nagra was involved in the European Thematic Network on the role of monitoring for geological disposal of radioactive waste (EC 2004). The network had the objective to improve both the understanding of the role of monitoring as well as to identify how monitoring can contribute to decision making. The work covered also potential monitoring strategies, requirements, and methods. Moreover, Nagra participated in two research projects where knowledge about plug and seal monitoring (Full-scale Demonstration Of Plugs And Seals – DOPAS) and about monitoring during construction and emplacement (Large Underground Concept Experiments – LUCOEX) were generated. In addition, Nagra participated in the EC project "Long-term Performance of Engineered Barrier Systems – PEBS" (Schäfers et al. 2014) where valuable experience was gained for THM monitoring in the bentonite based engineered barrier system. However, the most important R&D projects with Nagra participation on European level related to underground and pilot repository monitoring of the last 10 years were the following:

- Monitoring Developments for Safe Repository Operation and Staged Closure – MoDeRn (White 2014)
- Development & Demonstration of monitoring strategies and technologies for geological disposal – Modern2020 (White & Scourfield 2019)

In addition, particular valuable knowledge was provided by in situ experiments in the Mont Terri and Grimsel URL. These URLs offer the opportunity to test and evaluate different monitoring technologies under repository like conditions. A summary of the Modern2020 project as well as selected experience from URL experiments is presented in the next chapters.

6.1 Modern2020

The EC project Modern2020 was conducted from 2015 – 2019 and aimed to provide the means for developing and implementing effective and efficient repository operational monitoring programmes, taking into account the requirements of specific national programmes (White & Scourfield 2019). Nagra participated actively in the Modern2020 project. The project delivered significant progress on the development of monitoring strategies and technologies that can be used in the development of the pilot repository monitoring programme.

In the framework of the Modern2020 project the generic iterative monitoring workflow from the former EC project MoDeRn (Breen et al. 2013) was modified throughout (Fig. 6-1). A detailed description of the workflow is given in Farrow et al. (2019). The Nagra approach for parameter selection presented in the Chapter 7 covers many of the elements of the first two major steps from the Modern2020 workflow, namely the i) objectives, processes and parameters, and the ii) monitoring programme design, although the final step of designing an actual monitoring programme is not included, since the Nagra disposal programme is not currently at the stage when this is needed.

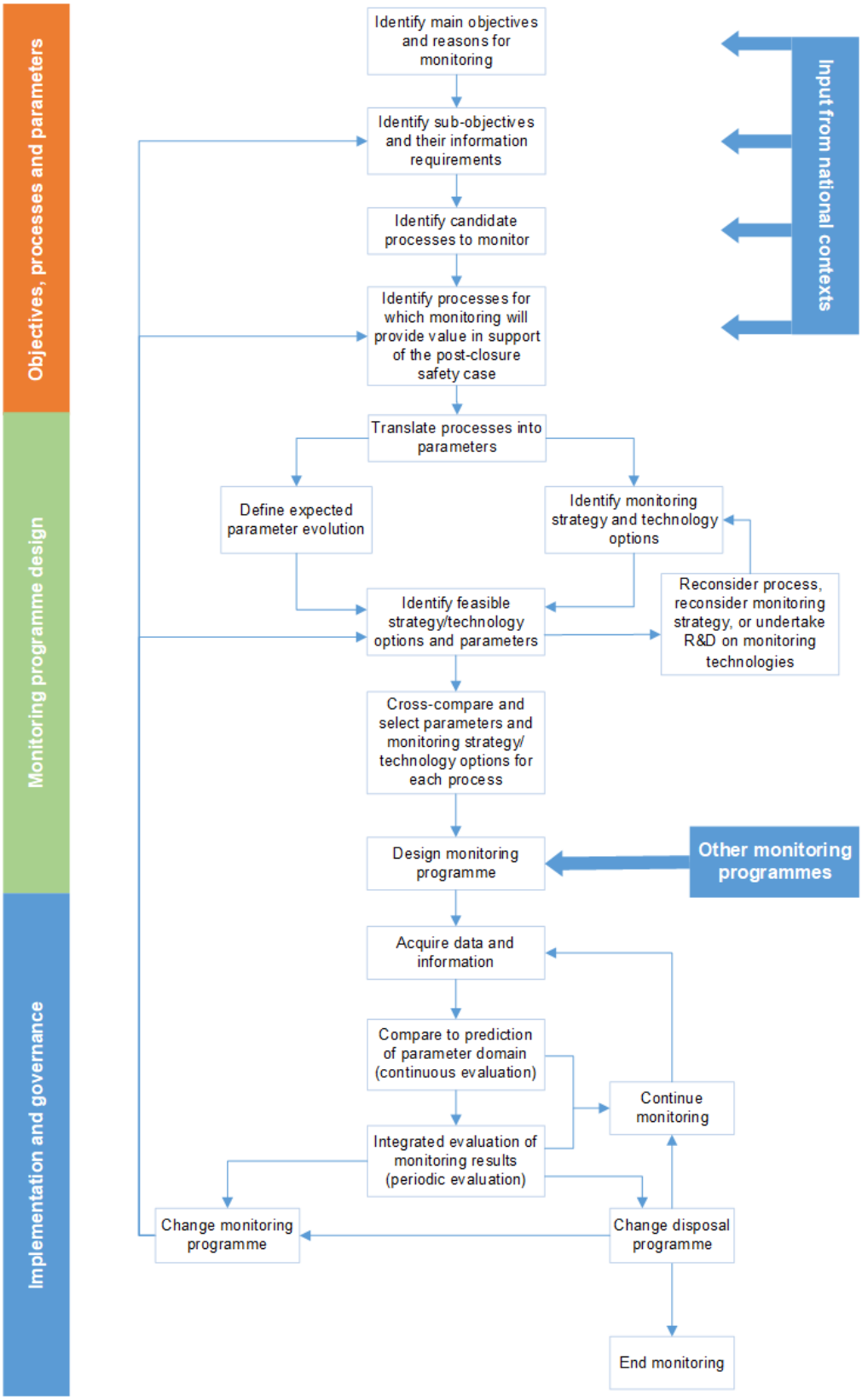

Fig. 6-1: Modern2020 Monitoring Workflow (White & Scourfield 2019)

The Modern2020 project focused on monitoring of the near-field during repository operations. Environmental monitoring and operational safety monitoring were neither the scope of Modern2020 project nor the previous MoDeRn project. The work addressed the following issues:

- strategy – development of a detailed methodology for screening proposed monitoring parameters to develop a needs-driven monitoring programme and to develop approaches for responding to monitoring information
- technology – resolution of technical issues in repository monitoring, including gaps in R&D in monitoring technologies. This included R&D into the coupling of different wireless data transmission technologies, power supply, geophysics, fibre-optic sensors, and reliability and qualification of components
- demonstration and practical implementation – enhancement of the knowledge on the implementation and performance of state-of-the-art and innovative monitoring techniques by running full-scale in-situ demonstrations
- societal concerns and stakeholder involvement – development and evaluation of the ways for societal involvement in international collaborative research into monitoring as basis for integration of public stakeholders concerns and societal expectations into national repository monitoring programmes

The Modern2020 project was structured into six work packages. The Nagra workflow presented in Chapter 7 presents a contribution to work package 2, which concerns the linking of monitoring objectives to the safety case and the decision-making strategies. The general objective was to test the methodology for the screening of monitoring parameters, which have been identified and developed (White et al. 2017). The methodology developed was high-level and generic with the following aims:

- evaluate the role of monitoring within the post-closure safety case
- evaluate high-level monitoring strategies
- consider the range of decisions to be made during repository implementation that will require information from monitoring
- develop screening methodologies used to develop monitoring parameter lists for different national monitoring contexts

It is, however, recognised in Modern2020 that the details of the used approach will depend on national and programme-specific constraints. A revised version of the Modern2020 screening methodology was therefore developed in response to the feedback from the different test cases (Farrow et al. 2019). The philosophy that underpins the Modern2020 screening methodology is to consider each potential monitoring process in turn at three interlinked levels:

- processes – identification of relevant processes to post-closure safety, i.e. objectives for monitoring taking the expected evolution of the disposal system during the monitoring period into account
- parameters – selection of parameters that should be monitored in practical (implementable) programmes by using the screening methodology
- technologies – prove of the technical feasibility and evaluation of the impact on safety and environment

6.2 R&D on monitoring technologies

Monitoring of the geosphere during site investigations and monitoring of experiments in URLs has demonstrated that it is feasible to collect detailed information to support understanding of the evolution of the disposal system, and to use that understanding to support the development of the long-term safety case (Nagra 2002a). A broad range of technologies exists for undertaking monitoring. However, monitoring of the disposal system during the Monitoring Phase provides particular challenges, specifically associated with ensuring the passive safety of the disposal system and the reliability and longevity of the monitoring technology. The ability to monitor the multibarrier system and the extent to which such monitoring can provide detailed understanding of its evolution can be enhanced through development of novel technologies. The pilot repository monitoring programme would benefit from further development of the most promising novel technologies.

6.2.1 Completed projects

Besides the strategic and screening work within Modern2020, R&D on a broad spectrum of monitoring technologies was performed. The aim was to make them suitable for repository monitoring purposes. The following list summaries the most important Modern2020 R&D topics related to monitoring technology:

- wireless data transmission (different ranges based on different frequencies)
- alternative power supply sources (nuclear batteries; energy harvesting from thermal gradients; chemical batteries with ceramic capacitor)
- non-intrusive geophysical monitoring techniques (seismic waveform inversion; electrical resistivity and induced polarization tomography)
- fibre-optic sensing (distributed fibre-optic sensing for temperature, strain and hydrogen detection; fibre-bragg gratings for pH and hydrogen sensing)

In addition, a common methodology for qualifying the components of the monitoring system was established and in-situ demonstrations of the implementation of monitoring technologies in large-scale experiments were conducted (Verstricht & Betrtrand 2019).

In addition to participation in international projects, Nagra has developed expertise in monitoring of the engineered barrier system (EBS) and host rock through conducting multiple reduced-scale and full-scale experiments in both the Mont Terri and Grimsel URL. Besides enhanced process understanding these experiments were used for further developing, evaluating, and testing different sensor and monitoring technologies. For this purpose, state-of-the-art monitoring techniques and prototype sensors have been used. First valuable monitoring expertise for large-scale heating experiments was gained with the "Full Scale Engineered Barrier Experiment" (FEBEX) at the Grimsel URL (Lanyon & Gaus 2016). Monitoring during tunnel construction in the Opalinus Clay was done successfully in the "Mine By" (MB) and the "Testing Different Tunnelling Support in Sandy Facies During Excavation of Gallery 2018/19" experiment (TS) at the Mont Terri URL. Non-intrusive geophysical monitoring techniques were being tested and further developed at the Grimsel Test Site in the "Test and Evaluation of Monitoring Systems" (TEM) experiment and at Mont Terri in the "Gas path through host rock and along seals" (HG-A) as well as FE experiments (Marelli et al. 2010; Maurer & Greenhalgh 2012). Wireless data transmission was tested in the long-term TEM experiment at the GTS (Breen et al. 2012; Tuñon Valladares et al. 2019). At the Mont Terri URL, the long-term evolution of hydraulic heads in Opalinus Clay around the URL was investigated by the "Long-Term Monitoring of Pore Pressures" (LP) experiment, designed to better understand construction-induced effects and the

evolution of water flow (Ababou et al. 2012). In addition, similar to dismantling of the Swedish prototype repository (Nilsson 2014), the dismantling of the remaining part of the FEBEX experiment at the Grimsel Test Site and the dismantling of the "Engineered Barriers" (EB) experiment at Mont Terri allowed the evaluation of the durability and reliability of typical sensors after decades of varying and challenging monitoring conditions (Martínez et al. 2016).

6.2.2 Ongoing projects

Particular expertise in monitoring on full scale provides the FE experiment at the Mont Terri URL, because different monitoring technologies were implemented to compare and evaluate their performance under repository-like conditions. After 7 years of heating (Fig. 9-1) important experience was obtained regarding:

- sensor calibration, performance and reliability of sensors, especially fibre-optic distributed temperature and strain sensing (Vogt et al. 2019)
- improvements of different non-intrusive geophysical monitoring techniques, including evaluation of differences and synergies in them (Maurer et al. 2019)
- management of data from several hundred point-sensors and about 2.5 km of fibre-optic sensing cables resulting in more than a million measurements per day (Yeatman et al. 2019)

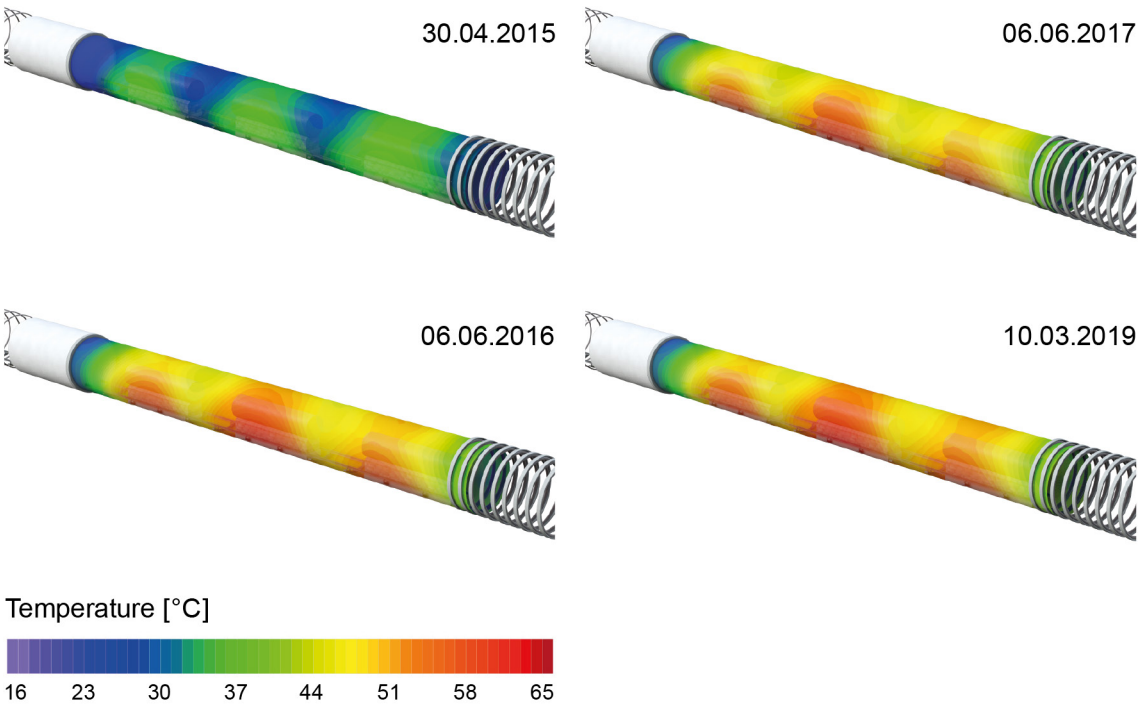

Fig. 6-2: Evolution of the temperature distribution along the tunnel wall of the FE experiment measured by means of fibre-optic distributed temperature sensing

In addition, valuable experiences are made regarding monitoring technologies for bentonite and sand-bentonite mixtures with high water saturation in the framework of the GAST experiment at the Grimsel URL (Spillmann et al. 2015), which is running now for 8 years. Moreover, the "high temperature effects on bentonite buffers" (HOTBENT) experiment, which was newly implemented at the Grimsel URL, will provide unprecedented experience on monitoring techniques under very high temperature conditions.

On European level the project "Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure – MODATS" is currently ongoing. The MODATS project is a work package of the joint programme EURAD and covers aspects of data management, treatment, and interpretation (see Chapter 8.1). Within MODATS the R&D on monitoring technologies is focussing on:

- geophysical methods, new sensor developments and their testing and application in experimental setups (joint geophysical inversion and tomography techniques, spectral induced polarization, automatized passive seismic monitoring, automatized digital mapping of leakages)
- new sensing capability, qualifying optical fibres for various monitoring technologies and gleaning additional insights from distributed measurements of temperature and strain (qualification of radiation tolerant cable, advancements in distributed fibre-optic strain sensing, distributed fibre-optic temperature sensing in extreme conditions, pH-optrode)
- interactions between sensors and the multibarrier system (FEP analysis of interactions, analysis of harsh environment impacts)

Within MODATS, Nagra will develop together with ETH Zürich novel geophysical analysis tools to:

- set up joint inversion of various geophysical data to better constrain the model parameters
- establish suitable constitutive relationships between relevant geotechnical parameters and physical material properties
- identify other constraints that can be supplied (e.g., geological a priori information), and
- combine all constraints and constitutive parameter relationships in the joint inversion schemes

This project will involve algorithmic developments and tests with synthetic data and application of the new methodology to the FE experiment.

The focus of Nagra's work on fibre-optic sensing will be in MODATS on distributed strain sensing. The application of distributed fibre-optic strain sensing under repository conditions requires advanced analysis techniques, detailed comparisons of different sensor types and measurement techniques, and the evaluation of possible time-dependent effects of the sensor performance from aging. Developments to these aspects will be achieved through analysis of strain data collected as part of the TS experiment in the Mont Terri URL.

6.3 AGNEB project «Auslegung und Inventar des Pilotlagers»

The AGNEB (Arbeitsgruppe des Bundes für die nukleare Entsorgung - Federal Workgroup for Nuclear Waste Disposal) project "Auslegung und Inventar des Pilotlagers", which was conducted by the Swiss regulator ENSI, addressed regulatory questions about the layout, inventory and monitoring of the pilot repository (ENSI 2021). The project evaluated the processes that will operate in the pilot repository on different timescales and identified the monitoring parameters that are of interest for the regulator. The project also considered the regulatory relevance of monitoring parameters whose associated processes will occur after the monitoring phase is completed.

ENSI (2021) concluded that there are currently no additional regulatory requirements for the pilot repository monitoring, besides the currently applicable regulations, i.e. G03 (ENSI 2020a). The stepwise procedure, consisting of development of a monitoring concept for the general license application followed by an actual project with detailed design of the monitoring programme for the construction application, is considered appropriate.

7 Parameter selection

This chapter presents an approach to identify parameters for the pilot repository that would be both useful for building further confidence in long-term safety and technically feasible to monitor. Parameters that might be monitored for other reasons, such as operational safety and environmental monitoring, fall outside the scope of the methodology as currently formulated. The presented methodology for parameter selection was developed by Nagra (Smith et al. 2019; Frieg et al. 2019) as a contribution to the Modern2020 project. This workflow is based on the results and workflows of the MoDeRn and Modern2020 projects and was adapted for the Swiss concept and safety case.

The methodology for the identification of potential pilot repository monitoring parameters consists of the workflow depicted in Fig. 7-1. The methodology for the identification of potential monitoring parameters, as well as its application to HLW disposal, has been implemented in a database to allow for transparency and traceability. Application of the methodology to the L/ILW pilot repository is yet to be undertaken. The following chapters contain selected examples of the database tool. The methodology consists of the following five steps (also shown in Fig. 7-1), which are described sequentially in the following sections:

STEP 1 – Identify key, safety-relevant parameters

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

STEP 3 – Consider the technical practicability of monitoring those parameters identified as being of first and secondary priority

STEP 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

STEP 5 – Assess and document the overall rationale for monitoring those parameters identified in Steps 1 through 4

The presented methodology is preliminary; however, it is flexible and allows regular re-evaluations. The next re-evaluations are planned for the preparation of the general licence application and include:

- integration of updates to the safety case
- re-evaluation of the methodology as well as of the content (parameter lists, state-of-the-art monitoring techniques) of the database

7.1 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. It should be noted that, although all parameters are identified on the basis of their relevance to long-term safety, a few of these may be of interest for other reasons as well, including, for example, operational safety, environmental impact and addressing the concerns of stakeholders, including the general public. These other reasons for parameters being of interest are noted in the database tool.

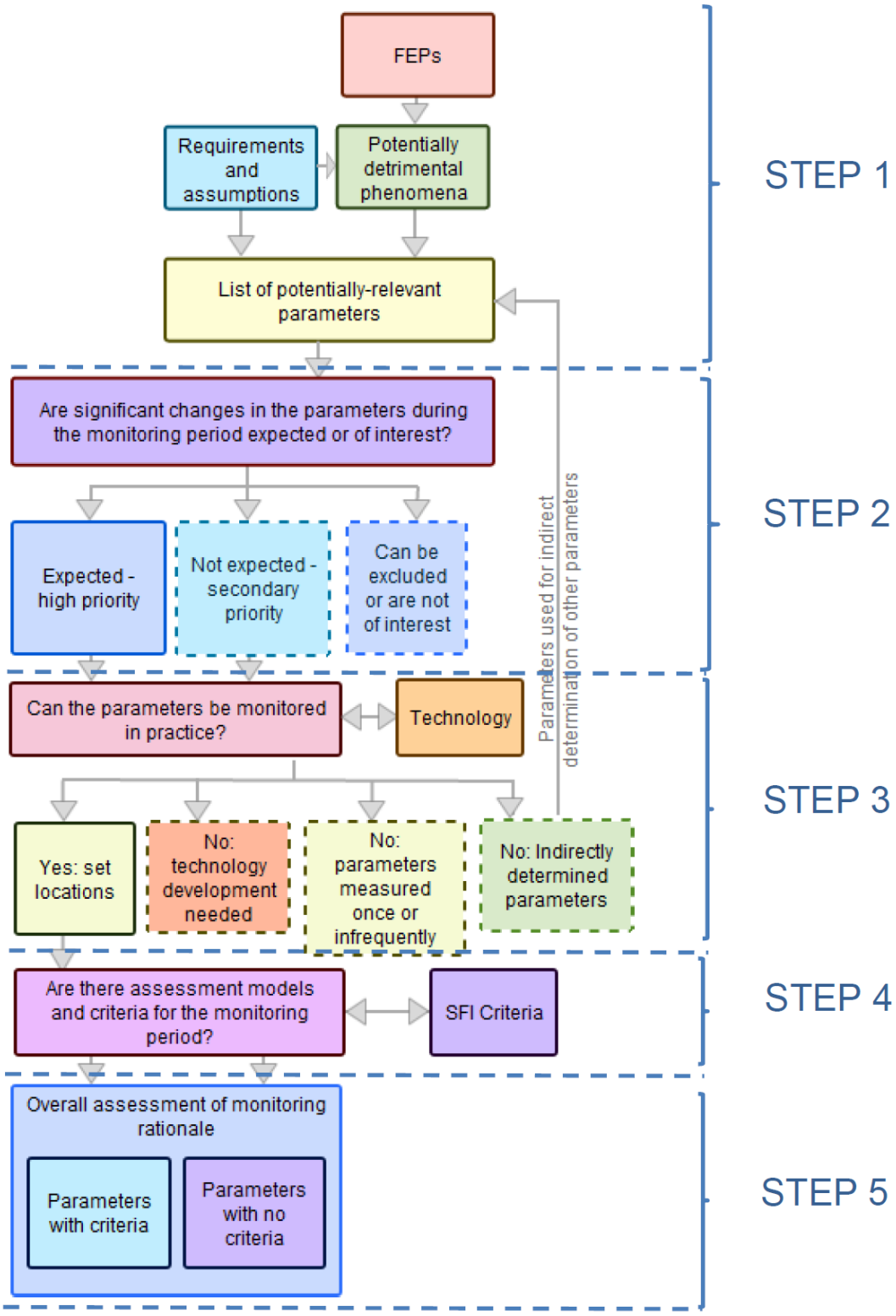

Fig 7-1: The five steps in Nagra's preliminary methodology for the identification of candidate monitoring parameters for pilot repository monitoring

7.1.1 Parameters that define safety-related requirements and reference assumptions for safety assessment

The set of parameters currently identified in the database tool as defining safety-related requirements on the overall system and its components and/or reference assumptions for safety assessment is shown in Tab. 7-1. The safety-related requirements and reference assumptions for safety assessment have been taken from previous Nagra studies (Leupin & Johnson 2013, Nagra 2002a, Nagra 2002b, Nagra 2008a, Nagra 2008b, Nagra 2014, Nagra 2016, Patel et al. 2012). The identification of these parameters involved going through the requirements and assumptions, one-by-one and picking out parameters that define (or appear prominently in) these requirements and assumptions.

Tab. 7-1: Parameters currently identified in the database as defining safety-related requirements on the overall system and its components and/or reference assumptions for safety assessment

Containment time (HLW canister)
Density (HLW buffer)
Eh (Opalinus Clay porewater)
Fluid flow rate (Opalinus Clay)
Fluid pressure (Opalinus Clay)
Hydraulic conductivity (Opalinus Clay)
Hydraulic conductivity (HLW buffer)
Ionic strength (Opalinus Clay porewater)
Liquid flow rate (emplacement room EDZ)
Minimum radionuclide transport distance (Opalinus Clay)
Outer diameter (HLW emplacement rooms)
pH (Opalinus Clay porewater)
Radiation dose (canister surface)
Seismic displacement/acceleration (Opalinus Clay)
Stress/strain (HLW canister)
Swelling pressure (HLW buffer)
Temperature (Opalinus Clay)
Thermal conductivity (HLW buffer)
Total stress (Opalinus Clay)
Vertical position (HLW canister)

7.1.2 Parameters related to potentially detrimental phenomena

Unlike the requirements and assumptions of the previous section, the set of potentially detrimental phenomena that has been used to support safety-relevant parameter identification has not been taken from existing Nagra work. Rather, it has been derived for the present study by considering:

- which phenomena could exist that might compromise the ability of the system to meet the safety-related requirements or conform to the reference assumptions mentioned in the previous section, and/or
- which phenomena are included in Nagra's FEP[1] list (Nagra 2002c) that 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.

In practice, the identification of phenomena involved going through the requirements and assumptions one-by-one and identifying phenomena that could compromise them. A completeness check was done against monitoring parameters discussed in Modern2020. Similarly, the FEPs within the FEP database have been assessed one-by-one for any potentially detrimental phenomena that they might incorporate. In the process, to keep the list of phenomena reasonably short, some FEPs have been merged; e.g. the various FEPs related to different canister corrosion processes have been combined within the phenomenon Corrosion (canister). The full set of potentially detrimental phenomena currently identified in the database as defining safety-related requirements on the overall system and its components is shown in Tab. 7-2.

The subsequent step has involved simply going through the potentially detrimental phenomena one-by-one and identifying parameters that quantify, influence, or indicate the occurrence of each phenomenon. During this process, the existing parameter list was considered first, and additional parameters added when needed. The set of parameters currently identified in the database as quantifying, influencing, or indicating the occurrence of potentially detrimental phenomena is shown in Tab. 7-3. Some of these parameters are also listed in Tab. 7-2; a parameter can be assigned more than one reason why it is safety relevant, and this overlap tends to favour comprehensiveness in the overall parameter set.

[1] The abbreviation FEP stands for "Features, Events and Processes".

Tab. 7-2: Phenomena currently identified in the database as being potentially detrimental to long-term safety

Activation of faults
Cementation (clays)
Chemical alteration (high-pH fluid/clay)
Chemical alteration (iron/clay)
Chemical degradation (seals)
Corrosion (canister)
Corrosion (tunnel support)
Corrosion/gas generation
Desaturation/resaturation (Opalinus Clay)
Displacement/sinking (canister)
Divergence/convergence (access tunnels)
Divergence/convergence (emplacement rooms)
Earthquakes/seismic activity/neotectonics
EDZ formation/evolution
Evaporation of water and precipitation of salts (Opalinus Clay)
Failure of quality control/Presence of defects
Fluid flow and advective transport (access tunnels)
Fluid flow and advective transport (HLW emplacement room EDZ)
Gas generation, pressurisation and migration
High-temperature creep and hydrogen embrittlement (canister)
Incomplete homogenisation/non-uniform swelling pressure
Mechanical load/deformation (canister)
Microbial activity under aerobic conditions
Mishaps during handling (canister)
Nuclear criticality
Oxidation of sulphides and organic carbon (Opalinus Clay)
Pathway dilation/gas fracs/hydrofracs
Slow saturation
Thermal alteration/illitisation/cementation (clays)
Thermal expansion (pore fluids and minerals)

Tab. 7-3: Parameters currently identified in the database as quantifying, influencing, or indicating the occurrence of potentially detrimental phenomena

Chemical composition (Opalinus Clay porewater)
Chemical composition (HLW buffer porewater)
Corrosion rate (emplacement tunnel reinforcement)
Corrosion rate (HLW canister)
Density (HLW buffer)
Dissolved gas concentration (HLW buffer)
Effective void volume evolution (EDZ)
Eh (Opalinus Clay porewater)
Eh (HLW buffer porewater)
Fluid flow rate (Opalinus Clay)
Fluid pressure (Opalinus Clay)
Fluid pressure (HLW buffer)
Fluid pressure (HLW emplacement room EDZ)
Gas composition (HLW buffer)
Gas entry pressure
Heat flux (canister surface)
Heat generation rate (HLW)
Hydraulic conductivity (HLW emplacement room EDZ)
Ionic strength (Opalinus Clay porewater)
Ionic strength (HLW buffer porewater)
Liquid flow rate (emplacement room EDZ)
Outer diameter (operational tunnels)
Outer diameter (HLW emplacement rooms)
pH (Opalinus Clay porewater)
pH (HLW buffer porewater)
Radial extent (HLW emplacement room EDZ)
Radiation dose (canister surface)
Radioactivity (HLW buffer in gas phase)
Saturation (EDZ)
Saturation (HLW buffer)
Seismic displacement/acceleration (Opalinus Clay)
Stress/strain (HLW canister)
Stress/strain (tunnel liners)
Swelling pressure (HLW buffer)

Tab. 7-3: Cont.

Temperature (Opalinus Clay)
Temperature (HLW buffer)
Temperature (HLW canister)
Thermally-induced rock heave
Total stress (Opalinus Clay)
Total stress (HLW buffer)
Vertical position (HLW canister)

7.1.3 Parameters 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.

For example, the parameter liquid flow rates (Emplacement room EDZ) is safety relevant, appearing in both Tab. 7-1 and Tab. 7-3. However, these flow rates cannot be measured directly using currently available technology. Rather, they are obtained indirectly (i.e. calculated) from parameters that include fluid pressure (HLW Emplacement room EDZ) and hydraulic conductivity (HLW Emplacement room EDZ), which can, in principle, be measured or monitored.

The set of parameters currently identified in the database as being needed for the evaluation of other key parameters that cannot be measured or monitored directly is shown in Tab. 7-4.

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, as shown in Fig. 7-1, there is a feedback from this later step to Step 1 and the full set of key safety-relevant parameters is developed iteratively.

Tab. 7-4: Parameters currently identified in the database as needed for the evaluation of other key parameters that cannot be measured or monitored directly

Chemical composition (HLW buffer porewater)
Electrical conductivity (HLW buffer)
Evaporation rate from open tunnel walls
Fluid pressure (HLW buffer)
Fluid pressure (HLW emplacement room EDZ)
Gas composition (HLW buffer)
Gas partial pressures (HLW buffer)
Heat flux (canister surface)
Heat generation rate (HLW)
Humidity prior to backfilling (operational and access tunnels)
Humidity prior to sealing (HLW emplacement room)
Hydraulic conductivity (HLW emplacement room EDZ)
Radial extent (HLW emplacement room EDZ)
Radiation dose (canister surface)
Saturation (HLW buffer)
Swelling pressure (HLW buffer)
Temperature (HLW buffer)
Thermal conductivity (HLW buffer)
Total stress (HLW buffer)

7.2 STEP 2 – Consideration of whether monitoring is of interest

The second step in the methodology, as shown in Fig. 7-1 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 Monitoring Phase, especially if there are significant uncertainties associated with those changes (Fig. 7-2a). By significant, it is meant e.g. that changes during the monitoring period could result in a criterion being approached or exceeded (see Chapter 7.4; Step 4). 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 (Fig. 7-2b). Finally, if significant changes in a parameter can be confidently ruled out, then the parameter is excluded from further consideration (Fig. 7-2c).

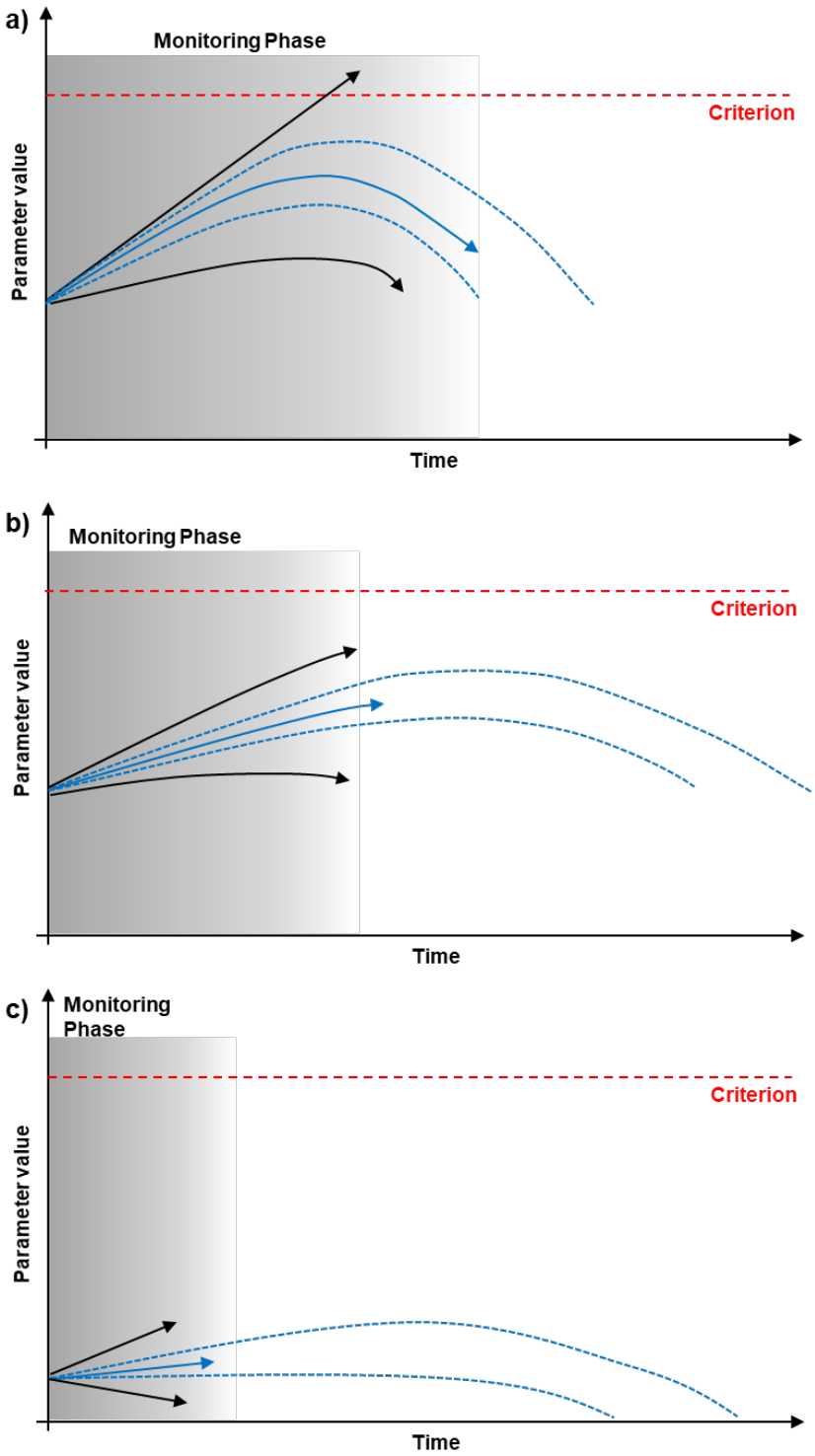

Fig. 7-2: Schematic illustration of the evolution of a parameter during the monitoring phase a) that changes significantly, b) where significant changes are not expected but cannot be entirely excluded, c) where significant changes during the monitoring period can be confidently ruled out

Note: The blue solid arrows represent the most likely parameter evolution, the blue dashed lines show the model predicitions (range), and the black solid arrows represent extrem parameter evolutions.

7.2.1 High priority parameters

Parameters currently identified in the database as being of high priority in that significant changes in their values could occur during the Monitoring Phase are shown in Tab. 7-5. It should be emphasised again that, at this stage, no assessment has been made of whether or not monitoring is possible in practice (this is the subject of Step 3).

The basis for assigning parameters to this category has included expert judgement, experience e.g. from experiments in the Mont Terri URL and also specific modelling studies, as described further in the context of Step 4 in Chapter 7.4.

Tab. 7-5: Parameters currently identified in the database as being of high priority in that significant changes in their values could occur during the monitoring period

Effective void volume evolution (EDZ)
Fluid pressure (Opalinus Clay)
Gas composition (HLW buffer)
Gas partial pressures (HLW buffer)
Heat flux (canister surface)
Hydraulic conductivity (HLW buffer)
Hydraulic conductivity (HLW emplacement room EDZ)
Liquid flow rate (emplacement room EDZ)
Liquid flow rate (inflow open tunnels)
Outer diameter (operational tunnels)
pH (operations tunnel porewater)
pH (HLW buffer porewater)
Saturation (backfilled operational tunnels)
Saturation (EDZ)
Saturation (HLW buffer)
Seismic displacement/acceleration (Opalinus Clay)
Stress/strain (tunnel liners)
Swelling pressure (HLW buffer)
Temperature (Opalinus Clay)
Temperature (HLW buffer)
Temperature (HLW canister)
Thermal conductivity (HLW buffer)
Thermally-induced rock heave
Total stress (Opalinus Clay)
Total stress (HLW buffer)

7.2.2 Secondary priority parameters

Parameters currently identified in the database as being of secondary priority in that significant or poorly predictable changes in their values are not expected to occur but nevertheless cannot be completely excluded during the monitoring period are shown in Tab. 7-6.

In the case of the parameter chemical composition (Opalinus Clay porewater), for example, it is likely (though not completely certain) that the buffer will remain too dry to measure changes during the monitoring phase.

Tab. 7-6: Parameters currently identified in the database as being of secondary priority in that significant or poorly predictable changes in their values are not expected but nevertheless cannot be completely excluded during the monitoring period

Chemical composition (Opalinus Clay porewater)
Chemical composition (HLW buffer porewater)
Corrosion rate (emplacement tunnel reinforcement)
Corrosion rate (HLW canister)
Density (HLW buffer)
Eh (Opalinus Clay porewater)
Eh (HLW buffer porewater)
Electrical conductivity (Opalinus Clay)
Electrical conductivity (HLW buffer)
Evaporation rate from open tunnels walls
Fluid flow rate (Opalinus Clay)
Fluid pressure (HLW buffer)
Fluid pressure (HLW emplacement room EDZ)
Heat generation rate (HLW)
Humidity prior to backfilling (operational and access tunnels)
Humidity prior to sealing (HLW emplacement room)
Hydraulic conductivity (Opalinus Clay)
Ionic strength (Opalinus Clay porewater)
Ionic strength (HLW buffer porewater)
Minimum radionuclide transport distance (Opalinus Clay)
Outer diameter (HLW emplacement rooms)
pH (Opalinus clay porewater)
Radial extent (HLW emplacement room EDZ)
Radiation (general)
Radiation dose (canister surface)

Tab. 7-6: Cont.

Radioactivity (HLW buffer in gas phase)
Stress/strain (HLW canister)
Thermal conductivity (Opalinus Clay)
Vertical position (HLW canister)

7.2.3 Excluded parameters

Parameters currently excluded from further consideration on the basis that significant changes in their values (or, in the case of containment time (HLW canister), estimated values) during the Monitoring Phase will not occur are shown in Tab. 7-7.

Tab. 7-7: Parameters currently excluded from further consideration on the basis that significant changes in their values during the monitoring period will not occur

Containment time (HLW canister)
Dissolved gas concentration (HLW buffer)
Thickness of uncorroded metal (HLW canister)
Gas entry pressure

7.3 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 in fact be undertaken in practice. Only these parameters are then carried through to Step 4 of the methodology, which concerns models and criteria. Parameters that are not amenable to monitoring are not considered any further (the parameters are "parked"). Parameters that are obtained indirectly from other parameters are used to identify additional safety-relevant parameters that are needed for their evaluation; this is the feedback loop to Step 1 already noted in Chapter 7.1.3.

7.3.1 Monitoring technologies

A list of the technologies identified as potentially useful for monitoring is given in Tab. 7-8. For each technology, and assessment has been made of the following attributes:

- the parameter(s) that the technology addresses
- the need for maintenance or repeated calibration
- the means of data transmission (wired, wireless or both possible), and
- technology readiness level (TRL), as defined in Tab. 7-9

The assessment has been implemented in the database tool.

Tab. 7-8: Technologies identified as potentially useful for monitoring

Acoustic sensing
Eh probe
Electrical conductivity probe
Evapometer
Extensometer
FDR
Fibre optics for distributed pore pressure
Fibre optics for strain
Fibre optics for temperature
Flowmeter
Gamma counter
Gas sampling and inline spectrometry
Gas threshold pressure test
Geiger counter
Humidity sensor capacitive
Hydraulic testing
Ion selective probe
LVDT displacement sensor
Mechanical/total stress pressure sensor
Mini ventilation tests
Modular mini packer systems (MMPS)
pH probe
Piezometer/pore pressure sensor
Porewater extraction and laboratory analysis
Psychometers
Radar (geophysical)
RTDS: PT100/PT1000
Seismics (geophysical)
Strain meter
TDR
Temperature distributed fibre optic
Temperature punctual fibre optics
Thermocouple
Total pressure cell

Tab. 7-9: Technology readiness levels (TRL)

TRL Level	**Description**	**Interpretation**
TRL 1	Basic principles observed	At TRL Level 1, basic science and engineering is applied to describe the overall preferred concept to meet the necessary safety functions.
TRL 2	Technology concept formulated	At TRL Level 2, the preferred concept is developed further, e.g. through development of conceptual design drawings supported by scoping calculations using analytical tools and identification of main THM processes through expert judgement.
TRL 3	Experimental proof of concept	At TRL Level 3, targeted R&D is undertaken using desk-based, analytical and surface laboratory studies, using representative data, which provides the basis for an Initial preliminary design (e.g. options for material specification).
TRL 4	Technology validated in lab	At TRL Level 4, testing of candidate materials or prototype machinery is undertaken in the laboratory or in mock-ups undertaken at standalone facilities.
TRL 5	Technology validated in relevant environment (Industrially relevant environment in the case of key enabling technologies)	At TRL Level 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.
TRL 6	Technology demonstrated in relevant environment (Industrially relevant environment in the case of key enabling technologies)	At TRL 6, full-scale testing is undertaken in a relevant environment (e.g. a URL in a representative geological environment) to demonstrate that requirements can be met using an initial version of the detailed design. This full-scale test is used to develop construction procedures and quality control requirements.
TRL 7	System prototype demonstration in operational environment	At TRL 7, commissioning tests are undertaken in the operational environment (e.g. the repository) to demonstrate compliance of the detailed design compared to construction procedures and quality control requirements.
TRL 8	System complete and qualified	At TRL 8, the results of a successful commissioning test would be translated into documentation and procedures in preparation for implementation.
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	TRL 9 corresponds to the system being operational and successful operational experience being gained.

7.3.2 Parameters amenable to monitoring in practice

The parameters currently judged to be amenable to monitoring in practice are those that can be evaluated using the technologies shown in Tab. 7-8. Among the high priority parameters, those that are judged to be amenable to monitoring in practice are shown in Tab. 7-10. Tab. 7-11 shows the corresponding secondary priority parameters.

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 central area and the facilities for underground geological investigations will be also used to provide monitoring data and experimental data for hardening the safety case.

Tab. 7-10: High priority parameters judged to be amenable to monitoring in practice

Fluid pressure (Opalinus Clay)
Gas composition (HLW buffer)
Gas partial pressures (HLW buffer)
Liquid flow rate (inflow open tunnels)
Outer diameter (operational tunnels)
pH (operations tunnel porewater)
pH (HLW buffer porewater)
Saturation (backfilled operational tunnels)
Saturation (EDZ)
Saturation (HLW buffer)
Seismic displacement/acceleration (host-rock)
Stress/strain (tunnel liners)
Temperature (Opalinus Clay)
Temperature (HLW buffer)
Temperature (HLW canister)
Thermally-induced rock heave
Total stress (Opalinus Clay)
Total stress (HLW buffer)

Tab. 7-11: Secondary priority parameters judged to be amenable to monitoring in practice

Chemical composition (Opalinus Clay porewater)
Chemical composition (HLW buffer porewater)
Eh (Opalinus Clay porewater)
Eh (HLW buffer porewater)
Electrical conductivity (Opalinus Clay)
Electrical conductivity (HLW buffer)
Evaporation rate from open tunnel walls
Fluid flow rate (Opalinus Clay)
Fluid pressure (HLW buffer)
Fluid pressure (HLW emplacement room EDZ)
Humidity prior to backfilling (operational and access tunnels)
Humidity prior to sealing (HLW emplacement room)
Outer diameter (HLW emplacement rooms)
pH (Opalinus Clay porewater)
Radial extent (HLW emplacement room EDZ)
Radiation (general)
Radiation dose (canister surface)
Stress/strain (HLW canister)
Vertical position (HLW canister)

7.3.3 Parameters for which monitoring technology development is needed

Currently only one parameter has been identified for which completely new technology development is needed before it would be possible to monitor it directly: Heat flux (canister surface).

At this point it should be noted that Nagra is carrying out R&D on monitoring technologies that are part of Tab. 7-8. See Chapter 6.2 for more details.

7.3.4 Parameters measured once or infrequently

High priority parameters that are currently considered likely to be measured once or infrequently (rather than monitored continuously) are shown Tab. 7-12. The secondary priority parameters within this category are shown in Tab. 7-13.

Tab. 7-12: High priority parameters currently considered likely to be measured once or infrequently

Hydraulic conductivity (HLW buffer)
Hydraulic conductivity (HLW emplacement room EDZ)
Thermal conductivity (HLW buffer)

Tab. 7-13: Secondary priority parameters currently considered likely to be measured once or infrequently

Corrosion rate (emplacement tunnel reinforcement)
Corrosion rate (HLW canister)
Density (HLW buffer)
Hydraulic conductivity (Opalinus Clay)
Ionic strength (Opalinus Clay porewater)
Ionic strength (HLW buffer porewater)
Radioactivity (HLW buffer in gas phase)

Note that some may be measured in situ, whereas, for others, it may be sufficient to use measurements from a generic underground rock laboratory, a surface laboratory, or the facilities for underground geological investigations.

7.3.5 Parameters obtained indirectly from other parameters

High priority parameters that are currently considered likely to be obtained indirectly from other measured or monitored parameters are shown in Tab. 7-14. The secondary priority parameters within this category are shown in Tab. 7-15.

Tab. 7-14: High priority parameters currently considered likely to be obtained indirectly from other parameters

Effective void volume evolution (EDZ)
Heat flux (canister surface)
Hydraulic conductivity (HLW buffer)
Hydraulic conductivity (HLW emplacement room EDZ)
Liquid flow rate (emplacement room EDZ)
Swelling pressure (HLW buffer)
Thermal conductivity (HLW buffer)

Tab. 7-15: Secondary priority parameters currently considered likely to be obtained indirectly from other parameters

Heat generation rate (HLW)
Minimum radionuclide transport distance (Opalinus Clay)
Thermal conductivity (Opalinus Clay)

7.4 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 feasible to monitor in practice are calculable using available models and are associated with specific criteria.

7.4.1 Parameters with criteria

There are currently only 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:

- fluid pressure (Opalinus Clay), for which it is planned to develop site-specific criteria related to mechanical failure of the clay, which could occur if fluid pressures are too high, and
- temperature (Opalinus Clay), for which the current criterion is that it should not exceed the maximum paleotemperature[2] at the selected site, to avoid the possibility of detrimental mineralogical alteration

Extensive modelling studies have been undertaken and are still ongoing for these parameters. While monitoring of these parameters would certainly be valuable for reasons outlined in Step 5, below, it should be noted that confirmation that the criteria associated with these parameters will be met through modelling and other argumentation, and not through monitoring.

Moreover, the current selection of only two parameters reflects the current knowledge and state of the project phase. With further progress additional parameters could be added, if specific criteria are developed.

There are four secondary priority parameters at this stage that are associated with criteria (or for which it is planned to develop criteria). These are:

- fluid pressure (operation tunnel and access tunnel EDZ) and fluid pressure (HLW emplacement room EDZ) for which, like the bulk of the host rock, it is planned to develop criteria related to mechanical failure of the clay, which could occur if fluid pressures are too high
- radial extent (HLW emplacement room EDZ), for which the current criterion is that the thickness of the undisturbed host rock above or below the EDZ (with hydraulic conductivity less that 10^{-12} m/s) should be greater than 20 m, and
- radiation dose (canister surface), for which the current criterion is that it should be less than 1'000 mSv/h

Criteria can have their origin in requirements and reference model assumptions discussed in the context of Step 1. In general, if such criteria are violated, then a system requirement is not met and possible actions need to be considered.

Other criteria may be so-called "safety function indicator criteria" (SFI criteria in the workflow, Fig. 7-1). The SFI are parameters that are chosen as indicators of the consequences of potentially detrimental phenomena on post-closure safety functions. The associated criteria are derived such that, if met, it can be assumed the safety functions will be provided as intended, irrespective of

[2] The maximum temperature to which the rock has been subjected throughout its geological history.

the detrimental phenomena. If these criteria are not met, then a safety function of the system may be compromised, or at least not be provided to the extent intended in the safety concept. This does not necessarily mean that the system is unsafe, given that safety relies on multiple, complementary barriers and associated safety functions; however, the consequences of the perturbation to the safety function must be assessed to determine if any further actions are needed.

The capability of the current repository concepts to meet these criteria or values has been tested in qualitative and quantitative assessments, in consideration of a subset of potentially detrimental phenomena collectively termed "repository-induced effects", as well as the couplings between these (Leupin et al. 2016). That the value of the parameter temperature (Opalinus Clay) should not exceed the maximum paleotemperature is an example of an SFI criterion from Leupin et al. (2016). If this criterion can be shown to be satisfied for all reasonably plausible paths of evolution, it is argued that thermally-controlled geochemical processes detrimental to the host-rock properties will not take place. Thus, temperature (Opalinus Clay) is clearly a notable candidate parameter for the monitoring programme.

7.4.2 Parameters with no criteria

High priority parameters with no associated criteria currently defined are shown in Tab. 7-16. The secondary priority parameters within this category are shown in Tab. 7-17.

Tab. 7-16: High priority parameters with no associated criteria

Gas composition (HLW buffer)
Outer diameter (operational tunnels)
pH (operations tunnel porewater)
pH (HLW buffer porewater)
Saturation (backfilled operational tunnels)
Saturation (EDZ)
Saturation (HLW buffer)
Seismic displacement/acceleration (Opalinus Clay)
Stress/strain (tunnel liners)
Temperature (HLW buffer)
Temperature (HLW canister)
Thermally-induced rock heave
Total stress (Opalinus Clay)
Total stress (HLW buffer)

Tab. 7-17: Secondary priority parameters with no associated criteria

Chemical composition (Opalinus Clay porewater)
Chemical composition (HLW buffer porewater)
Eh (Opalinus Clay porewater)
Electrical conductivity (Opalinus Clay)
Electrical conductivity (HLW buffer)
Evaporation rate from open tunnel walls
Fluid pressure (HLW buffer)
Humidity prior to backfilling (operational and access tunnels)
Humidity prior to sealing (HLW emplacement room)
Outer diameter (HLW emplacement rooms)
pH (Opalinus Clay porewater)
Radiation (general)
Stress/strain (HLW canister)
Vertical position (HLW canister)

7.5 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 identified 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 measured or monitored directly.

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

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

Examples of overall assessment of monitoring rational

There are currently only 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 (Opalinus Clay), and
- fluid pressure (Opalinus Clay)

No parameters are eliminated at Step 4, so these parameters, along with other high priority parameters without criteria and secondary priority parameters with and without criteria, progress directly from Step 4 to Step 5. It should be noted that the two currently selected parameters are a preliminary selection, based on the current knowledge and state of the project phase. With the progress of the different licencing steps regular updates and re-evaluation of the entire methodology and content in the database will be performed.

The overall assessment of these parameters, which is identical for both of them, is shown as a screenshot from the database tool in Fig. 7-3. The figure shows that there are serval high priority reasons why these parameters are priority candidates for the pilot repository monitoring programme. In particular, both of these parameters have been modelled extensively and building confidence in these models is a key motive for monitoring. The modelling results e.g. of Leupin et al. (2016) show that significant changes will develop for porewater pressure and temperature of Opalinus Clay (Fig. 7-4 and Fig. 7-5).

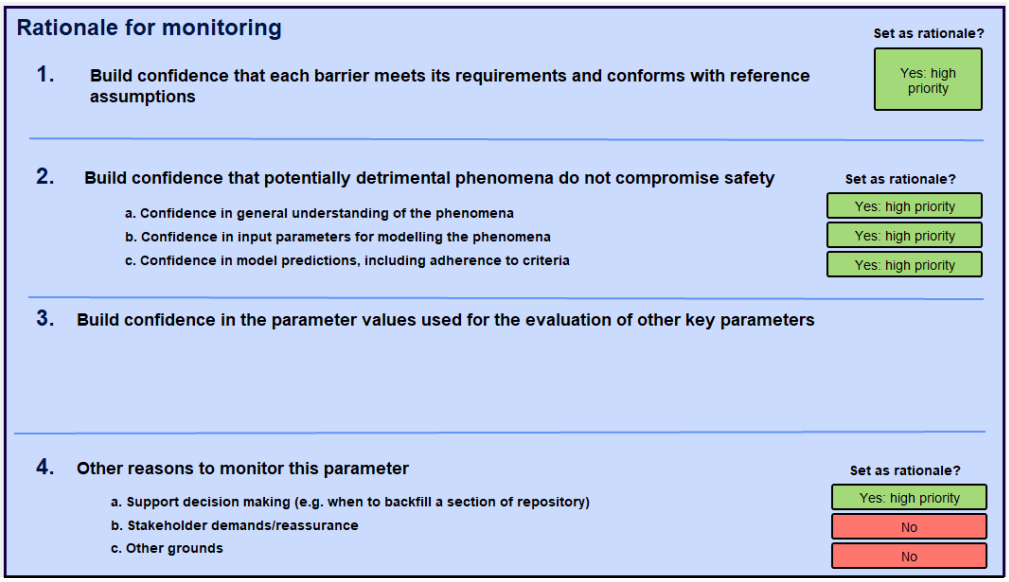

Fig. 7-3: Overall assessment of the parameters fluid pressure (Opalinus Clay) and temperature (Opalinus Clay) as a screenshot from the database tool

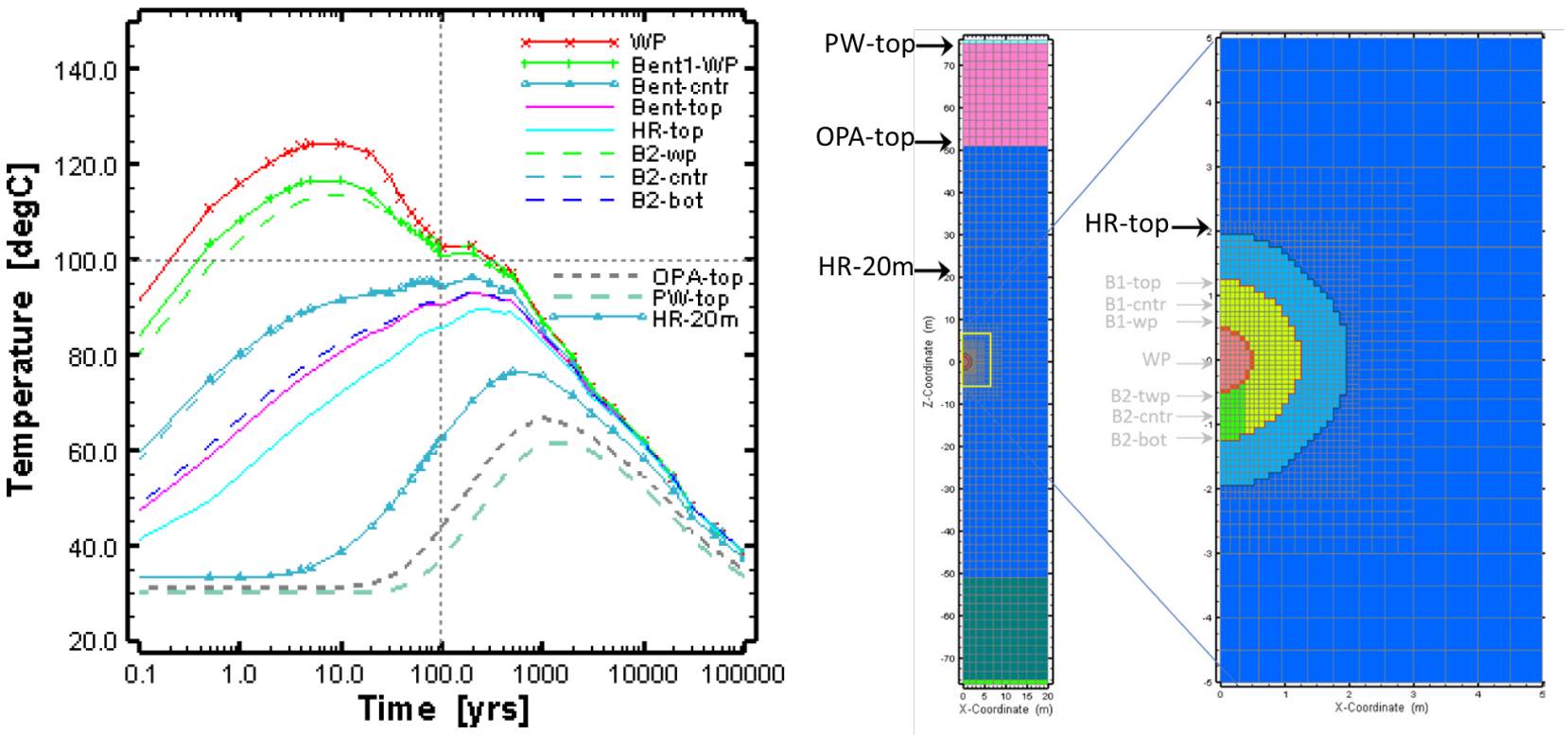

Fig. 7-4: Example of simulated temperature evolution at different locations in the bentonite buffer and surrounding Opalinus Clay of a HLW main repository as well as example model set-up (Senger et al. 2014)

Note: The following abbreviations are relevant for the host rock: HR top = boundary EDZ to undisturbed Opalinus Clay, HR-20m = undisturbed Opalinus Clay with 20 m radial distance to axis of emplacement drift. OPA-top = top of Opalinus Clay (boundary to Passwang Formation (PW)) with 50 m radial distance to axis of emplacement drift.

Temperature within and around the HLW emplacement drifts will evolve primarily as a result of radiogenic heat. No criteria are currently set for near-field temperature (buffer and EDZ), but, as noted previously the criterion for the host rock temperature is that it should remain below the maximum paleotemperature. If the temperature meets this criterion, significant thermally-induced mineralogical alterations can be excluded. Numerical sensitivity studies have been carried out on the temporal evolution of temperature in the bentonite buffer and the adjacent host rock after canister emplacement in HLW main repository (e.g. Senger et al. 2014). In case that the EDZ temperature would exceed the paleotemperature, the consequences are considered to be minor, because the undisturbed host rock satisfies the criterion. Monitoring the temperature evolution would clearly provide a test for the model used to generate these results and could also provide a strong indication that the temperature criterion is met within the bulk of the host rock even beyond the monitoring period.

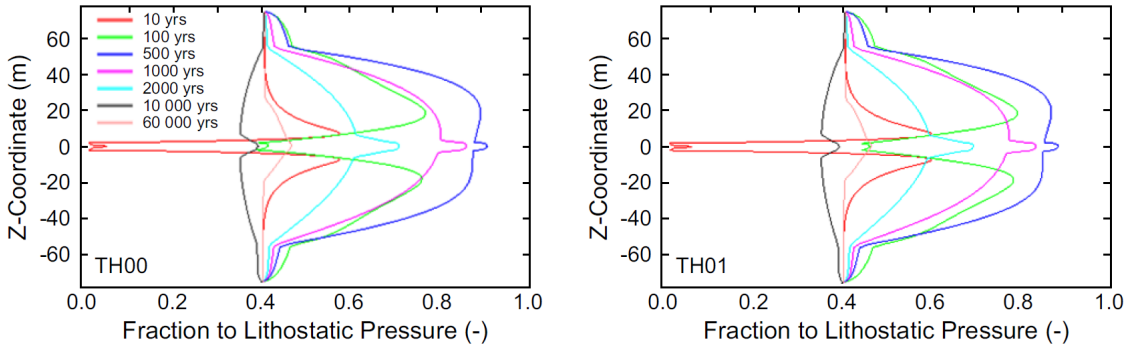

Fig. 7-5: Example from Leupin et al. (2016) of simulated vertical porewater pressure profiles relative to lithostatic pressures for 600 m repository depth and for two different heat production rates (columns: left-average, right-maximum)

Elevated temperatures will cause a transient increase of porewater pressure within the host rock. The fluid pressures attained will also potentially be influenced by the presence of, and generation by the repository of, gas. A criterion for fluid pressure related to mechanical failure of the host rock will be developed specifically for the selected site, but one possible criterion is that it should not exceed lithostatic pressure at repository depth. This criterion is used in the oil and gas industry as an indicator for the assessment of borehole stability and, if it is met, the possibility that a rock fracture will be generated and will propagate to a feature that could form a preferential release pathway can be excluded. As an additional, precautionary measure, the respect distance to such features will be set, based on site- and repository-specific considerations. Leupin et al. (2016) show that significant pore pressure build-up can develop around a HLW repository, but that the peak pressures remain below lithostatic pressures. As in the case of temperature, monitoring fluid pressure evolution would provide a test for the model used to generate these results, although, since the peak pressure may occur after the Monitoring Phase has ended, it is not expected to provide definitive proof by monitoring that the fluid pressure criterion is met.

8 Interpretation and transferability of monitoring data

The interpretation of data from the pilot repository monitoring and the transferability of the resulting knowledge to the main repository are important topics in the framework of the pilot repository monitoring and associated decision making. The following chapters show the first considerations and ongoing R&D work. For the general license application these considerations will be further improved.

8.1 MODATS

Significant international collaborative work on the reasons for, and principles of, repository monitoring has been on-going for decades (e.g. IAEA 2001, NEA 2014, White 2014, White et al. 2019). It has included:

- analysis of strategy and decision-making processes
- R&D of new and novel technologies specifically suited to repository monitoring
- in situ testing of sensors and monitoring systems in repository-like conditions
- research into the role stakeholder involvement may play in overall geological waste disposal

In addition, some organisations have begun monitoring programmes associated with construction of HLW geological repositories (e.g. Posiva 2012). There is also relevant experience from monitoring of operational L/ILW repositories. Although extensive work has been undertaken to date, much of this work has been strategic. Therefore, the joint programme EURAD identified a need to commence the development of more detailed aspects of monitoring. To address this need, the work package "Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure - MODATS" commenced within EURAD in summer 2021 and will run for three years. The ambition of MODATS is to undertake R&D on:

- data acquisition, treatment and management
- the application of the data to enhance system understanding
- consideration of the layout (optimisation) of monitoring systems to deliver the requirements associated with these needs
- consideration of how interactions with public stakeholders on these aspects of repository monitoring can proceed

The planned work will be supported from information of existing case studies and reference experiments. Nagra is participating actively by contributing knowledge and information from the FE experiment. The FE experiment simulates on full scale the construction, canister emplacement, backfilling and early-stage evolution of a HLW repository tunnel in a Opalinus Clay, using heaters in place of HLW canisters (Müller et al. 2017). The FE experiment represents one of the reference experiments in MODATS.

Implementation of repository monitoring, including pilot repository monitoring, requires that data can be acquired, treated, managed, analysed, and interpreted using methods that ensure information so derived can be used with confidence. It would also benefit from the use of novel technologies that can extend the current capabilities of monitoring technologies. MODATS will address implementation needs by undertaking R&D on data acquisition, treatment, management, analysis and interpretation in a task dedicated to data, and will address the need for novel technologies to be further developed in a task dedicated to technology.

Repository monitoring will seek to monitor at key locations based on identification of specific monitoring needs (e.g. pilot repository in Swiss concept). Monitoring information will be "sparse", as the repository cannot be intensively monitored without impacting the passive safety of the multibarrier system, and will be focussed on the pilot repository during the phase of emplacement operation and the Monitoring Phase of the Swiss concept. There is a need, therefore, to understand how "sparse" monitoring data can be compared to physics-based models (e.g. THM models) and data-driven models. To undertake this work, the MODATS project will utilise data from the reference experiments and undertake case studies as a basis for developing methods for comparing model predictions with monitoring data and for developing tools for transferability.

One way to compare monitoring data to models is through the development of a digital twin. A digital twin provides a digital replica of the disposal system, progressively becoming more detailed and more closely representative of the real-world system as more data is collected and information derived from the acquired data. The aim of the MODATS project is to develop the methodologies and software platforms through which digital twins can be developed and evolve during the operational period in response to collection of monitoring data. This will be achieved through defining, prototyping and demonstrating software platforms, developing living digital models integrated with artificial intelligence, machine learning and software analytics. The work will comprise development of computer codes and demonstration of the Digital Twin concept using data from the MODATS reference experiments.

8.2 Tentative generic response plan

The decisions that pilot repository monitoring will support are the decisions to backfill and seal the main repository (after part 1 of the Monitoring Phase) and to close and seal the entire repository (after part 2 of the Monitoring Phase). Thus, the monitoring data must create confidence in the performance of the multibarrier system and also in the reliability of the data themselves.

Therefore, 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. Based on the work of Modern2020 (White et al. 2019), Nagra developed a first tentative and generic response plan (Smith et al. 2019), which is shown in Fig. 8-1.

If a monitored parameter falls outside the expected range, e.g. as estimated from the system model, then the first step is to check for any possible malfunctioning of the monitoring system (sensor or measurement system, data acquisition system, data treatment or analysis methods). There are three possible outcomes to this check:

- A problem with the monitoring system causing the unexpected result is found and resolved, in which case monitoring of the parameter will continue.
- A problem with the monitoring equipment is suspected, but it is not practical to confirm this problem and/or resolve it. If continued monitoring of the parameter is not critical to the confirmation of the safety case (in principle it never should be), then the monitoring programme will continue without monitoring the parameter.
- No problem with the equipment is found.

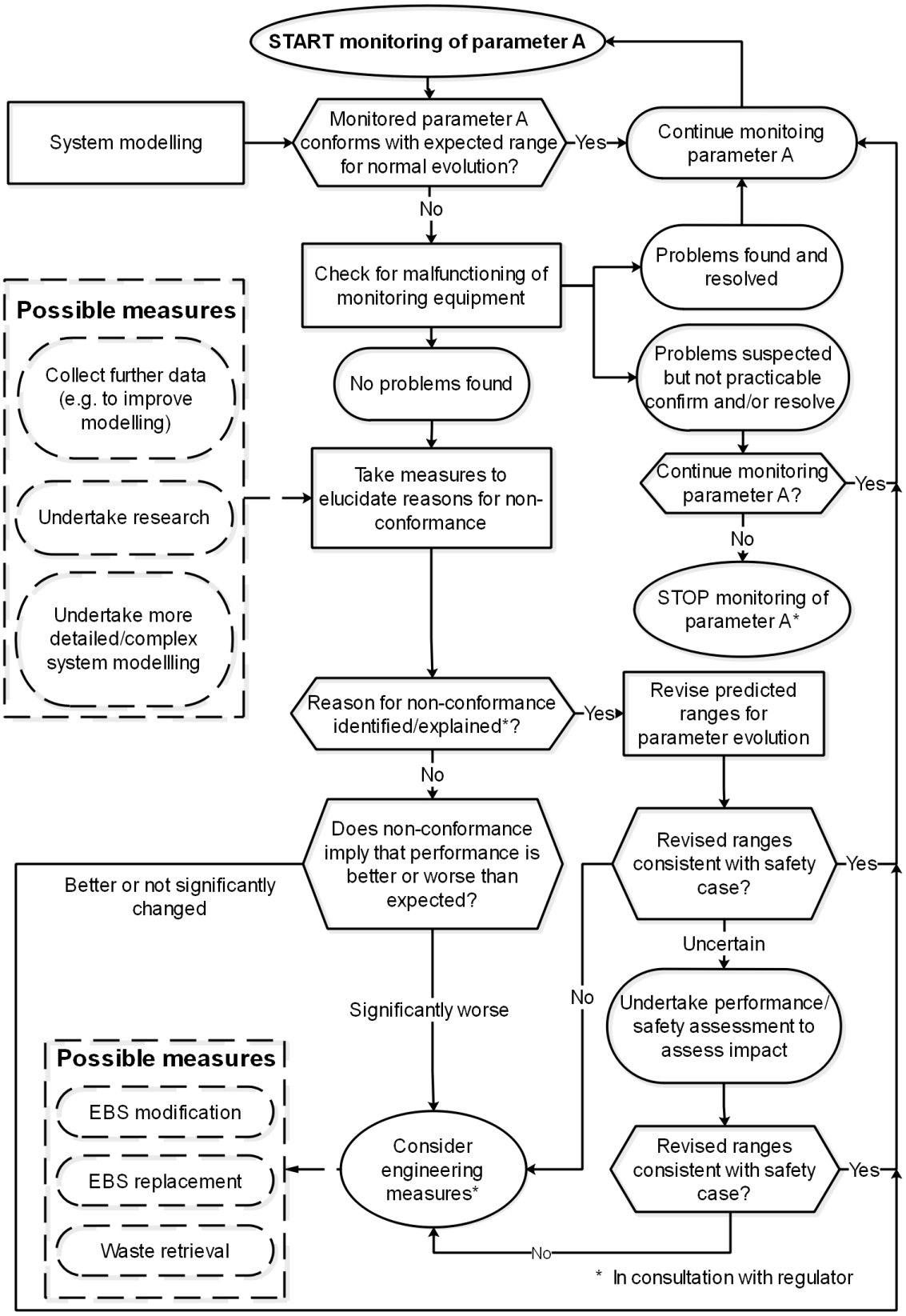

Fig. 8-1: Tentative, generic response plan in the event of non-conformance of monitored parameters with model predictions

If this last possibility turns out to be the case, then measures will be taken to elucidate the reason for non-conformance with model predictions. Possible measures include:

- undertaking further basic R&D on processes potentially influencing the parameter
- undertaking more detailed, system modelling to reduce uncertainties in the model predictions
- collect further data

These measures are not mutually exclusive, e.g. more detailed modelling may require both further basic R&D and additional data.

If the reasons for non-conformance turn out to be deficiencies in the model (including underlying assumptions and data), these model deficiencies will be corrected as far as possible and revised predictions made. If the monitored parameter is consistent with the revised predictions, and the revised predictions themselves do not compromise the safety case, then the monitoring of the parameter will continue.

If it is uncertain whether or not the revised predictions compromise the safety case, then a performance (or safety) assessment may need to be made to elucidate this point. If it is found that the revised predictions could compromise the safety case, then engineering provisions may need to be taken, including:

- EBS modification
- EBS replacement, or even
- waste retrieval

If no significant deficiencies in the model are identified and the reasons for non-conformance with model predictions continue to be unexplained, it is needed to assess whether nonconformance implies that the performance of the system is better or worse than expected. If the answer is that the performance is better than expected, then it may be decided to take no further decisions other than to continue monitoring the parameter.

If, on the other hand, the performance is worse than expected to a degree that could compromise the safety case, then the engineering measures listed above may need to be considered.

8.3 Transferability

The basic arguments for transferability of knowledge gained by pilot repository monitoring to the main repository will be guaranteed by placing the pilot and the main repository in geological and hydrogeological conditions that are comparable (Art. 66 KEV). As the construction, emplacement and sealing of the pilot repository must correspond to the main repository and the waste emplaced in the pilot repository must be representative, the observed THM processes of the pilot repository will be transferable to the main repository.

To keep the pilot and main repository in geological and hydrogeological conditions that are comparable and to ensure transferability, the distance between both must be appropriate. However, both structures must be spatially and hydraulically separated (Art. 66 KEV) and a negative influence on each other must be avoided.

The key data for geological and hydrogeological characterisation of the main repository will be acquired by a survey during the excavation of the drifts and caverns and by temporary monitoring instrumentation. During the EUU, methods and workflows will be optimised to gain significant

geological information accompanying excavation. In addition, the characterization methods based on temporary monitoring techniques in open drifts and caverns will be sophisticated after the EUU, so certain parameters can be confirmed. Moreover, substantial technology progress related to geological surveys accompanying excavation is expected in the period before the construction of the pilot and main repositories starts. Emerging topics of interested are:

- remotely operated geological survey techniques (e.g. photogrammetric methods)
- measuring certain operating parameters of e.g. a tunnel boring machine while drilling/ excavating in combination with machine learning for mapping geomechanical properties
- integration of the survey results into a "digital repository" that integrates the monitoring data base, modelling results of e.g. a digital twin, aspects of Building Information Modeling (BIM), and powerful visualisation tools

The transferability of monitoring data from the pilot repository will also be given by an appropriate selection of monitoring parameters. As described in Chapter 7.2.1 the monitoring parameters of the pilot repository should be safety relevant, high priority parameters.

Moreover, the planned sequence of monitoring and model verification is configured in a stepwise way to progressively improve this process, to increase confidence in the data and models, and to ensure transferability. The key processes affecting the EBS and host rock have already been investigated in the Mont Terri URL at different scales. That resulting understanding will provide the basis for an understanding of the EBS and Opalinus Clay at the selected site, although certain hydrogeological and geotechnical conditions (e.g. porewater pressure, temperature and stress) will be different at disposal depth of the selected site. Therefore, selected experiments will be repeated during the EUU to investigate the site-specific processes and to test predictions and understanding based on the Mont Terri experiments. Subsequently, pilot repository monitoring will provide data of the actual as-built multibarrier system and a verification of the predictions based on the EUU investigations. Fig. 8-2 shows this sequence for monitoring of the Opalinus Clay temperature in the pilot repository (see Chapter 7). Temperature has been monitored and modelled intensively e.g. in the FE experiment in Mont Terri URL. During the EUU, heat transport and thermal impact on the host rock will be studied before the pilot repository monitoring will commence.

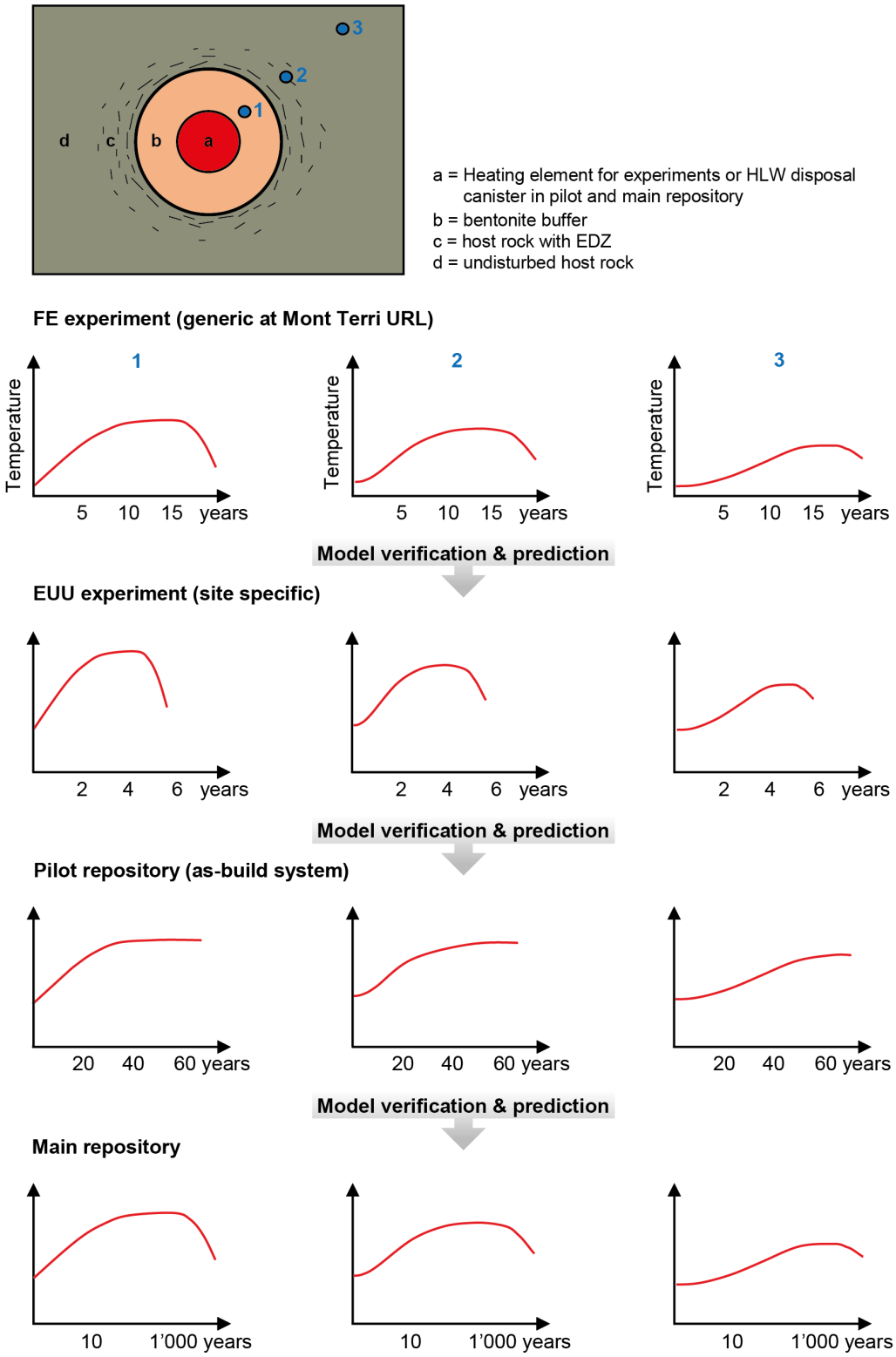

Fig. 8-2: Schematic overview for transferability of a safety relevant monitoring parameter, here temperature is shown as example, from experiments in a generic URL to site specific experiments and finally to the as-built HLW disposal system

The locations represent 1) bentonite buffer, 2) host rock within the EDZ, 3) undisturbed host rock.

9 Summary and outlook

The planning and licensing steps of a deep geological repository are configured to ensure safe construction, operation, and closure. The monitoring of the pilot repository will provide information on the initial behaviour of the as built multibarrier system for comparison with expectations developed in numerical models. In addition, monitoring data will provide an input to periodic updates of the safety case, and information to support stakeholder dialogue, confidence building, and decision making.

This report serves as background report ("Hintergrundbericht") to the 2021 Waste Management Programme (Nagra 2021a) and answers the condition 5.2 (see Appendix) of the Swiss Federal Council attached to the 2021 Waste Management Programme (Bundesrat 2018). It shows first conceptual considerations about selected aspects of the pilot repository monitoring. Objectives and development steps, regulatory requirements, as well as R&D on monitoring technology are discussed. The main parts of the report cover the preliminary development of Nagra's methodology for the identification of potential monitoring parameters (Smith et al. 2019; Frieg et al. 2019) as well as ongoing R&D and fundamental considerations about data interpretation and transferability.

For the general license application, the considerations about pilot repository monitoring will remain at a conceptual level. A specific project including a detailed monitoring programme for the pilot repository is needed not till the application for nuclear construction license.

The presented methodology to identify monitoring parameters considers both the technical feasibility to monitor, and the usefulness for building further confidence in long-term safety. The Nagra methodology for the identification of potential monitoring parameters, as well as its application to the HLW pilot repository, has been implemented in a database tool. The methodology consists of the following five steps:

STEP 1 – Identify key, safety-relevant parameters

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

STEP 3 – Consider the technical practicability of monitoring those parameters identified as being of first and secondary priority

STEP 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

STEP 5 – Assess and document the overall rationale for monitoring those parameters identified in Steps 1 through 4

The key candidate parameters for pilot repository monitoring identified by applying the methodology and that have associated safety-relevant criteria currently include temperature and fluid pressure of Opalinus Clay. There are also other high priority parameters without criteria, as well as parameters with lower priority (with and without associated safety relevant criteria). It should be noted that the two currently selected parameters are a preliminary selection, based on the current knowledge and state of the project phase. With further progress in the project additional parameters could be added.

The workflow and database content for identify monitoring parameters for the pilot repository are flexible and will be re-evaluated regularly and stepwise to identify additional monitoring parameters based on progress in monitoring technologies, in models and criteria, or updates of FEP lists and the safety case. Therefore, the next steps are the first application of the methodology to the L/ILW pilot repository, the re-evaluation of the parameters to be monitored in the HLW pilot repository, and the integration into the overarching monitoring concept. This work will be informed by planned updates of the safety case.

To address R&D topics related to interpretation and transferability of the monitoring data from the pilot repository, Nagra is participating actively in the recently started MODATS project. The ambition of the MODATS project is to undertake R&D on data acquisition, data management and presentation, as well as data interpretation for enhanced system understanding and confidence.

Unexpected monitoring outcomes, including non-conformance with model predictions, will require an appropriate response, which may involve decisions, for example, to engage in further R&D, to modify engineered design or even to retrieve waste packages. The tentative generic response plan developed by Smith et al. (2019) has been presented, but it is likely to require further discussion and development before it is finalised.

Transferability of monitoring information from the pilot repository to the main repository is ensured by following the legal and regulatory requirements related to the pilot repository (e.g. Art. 66 KEV). Comparable geological and hydrogeological conditions will be confirmed by detailed geological surveys accompanying excavation. The transferability of monitoring parameters, model predictions as well as safety case updates is validated by a step wise sequence starting with experiments in the generic Mont Terri URL, over EUU experiments at disposal depth of the selected site, to the monitoring and modelling of the as built multibarrier system of the pilot repository.

Currently a period of at least 50 years is assumed as planning basis for the Monitoring Phase (Nagra 2021a) before the closing and sealing of the entire repository starts. The effective monitoring duration of the pilot repository, however, will be 60 – 70 years, depending on repository type, because the pilot repository will be emplaced at the beginning of the operation phase. This period is judged to be sufficient to monitor processes occurring in response to construction as well as waste and EBS emplacement.

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Appendix: Beantwortung der Bundesratsauflage 5.2 für das Entsorgungsprogramm 2021

Bundesratsauflage 5.2: Die Nagra hat im nächsten Entsorgungsprogramm Umfang und Inhalt der Messungen zur Überwachung eines Pilotlagers für HAA bzw. SMA weiter zu konkretisieren und die aktuellen Erkenntnisse hinsichtlich des Aspekts der Interpretation bzw. Interpretierbarkeit der erfassten Messwerte sowie hinsichtlich der Gewährleistung der Übertragbarkeit der gewonnenen Erkenntnisse auf das Hauptlager darzulegen.

Das Pilotlagerüberwachungsprogramm wird schrittweise und stufengerecht mit den Realisierungsschritten eines gTL entwickelt. Mit dem RBG wird ein erstes integrales Überwachungskonzept eingereicht, welches auch ein erstes Konzept für die Pilotlagerüberwachung enthält. Das Projekt für die Beobachtungsphase muss erst mit dem Baubewilligungsgesuch eingereicht werden.

Die Nagra hat am EU-Forschungsprojekt "Development and Demonstration of Monitoring Strategies and Technologies" (Farrow et al. 2019) teilgenommen, bei dem Strategien für die Auswahl von Überwachungsparametern für verschiedene geologische Tiefenlagerkonzepte entwickelt wurden. Der Fokus lag auf der Überwachung des EBS (Engineered Barrier System) und des Nahfeld-Gesteins während des Betriebs eines geologischen Tiefenlagers. Die Nagra hat im Rahmen von Modern2020 (2019) eine Methodik für das schweizerische Konzept erarbeitet, das Überwachungsparameter identifiziert, die technisch messbar sind, die Sicherheit von Pilot- und Hauptlager nicht beeinflussen sowie relevant für die Demonstration der Langzeitsicherheit sind. Mit der entwickelten Methodik können die Überwachungsparameter für ein Pilotlager regelmässig unter Einbezug neuer Entwicklungen im Bereich der Messtechnik evaluiert und angepasst werden.

Im neuen EU-Forschungsprogramm "Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure" (MODATS) werden, mit Beteiligung der Nagra, in den nächsten drei Jahren Methoden für das Management und die Interpretation bzw. Interpretierbarkeit von Überwachungsdaten entwickelt, die auch auf Pilotlager anwendbar sein werden. Die Nagra wird dabei ihre Entwicklungen anhand von Überwachungsdaten aus dem FE-Experiment, welches im Felslabor Mont Terri durchgeführt wird, erarbeiten.

Die Bauweise, Einlagerungsart und Verfüllung des Pilotlagers werden mit der des Hauptlagers vergleichbar sein, und eine repräsentative kleine Menge von Abfällen wird im Pilotlager eingelagert werden (Art. 66 Abs. 3c und 3d KEV). Das Pilotlager wird so platziert werden, dass dessen geologische und hydrogeologische Verhältnisse mit denjenigen des Hauptlagers vergleichbar sind (Art. 66 Abs. 3a KEV) und gleichzeitig eine räumliche und hydraulische Trennung gewährleistet ist (Art. 66 Abs. 3b KEV), was im Rahmen der baubegleitenden Erkundungen beim Auffahren der Pilot- und Hauptlagerstollen untersucht wird. Durch diese Massnahmen wird die Übertragbarkeit der Überwachungsergebnisse vom Pilot- auf das Hauptlager (Art. 66 Abs. 2 KEV) gewährleistet.