MoDeRn

Monitoring Developments for Safe Repository Operation and Staged Closure

National Monitoring Contexts Summary Report

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Table of Content

1. Introduction

1.1 Background to the MoDeRn Project

The successful implementation of a repository programme relies on both the technical aspects of a sound safety strategy, and scientific and engineering excellence, as well as on social aspects such as public acceptance. Monitoring has the potential to contribute to both of these aspects and thus to play an important role as national radioactive waste disposal programmes move forward towards a successful conclusion, i.e. safe and accepted implementation of geological disposal.

The role of monitoring through the staged implementation of geological disposal has been considered on an international basis through production of an International Atomic Energy Agency (IAEA) Technical Document on monitoring of geological repositories (IAEA, 2001) and by the European Commission (EC) within a Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste (the Monitoring ETN) (EC, 2004). These two documents have described how monitoring can support the implementation of geological disposal in a broad sense.

The EC Seventh Framework Programme "Monitoring Developments for Safe Repository Operation and Staged Closure" (MoDeRn) Project aims to further develop the understanding of the role of monitoring in staged implementation of geological disposal to a level of description that is closer to the actual implementation of monitoring.

Monitoring provides operators and other stakeholders with in-situ data on repository evolutions, to help manage construction, operation and/or closure activities, and may allow for a comparison with prior safety assessments. The project focuses on monitoring conducted to confirm the basis of the long term safety case and on monitoring conducted to inform on options available to manage the stepwise disposal process from construction to closure (including e.g. the option of waste retrieval). It thus provides information to inform necessary decisions. If, in addition, monitoring activities respond to stakeholder needs and provide them with understandable results, they will contribute to transparency and possibly to stakeholder confidence in the disposal process.

MoDeRn project partners (in Table 1-1 below) represent organisations responsible for radioactive waste management in the EU, Switzerland, the US and Japan as well as organisations having relevant monitoring expertise. Other partners offer substantial experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organisations, industry) in highly technical issues.

Table 1-1: List of MoDeRn Project Partners

Partner number	Partner full name	Short name	Country code (2-letter ISO code)
1	Agence nationale pour la gestion des déchets radioactifs	Andra	FR
2	Asociación para la Investigación y el Desarrollo Industrial de los Recursos Naturales	Aitemin	ES
3	DBE Technology GmbH	DBE TEC	DE
4	Empresa Nacional de Residuos Radioactivos S.A.	Enresa	ES
5	European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environments	Euridice	BE
6	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle	Nagra	CH
7	Nuclear Decommissioning Authority	NDA	UK
8	Nuclear Research and Consultancy Group v.o.f.	NRG	NL
9	Posiva Oy	Posiva	FI
10	Radioactive Waste Repository Authority	RAWRA	CZ
11	Radioactive Waste Management Funding and Research Center	RWMC	JP
12	Sandia National Laboratories	Sandia	US
13	Universiteit Antwerpen	UA	BE
14	University of East Anglia	UEA	UK
15	University of Gothenburg	UGOT	SE
16	Galson Sciences ltd.	GSL	UK
17	Eidgenössische Technische Hochschule Zürich	ETH Zurich	CH
18	Svensk Kärnbränslehantering AB	SKB	SE

The project is structured into six work packages (WPs). The first four WPs are dedicated to (i) analyse key objectives and propose viable strategies, based on both technical and stakeholder considerations; to (ii) establish the state of the art and provide technical developments to match specific repository requirements; to (iii) conduct in-situ monitoring demonstration experiments using innovative techniques; and to (iv) conduct a case study of monitoring and its integration into staged disposal, including specific scenario analysis aimed at providing guidance on how to handle and communicate monitoring results, in particular when these provide “unexpected” information. The fifth WP regroups all dissemination and outreach activities and the sixth WP is dedicated to consolidating project results into a reference framework on how monitoring may be conducted at the various phases of the disposal process.

1.2 Report Objectives

This document “National Monitoring Contexts - Summary Report” and its companion report “National Monitoring Contexts – Country Annexes” reports on work conducted under project Task 1.1. The objectives of both reports are:

- To provide each project partner with the opportunity to present background information on the national context likely to influence repository system monitoring.
- To structure specific elements of national monitoring contexts in a set of societal and physical boundary conditions which may influence some of the upstream decisions for geologic repository monitoring.
- To develop an overview of these boundary conditions.
- To discuss how these boundary conditions may influence specific, national decisions on development and implementation of monitoring programmes.
- To provide a basis for a shared view on the development and implementation of a monitoring programme, including the required flexibility for its application in various national monitoring contexts.

In a first step, brief introductions of the various national monitoring contexts were provided in the “Country Annexes” report. To allow for some level of comparison between these, they were structured according to several “boundary conditions” to monitoring, as presented in chapter 2. In a second step, these country specific overviews were analyzed to develop this companion “Summary report”.

1.3 Report Structure

The report is structured as follows:

- Section 1 describes the background to the National Monitoring Contexts reports, the objectives of these reports and the structure of this “Summary Report”.
- Section 2 describes the broad aspects that were considered as National Monitoring Contexts, structured under the two categories of Societal Boundary Conditions and Physical Boundary Conditions.
- Section 3 provides an overview of the Societal Boundary Conditions discussed by the partners of this project.
- Section 4 provides an overview of the Physical Boundary Conditions discussed by the partners of this project.
- Section 5 provides an overview of possible decision points which are likely to be informed by monitoring data
- Section 6 provides conclusions drawn from the discussion presented in this report.

The “Country Annexes” companion report provides an introduction similar to this one, plus 12 chapters containing each a brief overview of monitoring contexts reflecting the diversity and commonalities of considerations brought to this project. Each was provided by the organization representing its nations program within this project.

1.4 List of Acronyms

ASN: Autorité de Sûreté Nucléaire (Nuclear Safety Authority), France

BfS: Bundesamt für Strahlenschutz (Federal Office for Radiation Protection), Germany

BMU: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), Germany

CFR: Code of Federal Regulations, USA

CEN: Comité Européen de Normalisation (European Committee for Standardization)

EBS: Engineered Barrier System

EC: European Commission

EDZ: Excavation Damaged Zone

EKRA: Expertengruppe Entsorgungskonzepte für radioaktive Abfälle (Expert Advisory Group for Radioactive Waste Management), Switzerland

ENSI: Eidgenössisches Nuklearsicherheitsinspektorat (Nuclear Safety Inspectorate), Switzerland

EPA: Environmental Protection Agency, USA

ETN: European Thematic Network

EIA: Environmental Impact Assessment

EU: European Union

EURATOM: European Atomic Energy Community

FEPs: Features, Events and Processes

FSC: Forum on Stakeholder Confidence

GRA: Guidance on Requirements for Authorization of Geological Disposal Facilities on Land for Solid Radioactive Wastes, UK

HLW: High-level Waste

IAEA: International Atomic Energy Agency

IBC: Isoleren, Beheersen, Controleren (Isolation, Control and Monitoring)

ICRP: International Commission on Radiological Protection

ILW: Intermediate-level Waste

KTM: Ministry of Trade and Industry, Finland

LILW: Long-lived Intermediate-level Waste

LLW: Low-level Waste

MoDeRn: Monitoring Developments for Safe Repository Operation and Staged Closure

NEA:	OECD Nuclear Energy Agency
NGO:	Non-governmental Organization
NRC:	Nuclear Regulatory Commission, USA
NSC:	Nuclear Safety Commission of Japan
OECD:	Organization for Economic Co-operation and Development
R&D:	Research and Development
RTD:	Research and Technological Development
RWMD:	Radioactive Waste Management Directorate, NDA, UK
SEA:	Strategic Environmental Assessment
STUK:	Radiation and Nuclear Safety Authority, Finland
SUJB:	State Office for Nuclear Safety, Czech Republic
URL:	Underground Research Laboratory
WDP:	Waste Disposal Package
WIPP:	Waste Isolation Pilot Plant, US
WP:	Work Package

2. Aspects to be considered as « National Context »

At the outset, the project has taken the position that there are a variety of factors that influence the decisions each waste management organization will take with regards to monitoring. They are introduced here and are regarded as “boundary conditions” which condition such decisions on monitoring. The sums of all such “boundary conditions” are referred to as a “National Monitoring Context”.

It seems self-evident that within the framework of differing national monitoring contexts, some differences are to be expected in strategic, upstream decisions on repository monitoring and even more so after the development of a detailed monitoring programme. It also seems likely that different national programmes adopt similar approaches to radioactive waste management, consistent with the recommendations, guidelines or requirements of international organizations such as the IAEA, Nuclear Energy Agency (NEA), or EC. Therefore, while national differences will exist and will be justified with respect to national context, certain choices and approaches to monitoring will also be shared.

The purpose of this chapter is to provide a brief overview of the “monitoring boundary conditions” that were considered for the analysis of the various national contexts and its potential implications on monitoring decisions. As for all information on monitoring, the following can only be understood as an initial version provided in the first part of the project. Indeed, this preliminary analysis had to rely on an understanding of a monitoring programme that for most contributing countries is not yet mature.

Overall, a distinction is made between societal boundary conditions and physical boundary conditions. The former address the way society may influence decisions on monitoring. The latter address conditions, needs and constraints for monitoring related to the physical environment of the repository and of the waste itself.

2.1 Societal boundary conditions

Societal boundary conditions to monitoring decisions can be interpreted very broadly, including for example also elements such as a country’s social geography. Covering an exhaustive list of such conditions was not assumed of relevance for the purpose of this project. In this report, we therefore focus on the following three groups: (i) the legal and regulatory framework, (ii) expert stakeholders’ expectations and (iii) lay stakeholders’ expectations. All monitoring programmes have to address any legal and regulatory expectations, either through direct implementation - if these expectations are given in the form of explicit requirements, or by proposing a technical answer of monitoring - if these expectations are given in the form of general guidelines without specific detail. As for all other aspects of repository development, the responsible organizations take into account any evaluations and feedback they receive from expert stakeholders, where expert stakeholders include all organizations (e.g. safety authorities), committees (e.g. a science advisory group) and review groups (e.g. national review boards) knowledgeable about radioactive waste disposal and tasked to provide an evaluation, opinion and/or review of the monitoring developments. Finally, these organizations also have to take into account lay stakeholder expectations.

For the purpose of this report, we define lay stakeholders as:

> *those who have some interest in the development of plans for geological disposal and in the activities carried out at a potential repository site, but who do not have an explicit role as an expert stakeholder, and are not expected to have specific expertise or background in radioactive waste management or in the nuclear industry.*

Therefore the term “lay stakeholders” encompasses a broad range of individuals or groups (which may vary from country to country), and can be identified at the national, regional or local level. Lay stakeholders include members of the public; members of non-governmental organisations (NGOs), including lobby groups and environmental campaigners; and members of governing bodies. There is, however, a thin line between the categories of “expert” and “lay” stakeholder, as they are distinguished here. For example, some environmental NGO’s (particularly those campaigning against nuclear energy) have developed technically-oriented expertise in the field of radioactive waste management and the nuclear industry. Also, when a repository is planned in the vicinity of other nuclear facilities, members of the local community may at the same time be nuclear experts working in those facilities, but nevertheless approach the issue of radioactive waste disposal from a more ‘personal’ perspective or interest (be it as an individual member of the public, a member of a local or regional NGO or stakeholder group, or as an elected politician).

Some individuals and industry groups have particular expertise in technologies that might be applicable for monitoring a repository, but are not directly involved in the nuclear industry. These individuals are more likely to be considered as expert stakeholders, because they typically have a scientific or technical background. Also, their expectations are often more closely aligned with those of other expert stakeholders than with members of the public and their representative bodies.

Therefore, it may be more useful to consider the distinction between “expert” and “lay” stakeholders as a distinction between those responsible for implementing a solution (the experts) and those (feeling) affected by it (the lay stakeholders or “the public” in its broadest possible sense). Given that the latter represent such a large and heterogeneous group (there will be a range of views and opinions held by the public), collecting and understanding their expectations and translating them into “boundary conditions” for monitoring is not an easy task. This is even more so, as the expert community also holds a variety of views and opinions.

That is why the MoDeRn Project is actively seeking to understand how experts consider that monitoring programmes meet lay stakeholder expectations, and the most appropriate method for understanding lay stakeholder expectations and accounting for them in developing a monitoring programme.

2.2 Physical boundary conditions

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

Indeed, the physical context of a repository system will influence the selection of processes and parameters to monitor, measurement locations and used technologies, and the specific constraints under which such monitoring would need to be done. Further developed are considerations related to:

- Waste inventories (quantity, properties)
- Natural environment hosting the repository
- Engineered system

The radioactive waste inventories are the primary input for all developments of a geological repository. Their quantity conditions the needed size of repository layout, and together with waste availability the minimum overall operational timeframe. Their properties condition heat management and may influence other key aspects of the repository system, e.g. related to the potential for gas generation by some types of waste.

The natural environment is a key component of the repository system and the selection of a specific site and host formation will directly influence monitoring decisions, as these are adapted to the site properties. Properties of the natural environment that are important to repository operation and safety are monitored to establish baseline conditions and for the evolutions of those properties influenced by repository construction and operation. Key features are related to the host formations' mechanical properties, heat conduction, geochemistry and flow and transport properties.

The repository, i.e. the engineered system, is adapted to its natural environment to ensure that the waste inventory can be disposed of safely. It is composed of a number of key elements, including the waste disposal package, disposal cells, buffer and backfill, seals, as well as structural support. All of these are designed to meet specific requirements related to operational or long term safety considerations, and may give rise to associated monitoring activities. The overall layout of the repository is adapted to the waste disposal strategy and may include specific features related to monitoring, such as pilot facilities.

3. Main societal aspects of national contexts

This chapter provides a brief overview of the variety of societal boundary conditions that may be encountered in different national contexts. To the extent possible, it provides some preliminary indication on the potential influence these may have on decisions pertaining to repository monitoring.

All developments are to be considered as preliminary and do not constitute a comprehensive overview of such national contexts, nor do they present definitive conclusions on associated monitoring decisions.

3.1 The legal and regulatory framework

There is considerable variation in the extent to which repository monitoring requirements and approaches are specified within national legislation or regulatory codes. Some national frameworks provide a very clear basis for what needs to be included in the monitoring program. The Swiss case demonstrates how a fairly detailed regulatory framework based on a defined repository concept directly translates into an overall monitoring strategy. Similarly, the US example shows how detailed monitoring objectives are directly linked to the basis for evaluating total system performance with regards to long term safety. In this latter case, the relative importance of parameters to total system performance is taken into account when selecting monitoring objectives. In some cases, such as Japan, there is indicative reference to repository monitoring in national policy and regulatory frameworks for radioactive waste management, while in others, such as Belgium or the Czech Republic, there are no legal or institutional requirements specific to repository monitoring. Where laws and regulations specific to geological repository development and operation exist, they typically specify that monitoring measures should not compromise barrier integrity and therefore long-term safety.

A commitment to retrievability or reversibility may have significant implications for monitoring strategies. In some countries there is a legal requirement that the waste be retrievable, for example in the Dutch, French and Swiss cases. The Dutch currently opt for long-term storage, the French are working to incorporate this additional requirement into their repository design concept, while the Swiss are required to ensure that the waste should be retrievable without “excessive effort”. In other cases, such as the UK, retrievability is viewed as a potential future option. Even where, as e.g. in the US, Swiss or French cases, there is a requirement that retrievability should be possible, the achievement of passive safety remains the goal.

Some legal frameworks, such as those in Finland and Switzerland, provide for a transfer of responsibility for the repository at its closure, including responsibility for any monitoring activities that may be conducted after closure. This poses the question of how the technical aspects of any post-closure monitoring that might potentially be required should be handled.

Beyond monitoring of the repository system that is required to ensure long-term safety, repository projects are also subject to other, more generic monitoring requirements under a variety of regulatory regimes. These include monitoring required by laws and regulations governing workplace safety, including radiological protection, the safety and environmental effects of mines and mining operations, the construction and operation of underground infrastructure projects, and the environmental impact of major construction projects, in addition to requirements deriving from the application of non-statutory codes and standards such as the European Committee for Standardizations' (Comité Européen de Normalisation - CEN) Eurocodes relating to the construction industry. Although the implications of these regimes for national repository programmes is not in every case discussed in detail, they are referred to in the national context reports appended below.

Finally, at the international level, the IAEA's Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management applies across national contexts, whilst the safeguards required under Nuclear Nonproliferation Treaty require post-closure surveillance in all signatory nations of repository sites containing controlled materials.

The remainder of this section summarizes key features of the frameworks in each country, details of which can be found in the National Context Reports appended below.

Belgium: There is no specific reference to repository monitoring in existing laws and regulations. However, applicable laws and regulations include the IAEA's Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, workplace safety regulations that require dose monitoring, health and safety regulations governing work in mines and underground galleries, and regulations implementing the European Union's (EU) Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) Directives that require baseline environmental monitoring for any major project.

Czech Republic: The Atomic Act 18/1997, which established the Radioactive Waste Repository Authority (RAWRA), and a number of decrees of the State Office for Nuclear Safety (SUJB) provide the general framework. Monitoring is defined, since June 2002 by Regulation No. 307/2002, in terms of radiation monitoring, for which the SUJB is responsible; there is no explicit reference to repository monitoring.

Finland: As in other countries, EIA legislation sets general requirements for monitoring and requires the formulation of a programme to monitor environmental impact. The Ministry of Trade and Industry (KTM 1999) also states that the principles defining a monitoring programme should be established before a licensing application for repository construction is submitted. There are however a number of very specific laws and regulations governing repository development, operations and closure. The Government Decree on general safety requirements for the disposal of the nuclear waste (STUK 2008) requires that a research and monitoring programme be implemented during the operational phase to ensure the long-term performance of the engineered barrier systems. This requirement is elaborated in updated Regulatory Guides issued by the Radiation and Nuclear Safety Authority during 2009 which detail specific requirements for monitoring during the construction and operation phases of the nuclear waste repository, including monitoring of the performance of the technical barriers and of the bedrock characteristics surrounding the disposal facilities that are important to long-term safety. The possibility of post-closure monitoring is mentioned in the Nuclear Energy Law but responsibility for this would rest with the State after the waste generators have paid a lump sum for the cost of such activities. However, the regulations also specify that any post-closure monitoring activities must not compromise long-term safety. Other official requirements for monitoring are concerned with the safety of underground work or with surveillance of the surface environment. In addition, obligations related to the Non-proliferation Treaty may impose additional monitoring requirements to safeguard potential fissile materials.

France: In addition to generic radiological, health and safety, and environmental regulations, France has a well developed and often detailed legal framework governing repository development, operation and closure. The 1991 Waste Act and Fundamental Safety Rule (Loi n° 91-1381), although not explicitly defining monitoring provisions, implicitly requires very specific monitoring objectives, for example in relation to hydrogeology, geological stability, waste package contents and characteristics, and engineered barriers, as well as post-closure monitoring of various parameters, in order to meet its requirements. The 2006 Waste Act (Loi n° 2006-739) and the Transparency and Nuclear Security Act (Loi n° 2006-686), which brought in a new legal framework and established a new nuclear safety authority, the Autorité de Sûreté Nucléaire (ASN), also pointed in its provisions to the need for some form of post-closure monitoring. The regular safety reviews that it requires imply the collection of various forms of *in situ* data. Monitoring requirements are addressed more directly in the 2008 Safety Guide (ASN, 2008) for Geological Repository, which states that a monitoring programme should be incorporated in the repository programme from the design stage, through operation to closure and, if required, during the post-closure phase. The objective is stated as being not only operational safety but also performance evaluation, by following the evolutions of a number of parameters, in order to inform decision making. Although the goal of the French programme is to achieve passive safety, the law requires that waste emplacement be reversible for a period of at least 100 years.

Germany: The country has a federal structure, which affects the structure of regulatory, licensing, and supervisory bodies in the field of radioactive waste management and disposal. However, competence for nuclear matters and responsibility for providing installations for radioactive waste disposal lies with the Federal Government. This responsibility is enshrined in the German constitution which came into effect in 1949. Pursuant to the German Atomic Energy Act, the Bundesamt für Strahlenschutz (BfS), which is a body of the federal administration directly subordinated to the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), is responsible for construction and operation of final repositories. It is the applicant for a license on behalf of the Federal Government, and legally responsible for the repository operation and its supervision in regard to nuclear matters. This supervision begins after the end of the licensing procedure. The legal supervision monitors the construction, operation and decommissioning of the repository in accordance with the regulatory content of the operational license. Under exclusive contract with BfS, DBE (i) carries out the repository planning, including preparation of the license application and of the supporting body of documents, (ii) constructs and operates the repository, (iii) performs the site survey and the complete repository monitoring.

In Germany, those laws and ordinances specific to this issue do not differentiate between high-level waste (HLW) or long-lived intermediate level waste (LILW) disposal, but deal with disposal of radioactive waste in general. They include more general legislation governing nuclear activities, radiation protection regulations and the Federal Mining Act, which was amended in 2002 and which governs the construction and operation of underground facilities for storage of goods and disposal of waste. A set of generic safety criteria for the final disposal of radioactive waste in a mine were published in 1983, which outline the measures to be taken to ensure safety and define the principles by which to demonstrate compliance. There are a range of different regulations, including several concerned with radiological protection, several with mining activities, and some specifically focused on radioactive waste disposal, that impose monitoring requirements. Hitherto, however, there have been none specifically concerned with the monitoring of deep geological repositories after closure. In July 2009, BMU issued the first draft of the Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste, which (after coming into force) are to be applied by BfS to a future final repository for heat-generating radioactive waste in Germany. The document details not only specific requirements for near-field and far-field monitoring during the operational and closure phases of a repository but also requires monitoring for a limited period after closure. It mandates the competent authority to decide who should perform post-closure monitoring and to decide when it should be discontinued. The current regulations do not however provide a comprehensive set of criteria that can be used to determine which safety-relevant data should be collected in the early post-closure phase.

Japan: The Nuclear Safety Commission of Japan (NSC) has formulated a basic framework for national safety regulations designed to facilitate the formulation of policies that are required to ensure the safety of geological disposal (NSC, 2000). The NSC's report defines "safety securing principles" that include measures to secure long-term safety (site selection, engineering measures) and safety assessment measures to confirm that safety has been ensured. The NSC states that safety should be confirmed in each stage of disposal operations. It also states that activities including monitoring and inspection may be implemented at each stage, from initial siting to the termination of operations. There is no explicit requirement for post-closure monitoring, although neither is that ruled out.

Netherlands: Current policy in the Netherlands requires that radioactive waste must be isolated from the biosphere by safe storage in a disposal facility and must be kept under surveillance (Isolation, Control and Monitoring (Isoleren, Beheersen, Controleren or IBC) -criteria). Although policy is to keep wastes in monitored interim storage for at least 100 years, while further research into long-term management and disposal options is carried out, when taking account of the particular geographical and hydrogeological conditions in the Netherlands deep geologic disposal is projected as a final solution for all waste categories under the assumption that disposal is the preferred management option. One relevant consequence of the application of the IBC-criteria to a geological disposal in the Dutch case is the requirement that a deep geological repository must be designed to include the option of retrieval of radioactive waste. Maintaining the retrievability option and the demand of surveillance in general both require monitoring for an extended period of time. The Dutch policy on radioactive waste management does not define the period, in which the option of retrievability has to be maintained or surveillance of a geological disposal is necessary.

The required surveillance includes on-site and off-site radiological monitoring, the results of which are reported to - and regularly checked by - the regulatory body. Under Article 36 of the Euratom treaty, the discharge data must also be submitted to the European Commission each year.

Spain: Regulatory requirements related to monitoring are associated with operational safety in terms of radiological protection to individuals (International Commission on Radiological Protection (ICRP) and IAEA standards apply as for any other nuclear facility). Mining regulations also apply, as for any other underground facility, to ensure the operational safety during the construction phase, in terms of preventing geotechnical and environmental problems (dust, gas concentrations, temperature, etc). There are until now no specific regulatory requirements linked to the reversible management of the waste disposal process in the repository. Monitoring during the post-closure phase is restricted to monitoring of environmental radiation and continuation of some monitoring activities initiated during the site characterization phase (seismicity, groundwater levels, precipitation, etc).

Switzerland: The proposal in 2000 (FOE 2000) by an expert advisory group (EKRA) to adopt the concept of monitored geological disposal has had a significant impact on subsequent Swiss law and regulations related to geological disposal of radioactive wastes. The concept involves the construction of a pilot facility as the first part of the actual repository; it is this pilot facility that will be monitored extensively, while the main repository is being constructed, filled and closed as planned. The Nuclear Energy Act (KEG 2003) and resulting ordinance specified the requirements for monitored geological disposal, which combines passive safety with a period of monitoring and the possibility of retrievability without excessive effort during the emplacement and observation period until final closure of the repository. These include the requirement: that monitoring may not compromise the functioning of the passive safety barriers; that the behaviour of the waste, the backfill and the host rock are to be observed in the pilot facility up to the end of the monitoring phase; that during monitoring data are to be collected to support the safety case with a view to repository closure; and that the pilot facility is to be equipped with the instrumentation required for monitoring activities. In 2008, the Swiss nuclear regulator (ENSI) issued G03 (ENSI 2009), which sets out specific requirements for the pilot facility, including the requirements that the monitoring programme of the pilot facility must measure the evolution with time of the pilot facility and its geological environment in such a way as to provide information: (a) on safety-relevant conditions and processes in the pilot facility and its geological environment; (b) for early recognition of unexpected developments; (c) on the effectiveness of the barrier system; and (d) to support the safety assessment. It also requires: that the information be transferable to the situation in the main facility and its geological environment; that the suitability of the monitoring programme for the pilot facility be checked periodically; and that the monitoring programme and its results are submitted periodically to ENSI for review. Institutional control after the receipt of the closure licence is not part of the monitoring concept, thus all monitoring activities associated with the repository would end with the closure of the access tunnel and shaft.

United Kingdom: The Nuclear Decommissioning Authority (NDA) is the implementing organisation for the geological disposal facility. Within the NDA, the Radioactive Waste Management Directorate (RWMD) is responsible for delivering the geological disposal programme. In the UK, there is not a single radiation protection regulator. Regulation of aspects of the geological disposal facility of relevance to the MoDeRn Project is undertaken by the Nuclear Installations Inspectorate of the Health and Safety Executive and by the Environment Agencies. A framework for managing higher activity radioactive waste in the long-term through geological disposal was set out in a Government White Paper published in June 2008 (Defra 2008), known as the "Managing Radioactive Waste Safely" White Paper. This White Paper defined an approach to implementing the geological disposal facility based on voluntarism and. The adoption of an approach to implementation based on partnership with local communities has significant impacts on the UK monitoring context. In February 2009, the Environment Agency and Northern Ireland Environment Agency published Guidance on Requirements for Authorisation (GRA) of Geological Disposal Facilities on Land for Solid Radioactive Wastes (Environment Agency and Northern Ireland Environment Agency, 2009), which sets out in a appendix the Technical Requirements specific to the monitoring programme required to evaluate changes caused by repository construction, operation and closure. In addition to the Radioactive Substances Act, the Pollution Prevention and Control Act, the Nuclear Installations Act and the Health and Safety at Work Act, a number of other laws and statutes relevant to the development of geological disposal facilities may have an impact on monitoring requirements. These include the Town and Country Planning Act, which implements the EU's Environmental Assessment Directive, and the European Atomic Energy Community (EURATOM) monitoring requirements. The regulation of radioactive waste disposal in the UK is not prescriptive. The responsibility for developing a monitoring strategy lies with the implementer, NDA RWMD, which has to demonstrate that the monitoring strategy applied at any site is consistent with principles laid down in regulations and is consistent with the requirements defined by the GRA. It will be necessary for NDA RWMD to develop an integrated monitoring plan that considers the overall programme of monitoring to be applied during all phases of the development of a geological disposal facility and to meet a wide range of requirements, including those related to the operational safety, the post-closure safety case, and environmental assessment, including SEA and environmental impact assessment EIA. Although the government position is that a repository should be closed at the earliest opportunity, the decision about whether to keep the repository open for an extended period of time has been left for regulators and communities to make at a later date. In the meantime, the design and construction will be carried out in such a way that the option of extended retrievability is not excluded and the monitoring strategy will therefore reflect this possibility.

United States: The nuclear waste repository programs in the United States are governed by the Code of Federal Regulations (CFR). The 10 CFR series of regulations are authored by the Nuclear Regulatory Commission (NRC) and require a confirmatory monitoring program to be initiated prior to operations and continuing until site closure. The 40 CFR series of regulations is authored by the Environmental Protection Agency (EPA). While the NRC regulates commercial nuclear power activities, the EPA has historically regulated or authored the requirements for disposal of waste generated or owned by the U.S. government. In general, these regulations require operational and post-closure monitoring of the disposal system. Operational monitoring ensures that dose limits to the public and the environment are not exceeded. These regulations also impose confirmatory monitoring requirements to identify parameters important to performance assessment that can be monitored during the operational and post-closure periods.

3.2 Expert stakeholder expectations

Expert stakeholders regroup those stakeholders directly associated with the implementation of a geological repository. These include regulators/safety authorities, national review boards, international peer review committees and the implementers' science advisory committee. The organisations producing the radioactive waste and thus responsible to finance repository developments and implementation often also take significant interest in the disposal process.

Their expectations are formalized by different means. Overall, regulators and safety authorities "expectations" are likely to be translated into the legal and regulatory framework, as well as guidelines for implementation. In addition, they may be communicated through reviews and comments on interim milestones in the development of disposal concepts and the associated safety case. National review boards may serve an advisory function to political decision makers. As such, their periodic evaluations, comments and recommendations on the implementers' progress are evaluated in view of incorporating them into further development work. The science advisory committee is tasked to advise the implementer on ways to improving developments, and the advice is analyzed with a view to incorporating it into future developments. Waste producers hold an important stake in the schedule and cost of repository implementation.

Monitoring is an expert-driven activity. However, there are different kinds of experts involved in monitoring, who are part of different organizations with different responsibilities in relation to monitoring. Moreover, there are important differences between the legal and regulatory framework in specific countries in relation to monitoring. These range from an absence of regulatory imposed monitoring requirements, over the provision of broad monitoring guidelines, to frameworks providing for specific requirements on monitoring.

Besides these differences there seems to be a shared view that monitoring is an important activity for assessing engineering quality: To verify and confirm scientific models and technical design. This means that the notion of monitoring is understood as a way to add value to the basis of knowledge already established via prior R&D work conducted in nuclear waste programmes. But monitoring has also been given a more specific objective of guiding the process from human surveillance to passive safety, i.e. guiding a decision process which is envisioned to lead from implementation and confirmatory activities to closure and passive safety, while progressively reducing, and eventually abandoning any monitoring activity (the latter may occur sometime after closure). More recently, monitoring has also been given a more communicative objective, foremost directed to regulators, as a tool for showing that implementers have provided a safe solution, but also to a wider audience, including publics, for informing and building confidence on waste management programmes.

In all these different aims of monitoring, experts are given a key role, as those who are monitoring, those who are reporting the results of monitoring activities to others, as well as those conducting external evaluations of monitoring results (regulators).

In what follows a few important questions, or tensions, are presented, that are important for understanding expert work in connection to monitoring activities. These are about expert requirements and expert expectations, but also about other groups' expectations on monitoring experts. The four tensions could be taken advantage of in the work of improving monitoring activities.

For example, while most experts in most countries tend to agree that some well adapted monitoring should be performed prior to repository closure in relation to aspects important to repository long term safety, expectations in relation to post-closure monitoring are less clear. It is envisioned that some type of post-closure monitoring will be done, but at the same time all experts agree that long term safety relies on passive barrier performance and does not require monitoring.

3.2.1 Assessment of ongoing disposal process vs. a tool of communication

This first tension is between monitoring as an activity contributing to the verification/confirmation of expected or predicted repository behaviour and an activity producing results that can also contribute to dialogue with stakeholders. Monitoring is usually considered as a natural undertaking for waste management agencies: a 'standard practice in science' (SKB, 2004: 15). In the context of managing the disposal process, IAEA is defining monitoring as 'continuous or periodic observations and measurements of engineering, environmental and radiological parameters, to help evaluate the behavior of components of the repository system, or the impacts of the repository and its operation on the environment' (IAEA, 2001: 1). But, according to IAEA, this engineering-based definition of monitoring could also serve a social ambition of 'strengthen confidence in long term safety' (IAEA, 2001: 3), by confirming to stakeholders that safety is satisfying, as was shown within the license application. These two different objectives are not necessarily in conflict. On the contrary, they could support each other in that the same monitoring activities could be used both (i) for experts (implementer, regulator, review board) analysis of the ongoing disposal process and (ii) for external communication activities with other stakeholders. Nevertheless, it is possible to identify a distinction between monitoring as contributing to a science/safety endeavour and monitoring as contributing to a social communicative activity. We should be aware of the information asymmetry between those who produce and distribute monitoring results and those who have to interpret these results from the outside. However, monitoring activities could give possibilities of interesting combinations on how to produce, present and interpret monitoring results, and which groups to include in this work, which will increase transparency of waste management programmes.

3.2.2 Confirming safety vs. questioning safety

The second tension is associated to the expected role of monitoring: To support the technical and scientific basis used to evaluate long term safety. After presentation (implementer), evaluation (safety authority), and acceptance of a safety case, which already took into account uncertainties when predicting repository evolution, it is assumed that such support from monitoring will lead to a confirmation of the knowledge basis. It may possibly also lead to improvement by reducing some of the uncertainties and thus showing that safety margins are larger than expected. However, the hypothetical case of monitoring providing some 'unexpected' results must also be considered, as well as their potential to question the basis used to evaluate long term safety.

In this context, it may also be asked whose responsibility it is to (i) develop a suitable monitoring programme and (ii) to evaluate monitoring results and confirm – or question – the basis for long term safety. This clearly casts implementing and regulating bodies in the same distinct institutional roles for which they were established, i.e. to develop and propose and solution (implementer) and to evaluate, agree or re-direct such a solution (regulator). In the particular case of monitoring programmes, it can be assumed that once such a programme has been proposed and accepted as part of a license, its implementation must respect the terms of the license. The respective roles when it comes to deciding on the progressive evolution of a monitoring programme are less well understood. It can be assumed, that decisions will be taken based on the same interaction: Proposal to reduce (and ultimately to end) monitoring activities, and evaluation of the proposal.

3.2.3 Ongoing monitoring vs. passive safety

Long term passive safety is the reason to implement geological disposal of radioactive waste (NEA, 1995). This raises two key considerations, first for the implementation of monitoring activities, second for the decision to end them. First, monitoring activities may present a risk to the integrity of repositories (IAEA, 2001: 4). It is therefore important to only implement those activities shown not to degrade long term safety. Second, while monitoring is considered with an emphasis on the phases before repository closure, its continuation after closure presents a number of technical challenges limiting its possible duration and scope, while the scope itself should be consistent with a prior decision of closing the repository. But to what extent should the scope of monitoring be reduced, and when to stop monitoring and thus decide that no further confirmation of a sound basis for the long term safety is needed?

In between the long term goal of passive safety and the potential for redirecting the disposal process shown by retrievability, we find the most embraced stepwise decision-making process, where assessments at different stages – where monitoring could help producing important data helping and supporting these assessments – give important contributions for taking further steps. How much monitoring is enough monitoring? How can the goals of transparency and continued visibility of repository performance, together with flexibility of pre-closure management including possible actions of retrievability be combined with an overriding concern with passive safety?

These questions are not easy to find a clear solution to but they should be further explored in monitoring activities, trying to improve the discussion of the connections between monitoring and prior R&D work and the available scientific and technical basis, retrievability, closure and post-closure.

3.2.4 Certainty vs. interpretations – what expectations on experts?

For good reasons there are expectations that monitoring should be carried out by experts, and that monitoring could be used for providing reassurance on an adequate basis for safety (and more recently communication – not only confirming the basis for safety but also enhancing confidence in safety to a wider audience). However, we should be aware that monitoring devices and monitoring experts are not producing certainty, but data that could be useful for interpreting safety. Usually citizens have too high expectations on expert work and the results produced by experts, assessing these as certain. Experts sometimes feel that they have to live up to these expectations, not least in relation to safety issues in situations where requirements of safety are high. In these circumstances it could be hard for experts to tell that they are not delivering certainty but only interpretations. It is of great importance to discuss the limitations of monitoring activities for being able to protect expert credibility in the long run.

3.2.5 Conclusions of Expert Stakeholders Expectations

Overall, expert stakeholders agree on the value of monitoring to provide for in-situ information related to the basis of long-term safety, specific aspects of managing the disposal process such as waste retrievability and to compliance with aspects of operational safety. There is also fairly broad consensus that monitoring results could be used to support communication with other stakeholders.

Several considerations that are inherently attached to monitoring were developed here to stimulate further discussion on monitoring. It is in the combination of these different tensions we find requirements and expectations of monitoring activities that could be used in a productive way for setting up important monitoring activities, which are at the same time technical and social achievements.

3.3 Lay stakeholder expectations

Expert stakeholders are increasingly recognizing the importance and value of engaging with lay stakeholders during the planning and development of repositories for radioactive waste. Many, but not all MoDeRn Partner countries have set up initiatives for active (lay) stakeholder engagement in radioactive waste management in one way or another. In some cases such initiatives have a relatively long history, in others they are of a more recent nature.

Differences also exist between the level at which these interactions take (or have taken) place: at the national level, in view of general policy decisions (such as the choice for geological disposal as the preferred final solution); or at the local and/or regional level in view of siting a disposal facility. Furthermore, in several countries different engagement initiatives were undertaken, following different approaches, for different types of options, facilities and/or waste categories. In this report we focus first and foremost on (the outcome relevant for monitoring of) these actions in relation to geological disposal for high level waste and spent fuel (and in some cases also geological disposal for other waste categories). Stakeholder engagement activities may be targeted to address topics at various levels of detail. They may consider general areas, such as perspectives on waste management or disposal, or they may focus on more specific topics such as monitoring.

The evidence provided in the national context appendices (see Annex 1) suggests that relatively few countries have engaged with lay stakeholders specifically on the subject of monitoring. One country that *has* held focused engagement activities on this topic is the UK, where Nirex held a series of workshops on monitoring and retrievability, some of which involved members of the public, campaign groups and other non-expert interested parties (UK CEED and CSEC, 2000; UK CEED, 2002). Key comments expressed during these workshops are summarised in the "UK national context" chapter of the companion "Country Annexes" report.

A range of initiatives to engage with lay stakeholders on broader issues of radioactive waste management in different MoDeRn Partner countries have nevertheless identified some key views and expectations that may influence decisions on repository monitoring. Based on the assembled information, we see some similarities in expectations across countries and some differences. Based on the national contexts prepared for France, Germany, Spain, Belgium, Switzerland, the UK, the Netherlands, Finland, the Czech Republic, Japan, the USA, and Sweden, which are presented in the "Country Annexes" companion report, this section compares engagement activities[1] and lay stakeholder expectations in different countries and provides some observations on how lay stakeholder requirements may impact on monitoring.

3.3.1 Approaches to Identify Lay Stakeholder Expectations

Engagement with lay stakeholders may be undertaken by expert groups, such as waste management organizations or regulators, or may be undertaken by non-technical groups/organizations representing the wider public, such as local authorities, siting partnerships or non-governmental organizations (NGOs). A range of approaches have been used to engage with lay stakeholders. These include:

- Dedicated engagement meetings with local communities and/or other lay stakeholder groups. Such meetings might take the form of:
    - Scientific presentations by experts to provide background.
    - Public consultations or debates, at a local, regional or national level.
    - Participation in conferences involving both expert and lay stakeholders.
    - Attendance of members of the public at local planning meetings.

- Canvassing of lay stakeholder opinions through web-based or postal consultations. Some websites aimed at the public (for example, the West Cumbria Managing Radioactive Waste Safely Partnership in the UK) provide facilities for individuals to give feedback or comments on an *ad hoc* basis.

- Visits by the public (individuals, groups and students) to nuclear sites including underground research laboratories (URLs) and visitor centres dedicated to providing public information. Such engagement enables lay stakeholders to gain firsthand experience of waste management activities that are undertaken, and to perceive the ethos of waste management organizations. E.g. in 2006, more than 7000 people visited the URL at Meuse/Haute-Marne in France; site visits are also organised on an annual basis for representatives of local communities in the Czech Republic.

The nature of lay stakeholder engagement activities, and the type of feedback provided, is strongly dependent on the status of the geological disposal programme, i.e. whether the disposal programme is in a generic or site-specific stage. The status of different national programmes is summarised for each country in the "Country Annexes" companion report.

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[1] The more "passive" informative activities, such as publications and newsletters, described in some of the national context reports in Annexe 1, are not considered in this overview as engagement activities in themselves. Here we will focus only on the more "active" engagement activities that allow for two way interaction, through which stakeholders can express their views and general expectations relevant for monitoring could be collected.

3.3.2 Lay Stakeholder Monitoring Expectations

We make a distinction here between direct and indirect expectations vis-à-vis monitoring. In two cases (UK and Switzerland) the issue of monitoring was either explicitly put to discussion, or emerged within engagement activities covering broader topics. In most other countries, we have only indirect indications from interpreting the outcome of broader engagement activities.

Explicit (direct) Expectations for Monitoring

Although many countries have not held dedicated engagement activities on the subject of monitoring, engagement activities covering broader topic areas *have* generated specific feedback on monitoring expectations.

A range of engagement initiatives were carried out in Switzerland in the late 1990s to identify the reasons underpinning a negative Cantonal ballot for a mining licence for a pilot tunnel facility at Wellenberg in the Canton of Nidwalden. Feedback indicated that a stepwise approach to disposal incorporating enhanced control through monitoring and retrievability was required to gain more widespread public support. This led to the EKRA group, established by the Federal Government, recommending that the repository design be amended to incorporate the concept of monitored, retrievable storage (FOE, 2000). Subsequent regulation included an obligation for a stepwise implementation of the repository, including in the design a specific pilot facility for monitoring purposes.

A further example is available from the UK where, in 2002, Nirex funded research into public concerns and perceived hazards of geological disposal (The Future Foundation, 2002). Participants expressed unease about the post-closure phase of geological disposal and argued that human management and monitoring of a repository should continue for as long as the waste exists. This implies an expectation for post-closure monitoring in the UK from some lay stakeholders, although further consultation would be necessary to identify whether this view is representative of a wider range of lay stakeholders than those consulted to-date.

Indirect Expectations for Monitoring

Elsewhere, interactions with lay stakeholders have identified concerns and expectations that, whilst not specific to monitoring, could influence the development of monitoring objectives and strategies.

For example, past and ongoing engagement activities in France have identified a strong preference for reversibility, which is a disposal management process within which the option for retrievability is incorporated into the disposal concept[2].

This preference was discussed in depth during the drafting of the 1991 Waste Law (Loi n° 91-1381), which was developed following public reaction to an earlier site selection process for a deep repository for HLW (Niel, 1996). Lay stakeholders and their elected representatives reiterated a preference for the study of reversible geological disposal during public enquiries in the late 1990s relating to the construction of URLs at three potential sites in France (Andra, 1998; Andra, 1996).

[2] Retrievability places a direct requirement for monitoring to supply the information on which a retrievability decision would be made and could therefore be classified as an explicit expectation.

The issue has been progressively further developed (Andra, 1998; Virtual Repository, 2010) and integrated into the proposed concepts and approach to managing the disposal process (Andra (2009a)). It also is being subjected to the scrutiny and analysis of Social Scientists (e.g. Aparicio, L. (Ed.) (2010)).

In Belgium, the issue of reversibility was recently discussed in a national citizen panel on geological disposal. The panel was invited to reflect on the question if geological disposal could be the preferred option for the long-term management of high-level waste. The participants concluded they could accept geological disposal as a solution to the waste problem, but that reversibility (during a "reasonably long period of at least 100 years") should be an essential precondition for implementing geological disposal (FRB, 2010).

It should be noted that definitions of what is required in terms of reversibility and/or retrievability vary somewhat from country to country. Nevertheless, if some form of reversibility/retrievability is required for a period following waste emplacement, it would clearly be necessary to monitor the condition of the disposal facility to ensure that waste retrieval remains feasible over the required timeframe (see e.g. EC (2000)). This is a key driver for post-emplacement monitoring and potentially, for post-closure monitoring. Some public interest has been expressed in France relating to the longevity and reliability of monitoring systems, which suggests an interest in the practicability of using monitoring to demonstrate the feasibility of retrieval over a significant period.

From other engagement activities, for example in Germany and the Czech Republic, public, and in particular local citizens', concerns about issues such as geological conditions, the impact of the repository on groundwater and on the environment, safety, transparency and the role of expert judgement in decision-making, all point to a potential role of monitoring and communicating about monitoring activity as essential in view of demonstrating the feasibility of constructing and operating a geological disposal facility and in building confidence in the disposal system.

3.3.3 Some more general expectations concerning building trust and confidence

Throughout engagement activities in the countries considered here, issues of (lack off) trust and confidence in the activities of waste management organizations and in the disposal programme have been raised. These were not directly related to the issue of monitoring, but should nevertheless be taken into account in this reflection.

Gaining and maintaining the support of lay stakeholders is, in part, dependent on a carefully planned strategy of ongoing engagement and communication. A lack of trust in waste management organisations and/or Government appears to be a view held by some lay stakeholders across many countries including France, Germany, Japan, the UK and the Czech Republic. Monitoring may have an important role to play in supporting commitments to provide assurance and to demonstrate good practice to lay stakeholders. It has clear potential value as a confidence-building tool, as observed in UK stakeholder workshops (UK CEED, 2002), but its effective use would require careful consideration within a wider communication strategy.

The expectation of ongoing communication with lay stakeholders is expressed in different countries and is relevant to stakeholder engagement at both the national level (e.g. Belgium – the citizen panel on geological disposal) and the local level (e.g. Germany – Forum on Stakeholder Confidence (FSC) meeting with local stakeholders). Recurring comments can be identified in feedback from lay stakeholders:

- concerns related to making enough time for lay stakeholder engagement;
- the need for lay stakeholders to be taken seriously;
- the need for waste management organisations to put trust in citizens and to be open to other interests.

The belief that an open and transparent approach is required for successful implementation of geological disposal is held in more and more countries, as reflected in ongoing approaches to partnership and engagement. There are expectations in many countries, including France, Germany, the Czech Republic Belgium and the UK, that lay stakeholders should be involved in the decision-making process in some capacity, and should continue to be involved and informed into the future.

Several countries currently involved in site selection for a geological disposal facility, including the UK and Japan, have adopted a site selection process based on voluntarism and partnership, whereby communities would volunteer to host a repository (Defra, 2008; NUMO, 2002). Potential host communities may specify requirements or conditions for their continued participation in a siting process (and ultimately, for their decision to host a repository). Such conditions could potentially include requirements for monitoring and/or retrievability. No specific examples have been defined at this time for either of the above mentioned countries. However, in Belgium, this has been the case for the siting of a near-surface repository for low-level waste (LLW) and intermediate-level waste (ILW), where local stakeholders expressed specific requirements for monitoring and retrievability, and engaged in negotiations with the implementer and regulator to agree on a common view on a disposal concept that incorporates special engineering features to support a monitoring strategy.

3.3.4 Summary of Lay Stakeholder Expectations

Based on the discussion above, it can be concluded that lay stakeholder expectations for repository monitoring across a wide range of countries are similar, are broadly consistent with the principles identified by expert stakeholders (e.g. IAEA, 2001), and can be represented by the following high-level principles:

- Monitoring should be carried out to ensure worker and public safety during construction and operation of a repository.
- Monitoring should be carried out to ensure long-term safety. In some countries there are indications that lay stakeholder expectations include some form of post-closure monitoring.
- Monitoring is often linked to the question of reversibility or retrievability. In that respect, monitoring is expected to be carried out to confirm that retrievability of waste and/or reversibility of the disposal process is feasible and continues to be practicable, at least during the operational phase.
- Monitoring should be carried out as part of an open and transparent approach to clear communication with lay stakeholders, in order to build public confidence and trust in the disposal programme.
- Monitoring should be used as a tool to inform decision-making by both expert and lay stakeholders.

One or more of these principles may apply in each of the MoDeRn Partner countries.

The breadth of lay stakeholder expectations, and particularly the need for confidence building, suggests there may be potential value in monitoring specifically for societal reasons in many instances.

3.3.5 Conclusions of Lay Stakeholder expectations

We have reviewed lay stakeholder expectations that have been identified, and discussed how these have influenced subsequent planning for geological disposal (and how they may influence future activities). We have also considered how lay stakeholder inputs might affect the development of national monitoring programmes in future.

Very few dedicated stakeholder engagement meetings have been undertaken on the subject of monitoring. This is mainly because national disposal programmes are at a relatively early stage of implementation. In countries that have not identified a specific site or geological environment for disposal, discussions are mainly held at a generic level and site-specific considerations are not accounted for. Furthermore, engagement activities with lay stakeholders even at this generic level often are still at an early stage. Finally, in the majority of countries planning to implement geological disposal, the implementers are still at a relatively early stage of developing their approach to monitor a repository. Many countries are at the stage of developing objectives and strategies for monitoring and may find it difficult or even feel it is premature to consider more detailed inputs from lay stakeholders at this point.

Lay stakeholder expectations of monitoring, for that reason, have mainly been expressed indirectly and at quite a high level to-date. Such expectations could be factored into the development of monitoring objectives and strategies. However, it is unlikely that current understanding of lay stakeholder opinions could be used to guide the selection of specific monitoring parameters, or the development of a monitoring programme, because available information is not sufficiently detailed.

At this stage, the understanding of the impact of lay stakeholder views on the development of monitoring programmes requires further development. The extent of lay stakeholder engagement to-date on the subject of monitoring suggests that definitive conclusions should not be drawn without more extensive consultation and debate.

4. Main physical aspects of national contexts

The physical context for a national repository of radioactive waste is given by three major considerations: (i) the waste inventory, (ii) the natural environment of the selected host formation, and (iii) the engineered system and associated method of disposal. These three define the features, events and processes that are developed and analyzed in safety case arguments, which comprise a primary purpose for performance confirmation monitoring. Owing to unique combinations of these three intersecting parameters of waste, host rock and disposal concept, the features, events and processes (FEPs) for each repository are expected to be divergent. However, the monitoring concepts, requirements and goals are similar at the strategic levels of confirmation and public acceptance.

The following sections provide a brief overview of these physical boundary conditions. Where appropriate, first considerations on how they might influence monitoring decisions are provided.

4.1 The waste inventory and disposal packages

Type and quantity of waste influence repository design requirements, time frame for disposal, and may induce certain waste specific considerations such as heat load, criticality, potential for release of contaminants during the operational phase or any considerations related to the matrix used to confine the radionuclides. Descriptions are provided in waste inventory and property reports (e.g. Andra (2009b)). In addition, different categories of waste (intermediate level and high level waste as well as spent fuel, are considered for geological disposal) may entail different monitoring needs with regard to occupational safety aspects.

The overall waste quantities considered include currently existing wastes and an estimate of future waste that would be generated during the anticipated operations of existing facilities. They are thus based on assumptions pertaining to residual operation time of nuclear power plants and to choices of reprocessing (or not) the spent fuel. It is generally acknowledged that estimates will need to be updated as significant decisions are made on the upstream fuel cycle (e.g. longer lifetimes of operating power plants). The overall waste quantities considered do not take into account future wastes that may arise from new build of nuclear power plants.

Among the waste types considered are spent fuel, high level waste and long-lived intermediate level waste. A complete inventory (see e.g. the UK CoRWM 'baseline inventory', CoRWM 2005b) may also include Uranium and Plutonium, as these materials might one day be considered waste. In addition, some countries have included low and intermediate level wastes which are not long lived, and these are either destined to a separate repository (e.g. Nagra, NDA) or to be included in the same repository (NRG – the Netherlands do not provide the option for shallow land burial and the small overall amount of waste makes regrouping in a single repository the preferred option).

The issues of time frames that are expected to manage the waste inventory (i.e. to construct, operate, monitor and close a repository) refer to an overall duration required to construct the corresponding repository structures, to condition, transfer and emplace the waste, and to safely manage the repository until its closure is decided. As repositories are designed taking into account existing and future wastes expected to be produced by ongoing industrial operations (of power generation, of reprocessing, reconditioning…), it also refers to an expected schedule of future waste becoming available for disposal. It may refer to cool-down periods required to respect maximum heat load conditions as part of overall disposal specifications. It may finally refer to an additional, post-operational monitoring period prior to closure. This can lead to an overall time span between begin of construction and closure of the order of a century. The durability of the used measurement equipment is therefore an important technical requirement to take into account for the design of monitoring systems and for the selection or development of adequate monitoring technologies.

The waste inventories and properties of high-level waste determine the residual heat generation. The heat signature of the disposed waste relevantly influences the geometry of the repository design and determines the near-field evolution. For that matter, monitoring of the heat transfer from the heat producing high-level waste through the engineered barrier system into the host rock is an important monitoring objective to ensure that temperatures that may impair the engineered barrier system (EBS) or host rock, or that may impair the capacity to model their respective evolutions, are not reached.

Initial information provided by the country annexes included few or no explicit monitoring issues linked to the waste inventory (waste disposal packages are discussed separately). A notable exception is the thorough description of radiological/radioprotection monitoring conducted within the Dutch Habog long term storage facility (NRG). This provides a very useful input to the type of monitoring that may be needed in surface facilities of a repository. It is, however, not obvious to what extent these approaches can be transferred to the subsurface. While radioprotection will obviously be a monitoring goal, this is related to operational safety. The link to performance confirmation of long term safety is not self-evident but deserves analysis.

4.2 The natural environment

4.2.1 The host rock

Host rock characteristics play importantly into the purposes and possibilities for monitoring. This section describes national contexts for repository host rock under investigation or consideration by members of this consortium.

It is historically well documented that three primary rock types have been considered around the globe for geologic disposal of radioactive waste on land; namely, granite/gneiss, clay/shale, salt (crystalline, sedimentary and saline). Further, it has been established by the cognizant technical community that long-term safety can be assured for nuclear waste disposal in any of these host media. As an aside, the United States legislated that volcanic tuff be the pre-emptive choice for their repository; however, they are unique in prescribing that host rock for HLW and that decision is in the process of retraction. Therefore, further consideration of volcanic rocks will not be included as a specific host rock type.

Monitoring prerogatives for each rock type vary as a function of waste and rock properties in concert with disposal concepts. With regard to host rock properties, salt possesses well recognized and characterized properties, clay/shale comprise a comparative spectrum of properties depending on mineralogy, environment of deposition and geologic history, and crystalline rock encompasses yet another set of repository-relevant characteristics. Each host rock type has attributes that on the one hand ensure suitable performance as a repository and on the other hand provide differing disposal operations.

Monitoring objectives that might be further developed to contribute to performance confirmation are likely related to:

- Confirmation that the hydrogeological environment is consistent with the licensing baseline.
- Demonstration that favourable rock properties characteristic of the undisturbed host rock are preserved, minimally altered, or understood sufficiently while creating and utilizing the underground space.
- Alteration of the underground setting in the process of operations creates both a need and an opportunity to monitor response. Logically, monitoring during operations comprises initial elements of the long term testing and monitoring program and is by definition the early stage of performance confirmation. Repository conditions that evolve from the waste/rock/EBS interactions will give rise to monitoring objectives aiming at detecting thermo-hydro-mechanical response in the near field environment.
- One of the most recognized characteristics of any host rock is the disturbed rock zone and its creation and impact to performance varies greatly with the different host media. Possible monitoring to confirm EDZ characteristics described in the technical baseline will help address the extent of possible performance impact and mitigation plans pertaining thereto.
- Finally, the relationship of host rock and waste within the environment of the disposal concept will likely provide key elements for monitoring considerations. Damage imparted to the host rock influences permeability proximal to the disposed waste, while the near-field process models define the source term for performance assessment.

Attainment of monitoring goals articulated above would necessarily have differing levels of importance to repository performance and hence the priorities and implementation strategies will differ depending upon the host rock.

Crystalline rock is typically characterized by excellent long term stability (SKB (2008), Posiva (2009)), which thereby lessens the need or utility of structural monitoring. Long term safety is thought to be sensitive to hydrogeologic heterogeneity (fractures), which may provide a fast pathway to the biosphere. The concept of operation may therefore include high performance standards for waste disposal packages and attendant monitoring of the package itself and the near field environment (e.g. SKB (2006)). Commonly, disposal concepts include an intimate engineered barrier, such as bentonite in concert with a robust waste package, giving rise to possible monitoring applications consistent with the elements of the safety case.

The brittle and elastic properties exhibited by typical crystalline host media might require monitoring of construction effects and their evolutionary contribution to the near-field environment. Here again, primary monitoring goals are consistent with a desire to preserve perceived favourable host rock properties, to monitor and understand changes to these properties and to implement mitigation strategies based on this knowledge. A significant underpinning of the licensing basis would include evaluation of the extent to which these processes influence host rock potential to contribute to long term safety.

Sedimentary rock usually represents a range of geologic monikers, including mudstone, clay, shale and argillite. At this time, there are no countries within the collaborating partners that propose HLW repositories in sedimentary lithologies of sandstone or limestone. The sedimentary rock considered within the country contexts is typically more or less plastic clay (e.g. Andra (2005), Nagra (2002), Niras (2001)). Plastic properties and risks for breakouts combined with an operational period on the order of a century may require substantial effort be placed into ground support. These circumstances may generate specific monitoring objectives. Beyond the operational period, long term safety tends to rely on homogeneous transfer conditions via diffusion, which suggests possible utility of a form of a very long term tracer diffusion test.

Notwithstanding testing that directly confirms the basis of the long-term safety case, the basis of that perception includes elements that can be monitored during operations. In certain sedimentary host rocks, it may be especially important to confirm the limits of the EDZ as it pertains to increasing permeability or re-establishing low permeability via self-sealing mechanisms. Near-field monitoring might be devised for possible chemical interactions between the host rock and iron or concrete components of the engineered barrier materials. Process models for sedimentary rock usually embrace diffusion-limited transfer, reducing environments and sorption, all of which constitute possibilities for confirmation by way of a long-term testing and monitoring program. Another relevant parameter to long term safety is the very low potential of water influx from the host rock to the excavated structures. While this would only mature in the millennia after closure (after the underground setting has rehydrated and re-equilibrated with its natural setting), evidence for this evolution may very well be ascertained by monitoring potential water influx from the host rock into the repository during the operational phase.

Saline rock is typically very plastic, even at ambient temperatures (e.g. CORA (2001), Bollingerfehr et al. (2008), Hansen et al. (2011)). When heat-producing nuclear waste is placed within a salt horizon, operational and mining considerations become important. Monitoring geomechanical deformation is common practice and would be fundamental in an operating repository. In the case of salt deformation, a mechanistic understanding has been established by the research community such that projections of room and drift closure can be made with confidence. Thus, entombment of the waste in the host medium is expected, perhaps minimizing the need for waste package performance.

As with other host media, the licensing process includes science-based expectations of performance of the host rock. Thus, structural evolutions including features of the EDZ and disposal room closure are obvious candidates for confirmation monitoring. Extensive ambient experience at the Waste Isolation Pilot Plant (WIPP) facility in the United States has shown that brittle (EDZ) and plastic deformational processes are substantial as well as conducive to confirmation measurement. Thermal activation is acknowledged to provide first-order effects to the evolution of the disposal room.

Thus, thermo-mechanical measurements appear key to saline host rock performance. In addition, the small amount of brine residing in salt formations will be liberated by creation of the EDZ and accelerated by the thermal pulse. Thus, an evaluation of the moisture liberation, progression and ultimate fate appears to be uniquely applicable to disposal in saline host rock.

Summary of host rock considerations for monitoring

Taken collectively, the impact of the host rock on monitoring can be summarized at a high level by considering some of the key attributes of each media, as done in Table 4-1. Representative features listed in the table would be integrated into site characterization and the process models used in the safety case. The technical baseline that substantiates the license application would document the testing and monitoring program for continued assurance that the repository performs as subscribed. These continued measurements, either in the laboratory or in situ, firm up the licensing basis and provide public confidence in repository performance.

Table 4-1: Features of repository host rock

Feature\Rock type	***Saline***	***Sedimentary***	***Crystalline***
Thermal conductivity	*High*	*Low*	*Medium*
Permeability	*Impermeable*	*Very low*	*Unfractured = low* *Fractured = high*
Strength	*Medium*	*Low or very low*	*High*
Rheology	*Plastic*	*Plastic to brittle*	*Brittle*
Room stability	*Self supporting on decade scale*	*Reinforcement required*	*Stable unfractured* *Support required if fractured*
Dissolution	*High*	*Low*	*Low*
Sorption	*Low*	*High*	*Medium*
Engineered barriers	*Minimal*	*Minimal*	*Medium*

4.2.2 The impact of local and regional hydrogeology

Hydrogeology plays a major role in monitoring the construction and operation of most geologic disposal facilities, as well as in the assessment of their long-term safety, for a number of reasons. First of all, advection and diffusion in groundwater are the principal mechanisms by which radionuclides could potentially be transported to the biosphere in the case of a release from an underground repository. Furthermore, groundwater properties and dynamics have a great influence on the performance and durability of the engineered barrier system in many disposal concepts. In particular, the planned use of swelling clays (e.g. bentonite) as buffer, backfill, and tunnel sealing material necessitates a careful investigation and monitoring of the local and regional hydrology. Also, the corrosion resistance of waste containers intended to remain tight for millennia relies on favourable chemistry and very low mobility of groundwater. Due to disturbance to the natural hydrological system, a repository can be expected to have a local environmental effect of hydrological nature as in the case of mines and tunnels.

The hydrogeological setting for the repository depends strongly on the chosen type of host rock, and, to a somewhat lesser extent, on surface water systems and climatic conditions. Elevation and topography of the site may also be regarded as a part of the hydrological context, while locations already chosen or being considered in different countries vary from coasts or even beneath the seabed to elevated plateaus and mountainous areas. Development of the climate in time (e.g. past and future periods of glaciation in northern Europe, post-glacial rebound, changes of sea level due to global warming, etc.) may affect the hydrogeological setting of the site and may have to be taken into account in the design of the repository. However, considering the long time spans of climate developments, viz. thousands or tens of thousands of years, monitoring the long-term hydrogeology may not be feasible.

Monitoring efforts on the hydrogeology are generally intended to confirm that subsurface conditions and geotechnical parameters are as anticipated and that changes to these conditions are within limits applied in the design and licensing processes. Some overlap may exist between monitoring objectives during construction and operation and monitoring that was conducted to during site exploration and to obtain baseline information.

In **crystalline rock** there are typically fractures or fracture zones with notable transmissivity that act as preferred paths for groundwater flow and enable advective transport of solutes. Between these zones there are blocks of tight rock suitable for waste deposition. Hydrogeological monitoring, in addition to other methods, can contribute to the knowledge of the heterogeneities of the host rock, which is necessary to confirm its favourable behaviour during and after waste emplacement. With the water-conducting structures identified, monitoring activities can be focussed on them to detect the impact of the repository construction, and to verify that no release of radionuclides from the repository occurs. Crystalline rock has been chosen as the host rock in Czech Republic Finland, and Sweden, and is one of the options in Japan, Spain, and the United Kingdom.

In **sedimentary rock**, clay in particular, water-conducting fractures are sparse or totally absent, so that diffusion is the only transport mechanism for radionuclides. In addition, many of the anticipated dissolved ions are effectively retarded by sorption. Desaturation and eventual resaturation of the host formation are important hydrological phenomena regarding the structural stability of the repository. One aspect that has received much attention in recent years is the healing capacity of clay after a disturbance such as gallery excavation and the heat-up after the displacement of waste canisters. It is likely that as a result of the elasto-plastic properties of clay the imposed damages will be healed in time and the clay will return more or less to its original state as time progresses. Confirmation of this healing effect would be an important objective of monitoring of a repository in sedimentary rock. Belgium, France, and Switzerland aim at deposition in clay, and it is an option in Japan, the Netherlands, Spain, and the UK.

Saline rock is characterised by an extremely low value of hydraulic conductivity, and a much lower porosity than clay formations. In analogy with sedimentary rock, saline rock is a plastic material that has also healing properties after an imposed disturbance. Confirmation of this healing effect would also be a monitoring objective for a repository in saline rock. Disposal in rock salt is the reference concept in Germany and an option in the Netherlands and the UK. The already operational WIPP, for transuranic waste in New Mexico, United States, is located in a salt formation.

4.3 The engineered system

The engineered system is designed to allow for emplacement of the waste inventory in the host rock, and is adapted to waste and host rock properties. Engineered barriers comprise all man-made structures to enhance the safety and performance of a repository, such as overpacks, disposal drifts, boreholes or caverns and their associated buffer and support structures, seals and backfill. A comprehensive overview of engineered barrier systems is provided e.g. in the EC Engineered Barrier System project report (EC, 2010).

Various engineered barriers, including overall repository layout, are briefly introduced below and first considerations on possible associated monitoring activities or on possible implications for the implementation of monitoring are provided. Given the variety of national contexts, different engineered barrier components may have different safety functions in a given context. Corresponding monitoring objectives should be developed to contribute to the lines of evidence that the barriers will perform as designed. For this it should be kept in mind that engineered barriers work in tandem with the natural system and provide for an integrated analysis of pre-closure operations and post closure assessments.

By way of example, Figure 4-1 below illustrates disposal cell designs of four national programmes for a repository in argillaceous rock.

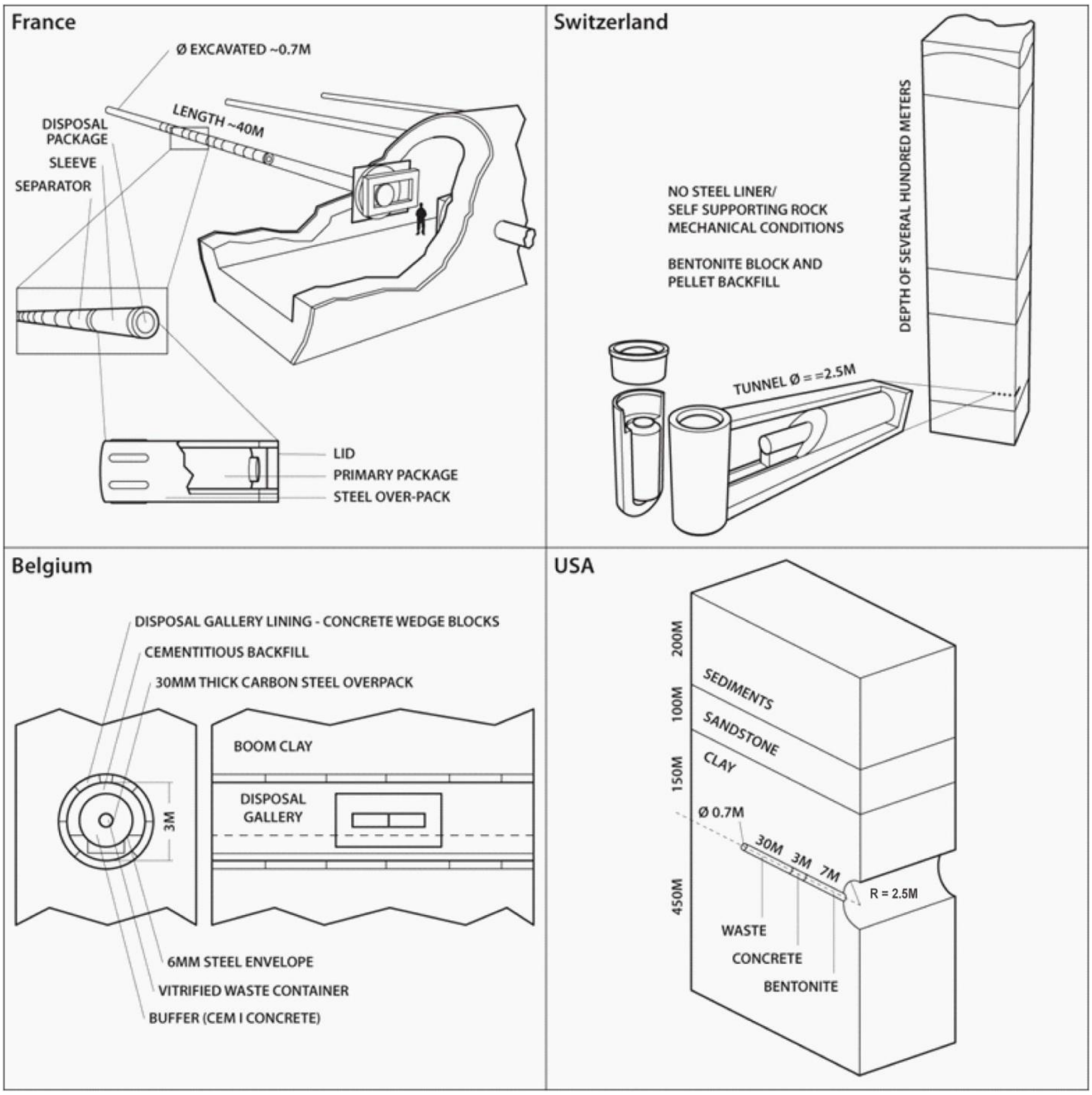

Figure 4-1: Various disposal cell concepts proposed for argillaceous host rock

4.3.1 Overall repository layout

In a few cases, repository concepts are sufficiently developed that the impact of overall repository design on the general approach and possibilities for monitoring can be discussed to examine differences and commonalities. In other cases the concepts are quite general and the design-related aspects and sequences of activities are not sufficiently defined to comment.

It is first worth noting that repository layout and envisioned construction, operation and partial closure, may induce greater or lesser technical challenges to conduct monitoring – e.g. when monitored areas are no longer accessible, separated from accessible areas by buffers and/or seals. In the event, implementation strategies for monitoring activities must be developed commensurate with repository layout and sequence of operations, while ensuring that remaining monitoring equipment (if any) will not impair the post-closure effectiveness of the safety barriers. While this in no way determines the selection of the specific repository design concepts, it clearly constrains the monitoring possibilities, which then may interact with the chosen repository design. Some aspects are discussed below.

The selected design concept of a repository is often strongly influenced by factors such as:

- Thermal management requirements;
- Operational requirements (e.g. excavation and waste deposition in parallel);
- Excavation stability;
- Preservation of the host rock's isolation capacity (e.g. clay rocks and rock salt).

In addition, overall layout may be influenced by considerations of e.g. (i) progressive steps combining each construction, emplacement and disposal cell closure, (ii) modular grouping of subsets of waste inventory into sealed off fields of disposal, (iii) operation of test and/or pilot facilities.

One of the factors indirectly affecting the design concepts and the associated sequence of exploitation is the rate of convergence of the host rock. In a rapidly converging rock such as rock salt, groups of emplacement cells would be excavated with waste emplacement and backfilling following immediately after, before the next field of tunnels or cells is excavated, as e.g. done in WIPP and proposed in the German concept. Compliance monitoring, quality assurance and inspection is possible at an early stages (construction, operation and emplacement), but is limited after emplacement and sealing to techniques that will not impair the system.

In an argillaceous rock converging at moderate rates, extended access and operations can be planned for but require robust rock support. If this is provided (e.g. as illustrated by Andra's concept), extended access can also provide relative ease of extended monitoring of disposal cells and their near field.

In Germany, the general approach calls for each emplacement field (group of drifts and waste emplacement boreholes) in a rock salt repository to be monitored during its operation (thermo-mechanical responses and rock mechanic) until the field is closed. Present laws and criteria are broadly defined at this stage, with limited specific implications for monitoring.

The Swiss repository concept includes a so-called pilot facility, where specific monitoring will be carried out for an extended period of time after the end of the operational phase of the repository until the final closure of the repository. The repository implementation involves a stepwise process that will take several decades and includes monitoring as an integral aspect of the concept. The broad requirements for monitoring of a disposal facility are outlined in a guideline of the safety authorities (ENSI 2009). While many aspects of monitoring described therein are related to the operational phase and not necessarily related to confirming the basis of long-term safety, this guideline explicitly calls for monitoring of a pilot facility. The ENSI requirements for the pilot facility provide broad guidance in terms of objectives and constraints for the monitoring and allow an overall concept to be developed. The main purpose of the monitoring programme of the pilot facility is, according to ENSI, to provide information on the condition, processes and effectiveness of the barrier system and to permit early identification of unexpected developments. The information obtained should support the safety assessment for final closure of the repository.

To a greater or lesser extent, currently envisioned repository monitoring programs consider monitoring to be limited to a set of representative structures. A key assumption underlying this is that monitored host rock and engineered components are representative of the overall repository. The implementation strategy of monitoring is conditioned by host rock properties and by the overall repository layout. Especially for the later, it is conditioned by the sequence of construction, operation and partial closure of individual disposal cells and of fields or modules of disposal cells. Representative structures can be either provided by a pilot facility, or included as some of the structures in the main disposal zone.

The time scales during which e.g. disposal cell monitoring can be conducted are closely related to above considerations. Access to the structures vicinity provides for greater flexibility in the choice of monitoring equipments and instrumentation approaches, while distant monitoring imposes constraints and additional technical challenges. It is generally assumed that progressive closure will be accompanied by a progressive reduction of monitoring. Conversely, the results of monitoring efforts are used in the decision-making process to gradually close disposal cells, access tunnels and shafts, or on the other hand to postpone such decisions. Once a structure itself is no longer directly accessible, as is e.g. the case after waste emplacement, in-situ sensors can no longer be replaced in case of failure. This may lead to durability requirements.

Conversely, certain access structures, and in particular surface to depth shafts and ramps, must remain operational for the full duration of the disposal process. For these, monitoring to verify and predict remaining mechanical stability until closure of the repository is important to ensure sufficient remaining life time and/or to recommend needed maintenance. In addition, these structures will be sealed after a decision for final closure of the repository was taken. It may therefore give rise to monitoring objectives of these structures and their near-field, to verify the initial conditions in which seals would be emplaced.

An import aspect with regard to the monitoring of EBS components is that the intended monitoring activity should not impair the safety function of the EBS component. As result, for any monitoring activity in the EBS a decision must be taken if the use of cables for the transfer of sensor signals is appropriate or not. Dependent on the repository design and the actual parameter under consideration, the use of wireless data transmission techniques may be required.

4.3.2 Waste Disposal Package

The Waste Disposal Package (WDP) may have a role both for operational aspects (retrievability) and for long term safety (EC, 2010).

Depending on the design, the WDP can be a simple or a composite structure. In the case of a simple package, it is typically the conditioning package (manufactured during reprocessing) that is disposed of. In contrast, other designs consider a disposal package in addition to the conditioning package when reprocessing waste is considered. For spent fuel, a specific disposal package is always envisaged – as the spent fuel elements as such are not suited for direct disposal. Also the Intermediate Level Waste forms usually get a disposal package (concrete monolith). Some designs further specify a temporary package to facilitate the handling/transport and installation of the waste forms (e.g. Spanish concept: steel overpack with 15 cm neutronic shield). The Belgian (and Dutch) Supercontainer design with its inherent shielding (concrete) have also been designed to avoid remote handling operations by reducing the radiation level to less than 25 µSv at 1 m from the WDP surface. Other overpack designs also provide some shielding which contributes to radiation protection during the operation phase.

Another possible function of the WDP expected for time scales typical of the operational phase (on the order of 100 yr) responds to the requirement for retrievability (put forward by e.g. France as part of a reversible management approach, and the United States for the Yucca Mountain Project). The WDP should provide structural integrity and containment during that period for safe retrieval operations.

Several national programmes have specified requirements on the WDP to contribute to long-term safety. This may be by providing containment of the waste (no contact with the formation – in particular with its water) during the thermal phase. The typical time scales depend on the thermal management, waste properties, the specific limit of the thermal phase, and may thus span from 100s to several 1000s years. Depending on the overall repository safety strategy, longer containment periods may be required as well. This containment is to be ensured by the design of the packages, in particular by minimizing the risk for corrosion in its given environment, and by the design of additional barriers as required to surround the WDPs. Typical design solutions rely on a composite package, such as:

- a cast iron insert in a copper canister (Finland);
- carbon steel covered by corrosion resistant Ni alloy layer (Czech Republic);
- a steel overpack (France, Japan, Spain); or
- a steel overpack with thick concrete layer ("Supercontainer" – Belgium, Netherlands).

Regarding monitoring – the whole spectrum of requirements can be found in the different national contexts. Monitoring of the waste package conditions – together with a confirmation that the waste retrieval option is preserved – is e.g. a specific requirement of the Yucca Mountain monitoring (performance confirmation program); Enresa on the other hand states that there are no provisions to monitor the WDPs when emplaced in the disposal area of the repository. Another, specific monitoring requirement is mentioned by Andra and relates to gas production (gas build-up in LILW forms, gas release from HLW forms).

In addition, a number of possible reasons why monitoring of the WDPs after final disposal might be considered unnecessary – even inappropriate – were provided:

- WDP are manufactured with well characterized and proven, engineered materials (steel and other alloys, concrete,…) which exhibit less variability than geo-materials; reducing uncertainty – one of the reasons for monitoring – is less an issue in this case;
- waste packages are produced in well-controlled conditions at the surface, allowing an extensive quality control;
- waste packages can be manufactured some time before disposal, allowing temporary monitoring at the surface. Although heat-dissipating HLW forms are typically stored for 50 years or more at the surface, they might be reconditioned

with an overpack only shortly before the actual disposal; the timing of this operation might be optimised such that some monitoring of the final WDP is still possible during some years;
- monitoring of the WDP with wired sensors might jeopardize the isolation function;
- the high radiation at the surface of the WDP might be problematic for the reliability of the sensors (in particular when long-term monitoring is considered).

The pilot facility concept put forward in the Swiss design could involve some monitoring of the packages, although intrusive methods (e.g. measurement of surface temperature of the packages) are not advised. Retrieval of the waste packages (upon transfer from pilot to main facility) could on the other hand allow to check for corrosion.

In many concepts, the performance of the WDP is associated with the performance of a bentonite based buffer emplaced around it. The latter may have a buffer function related to mechanical and chemical evolutions – by providing a homogeneous stress field and by providing a geochemical environment controlling corrosion rates of the WDP. It also limits water flux from the host rock to the WDP and ultimately provides a transport barrier to radionuclides and colloids.

Monitoring buffer conditions and evolution may be considered to confirm base knowledge used for the safety case. In many cases, however, evolutions may be too slow for direct in situ monitoring.

4.3.3 Cavern, drift or borehole disposal of Waste Packages

Various engineered structures are envisioned for waste emplacement. These are, for their respective concept, the disposal unit.

As far as known, the disposal of high-level heat-generating radioactive waste in large caverns (as proposed for low- and intermediate-level waste) is not considered in any concept, i.e., only borehole and drift disposal options are considered.

The monitoring options from the exterior of the repository, i.e. from the surface, and of the exterior of the repository, e.g. of earth surface movements (up and down) due to thermal expansion or groundwater monitoring, all seem to be very identical. In the case of monitoring within the underground facilities, differences may arise from the monitoring objectives and strategies as well as from the effort one is willing to make regarding monitoring activities. A distinction has to be made between concepts considering disposal in long or short vertical boreholes and between horizontal and vertical boreholes. These may lead to specific technical challenges if in-situ emplacement of monitoring equipment needs to be considered.

By way of example, one of the German reference concepts proposes disposal in vertical boreholes in rock salt with a length of 300 meters containing about 50 canisters (Bollingerfehr et al. (2008)). Actual monitoring requirements depend very much on identified objectives and on whether monitoring close to the waste is considered or not. Monitoring seems possible, but may be met with technical challenges and in situ implementation may require substantial effort, especially if rock deformation in the vicinity of the borehole is an issue at greater depths. In the case of drift disposal, monitoring systems can be installed prior to waste emplacement and backfilling, based on available experience. Particular technical challenges may nevertheless be associated with drift dimensions, accessibility and construction procedures. Installation in a drift is closer to routine work whereas installation in a deep borehole may require research and development activities regarding measurement devices and installation technologies before a detailed planning of a monitoring system is possible.

Installation of monitoring systems in short boreholes, designed e.g. for one or two canisters only, as for the example of the KBS-3 concept considered in Sweden and Finland (SKB (2006)), may present a lesser technical challenge, comparable to that in a drift.

Another difference may arise from the necessity to consider waste retrieval as is stipulated e.g. in France, more specifically when design requirements address relative ease of retrievability. In this case, the disposal in horizontal boreholes is preferred. Reversibility requires that information on the capacity to handle (retrieve) waste canisters be made available. At the same time, monitoring of the host rock and engineered barrier conditions provides some of the information made available to disposal process management, allowing evaluating available options to management. It is expected that less monitoring equipment is required in the case of disposal without reversibility consideration, i.e. when lesser emphasis would be placed on structural health evaluations and predictions prior to closure. It is expected that there is no difference between drift disposal and borehole disposal regarding retrievability. Rather, such a difference would be related to any structural components providing for a relative ease of retrieval prior to repository closure.

Data transmission should be the same for all disposal options. For example, a wireless system can be used for both the borehole and the drift disposal option and thus ensure that neither backfill material nor sealing constructions would be breached by any cables.

Monitoring of the disposal unit may focus on either confirming the basis for the safety case and thus on the evolution of the waste disposal package, on engineered buffers and seals, as well as on relevant near field evolutions – for example to verify that initial conditions of long term evolutions are consistent with that basis. It may also focus on pre-closure requirements, e.g. on retrievability, if this is a required design feature. Monitoring data may be consulted to judge if and how the retrieval of waste canisters can be carried out safely and possibly focus on the integrity of the packages, the ambient conditions on the disposal unit, and the conditions of structural support (if any).

4.3.4 The role of gallery and shaft seals for long term safety

The performance of seal systems often play an important role in the technical bases developed for the long-term safety case. In the ensuing discussion, these elements are differentiated into horizontal gallery elements and vertical shaft seals. Similar considerations would be given ramp entrees, if they are incorporated into the final disposal concept. Consistent with the nature of step-wise repository development, technical bases for seal elements are developed within a framework of site characterization, underground research laboratory testing, laboratory testing, and testing and monitoring during operations and disposal. The latter testing focuses on performance parameters and would be integral to the performance confirmation program. However, seal system testing and monitoring must ensure inviolability of the seal function. In this section, seal system strategies are developed for the three primary rock types and particularly address existing strategies to obtain seal capability.

As noted elsewhere, many repository elements derive from the functional and operational requirements of the disposal system, which involve the waste, the host lithology, and the concept of operations. The role and therefore the design of seal systems manifest from features events and processes. The seal systems are designed features that are expected to exhibit particular barrier capabilities within the safety analysis. In almost all safety cases, the seal systems either prevent or mitigate transport of radionuclides from the repository horizon to the regulatory boundary. Barrier capability is assessed based on structural, chemical, mechanical, thermal, and hydrologic sciences and the relevant process models are implemented into performance assessment methodology.

An acceptable seal system should be designed and constructed using existing technology and the seal system should readily meet requirements associated with repository system performance. Guidelines include:

- Limit waste constituents reaching regulatory boundaries
- Restrict formation water flow through the sealing system
- Use materials possessing mechanical and chemical compatibility
- Protect against structural failure of system components
- Limit subsidence and prevent accidental entry
- Utilize available construction methods and materials.

Guidelines are met through a commitment to quality control and accepted engineering principles and practices. Seal systems may compensate for some of the disturbance underground excavations have caused to the prior, unperturbed hydraulic functioning of the host rock. They are emplaced to work in tandem with the natural system and are integrated into the design, analysis, pre-closure operations and post closure assessments.

Most national programmes combine vertical shaft and access ramp seals with underground disposal drift seals and access gallery seals as part of their overall concept. This may serve several purposes. First, it would clearly relate progressive closure to the emplacement of an engineered component having an isolation function, thus bringing the overall repository closer to a passive long term safety stage. Second, it would provide redundancy with respect to the safety function of preventing or mitigating water flow and radionuclide transport.

The sequence of repository operations would include construction, waste emplacement, and installation of seals, repository closure, and abandonment. However, owing to the potentially long time periods involved, considerations such as loss of institutional control enter into the design and concept of operations. Events such as war or natural disaster may lead to premature repository abandonment. These hypothetical futures have been considered by many, if not all, repository programs. The impact of these unlikely situations is minimized by sealing emplacement drifts in modular compartments in due course of disposal operations.

In parallel to structure sealing, galleries are backfilled upon closure. Backfilling requirements tend to be associated with restoring the waste environment to conditions that approximate those of the unperturbed host rock. In particular for sedimentary and saline rocks, their main function is to minimize the long term deformation of host rock around excavated galleries. Backfills may be monitoring e.g. for initial density, subsequent compaction and/or deformation and progressive resaturation. However, crystalline rock is not expected to deform and, in the event mechanical gallery support structures remain in place for sedimentary rock or saline rock, recompaction of backfill due to host rock deformation is not likely to happen during the time scale available for monitoring. Likewise, resaturation may be very slow in all cases. The feasibility of monitoring backfill evolutions needs to be assessed since it is likely to be subject to time scales far beyond what can be achieved in practice.

Crystalline rock: As in other host rocks, the basic function expected from the sealing system is to restore the overall permeability of the host rock. In the case of crystalline rock, this means that the average permeability of seal and damaged near field should be close to the original average permeability. In addition, the seal system in crystalline rock provides a hydraulic break between any water bearing features and the galleries and shafts.

The construction of seals and understanding of their evolution can take reference e.g. from results obtained from the 10 year tunnel sealing experiment (AECL (2008)) conducted in the now closed Canadian crystalline rock URL. This provided information on technical feasibility as well as indications on mechanical and hydraulic evolutions after seal emplacement. In addition, an ongoing shaft sealing experiment consisting of instrumenting the shaft seal of that URL aims at monitoring mechanical and hydraulic evolutions of the bentonite seal and the two concrete support blocks.

As opposed to seals placed in very low permeability sedimentary rocks or in dry saline rocks, the natural resaturation of swelling clay may actually be monitored over reasonable time scales, depending on the production of the water bearing features the seal intersects.

Sedimentary rock: The fundamental design principle for seal systems in a clay/shale repository is to ensure that radionuclide transport is controlled by diffusive rather than advective processes. Access tunnel and shaft seals have a hydraulic function to limit water flow from disposal cells to access shafts or ramps, to zero or specified acceptable levels. Vertical (surface to depth) seals could be designed to provide redundancy with the horizontal disposal cell and access tunnel seals.

The seal system at depth applied to a clay/shale repository could include a modular concept whereby the whole repository comprises sections or modules that are sequentially partitioned and isolated with horizontal panel closures (seals). The French concept, as an example (Andra (2005)), closes the repository in stages, i.e., disposal cell sealing, backfilling, and sealing drifts and then shafts. Seal materials include concrete and swelling clay, consistent with WIPP shaft seal material specifications. The repository modules would be separated from one another by sufficient distance that thermal, hydrologic, and other possible modes of interference are inconsequential.

After the repository is filled with emplaced waste and horizontal panels are closed, seals would be installed in the access shafts.

A major intrinsic advantage of repository development in a clay/shale formation is an overall lack of groundwater to seal against. Even though regional aquifers may be proximal to the host clay/shale unit, the shaft seal system would be designed to perform in contact with groundwater. If water flow occurs within the repository openings or in the EDZ, the chemistry of water or brine could impact engineered materials. However, the geochemical setting will have little influence on the concrete, asphalt, and clay shaft seal materials. Each material is durable with minimal potential for degradation or alteration. Note that microbial degradation, material interactions, and mineral transformations are often incompletely understood, and therefore are the focus of ongoing research.

This aspect, however, makes it impossible to directly monitor the natural resaturation of a seal. Given the time scale for natural resaturation of swelling clay seal materials limited by the slow inflow of water from the near field, corresponding activities must be developed to provide evidence that seals will function as designed, without having to monitor the seals in their long-term configurations. Monitoring could emhpasize “dry” conditions and early evolutions upon emplacement, to verify e.g. the absence of unexpected mechanical deformations. Already, extensive design, analysis, and testing of seal components, such as speciality concrete or bentonite, have been performed. For instance, the design of a seal system for a shale repository benefits from available design and performance calculations on comparable seal systems developed for the WIPP, which were subject to extensive technical peer review.

The WIPP experience established that effective seal systems can be designed, tested, analyzed and subsequently installed. The design approach applies redundancy to functional elements and specifies multiple, common, low-permeability materials to ensure reliable performance. In addition, long term monitoring of a representative seal subjected to forced resaturation could be considered. Such an activity might be carried out in situ or under the framework of a larger science program, to enhance the basis for the safety case prior to repository closure.

Saline rock: Salt as a disposal medium is very robust and provides a natural and primary barrier to release, regardless of the engineered systems (Hansen et al. (2011)). The salt formation by itself offers several favourable attributes for long-term waste isolation, such as ease of mining, impermeable strata and high thermal conductivity. Engineering investigations that established the compliance basis included fundamental thermomechanical constitutive model development for natural rock salt deformation and reconsolidation of granular salt for sealing elements. These mechanistic models help predict evolution of the underground setting, and bode well for extension of this technical baseline to future salt repository considerations. Seal systems in Salt formations were discussed e.g. in the BAMBUS project (EC (1999)).

The interplay between the geophysical response of the salt formation and engineered barriers at the Waste Isolation Pilot Plant was subject to extensive investigations during site characterization. The WIPP studies showcase elements of the objectives stated above, including the waste itself, interactions with the geologic stratigraphy, and the engineered barriers. At WIPP, design, engineering and analysis of the shaft seal system is contrasted with a modular panel closure system in the horizontal access drifts. These engineered barriers represent first-of-its-kind analyses and construction tasks, which involve unique design objectives, tailored materials, and performance demonstration. Treatment of the panel closure systems—now required for WIPP operations—was advanced by seal material performance testing in the underground at WIPP, as well as analogous, real-world situations.

The German programme is currently developing the design for shaft and drift seals. Prior experience from corresponding research and in-situ tests have shown that correct installation of a seal can be a difficult task. Therefore, care should be taken that no additional activities, such as monitoring, interfere with its success.

The high degree of plasticity in saline rock suggests that monitoring of mechanical deformation may contribute to confirming good integration of a seal with its natural environment. Conversely, the host rock being "dry", it may not be relevant to monitor water uptake by the sealing material.

5. Monitoring and the decisional process

All national programmes have clearly identified three major decision points governing the overarching development phases of the disposal process:

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

Most national programmes have identified a requirement to confirm the basis for the long term safety evaluation prior to obtaining authorization for repository closure. In part, this calls for a monitoring activity whose results will contribute to the analysis and decision whether to provide a closure license.

In addition, most national contexts consider progressive construction, operation and closure of the repository. This gives rise to the opportunity to associate a series of decision points to the disposal process from initial construction until closure. Such decisions are taken by those entities responsible for the disposal process management. They may in certain cases require further authorizations by the safety authorities (e.g. if future plans propose changes from the original license basis) and may have taken into account other stakeholder input.

Such decisions may in part be informed by results obtained from a monitoring programme. The IAEA (IAEA (2001)) considers that “the primary objective of monitoring is to provide information to assist in making those decisions”. Among the information of interest to manage the disposal process are (i) verification of the adequacy of the license basis for long term safety and (ii) options available to further conduct the disposal process, e.g. regarding temporal flexibility, if any, to delay further closure, or on contrary, added benefits, if any, to accelerate such closure. The following attempts to outline when such decision points might be relevant.

There seems to be consensus that at first, the main surface to depth infrastructure will be built and a first subset of disposal units (which may be disposal vaults for LILW, disposal cells, drifts or boreholes for HLW or spent fuel). These first disposal units may play a particular role, e.g. the Swiss concept identifies initial construction of a pilot facility.

Depending on host rock properties and/or the selected approach to manage this disposal process, closure of disposal units may be decided swiftly after emplacement or may be delayed for some period of time, either for ease of operations, to provide for an extended duration of easy retrievability and/or to facilitate some in-situ monitoring of these disposal units.

Construction and waste emplacement of groupings of planned disposal units (e.g. modules of disposal cells or disposal field of boreholes) will be started pending a corresponding disposal process management decision. Such decision may take into account prior monitoring results, e.g. to improve on disposal unit design, to incorporate a monitoring system better adapted to in-situ monitoring, etc.

Closure of individual units or of such groupings of disposal units will be performed pending a corresponding disposal process management decisions.

Throughout this process of stepwise construction, operation and closure, the question whether the disposal process should be redirected is addressed either implicitly (i.e. verification that progress to date and available monitoring data support the viability of the original disposal plan) or explicitly (e.g. analysis of monitoring results to provide design updates for future engineered components).

The decision points probably should address all aspects of the disposal process, including how to pursue monitoring during the next step. For example, it may be that the decision to close a disposal unit, or a grouping of such units (modules, disposal fields...), would be associated with a decision to evolve, reduce or end monitoring activities.

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

6. Key conclusions of National Context analysis

This report provides a first overview of items that characterize "national contexts" within which monitoring activities will be developed. To provide initial understanding and to allow for an initial comparison, the national context was defined as the sum of relevant boundary conditions influencing the development and implementation of a monitoring programme. These were broadly structured into societal boundary conditions and physical boundary conditions. The former was further broken down into the legal and regulatory framework relevant to monitoring, expert stakeholders (e.g. safety authorities) expectations and lay stakeholders (e.g. local residents) expectations. The latter was further broken down into the waste inventory, the natural environment and the engineered system.

In addition to pointing to similarities and to what appear to be shared views of how monitoring can contribute to the disposal process, this report also provides a first basis against which differences of envisioned monitoring programmes can be analyzed and justified. These boundary conditions may indeed influence the analysis leading to the identification of specific technical monitoring objectives and associated relevant processes and parameters and may direct the choices of an implementation strategy that appears as most suitable in a given context.

It is indeed not the purpose of this project to develop a definitive set of technical monitoring objectives and approaches for implementing these. This would be impossible, as different national contexts are directed by different regulatory requirements and rely e.g. on different combinations of host rock and engineered barrier performances for long term safety. Therefore, a detailed monitoring programme would not be transferrable from one context to the other, and a "reference programme" does not exist.

Rather, developments focus on the general approach to developing a monitoring programme and thus on a "reference framework" allowing to tailor the monitoring programme to the national context. Such developments cannot, however, be done at an abstract level and therefore must rely on work conducted with specific examples, as provided by the national contexts. Indeed, one of the objectives of the project is to further develop high level understanding of repository monitoring to a level closer to practical implementation. Therefore, future project work provides for the development of specific case studies. Understanding how each proceeded to developing the basis for a monitoring programme, and comparing them, may provide lessons that allow to propose a generally applicable approach, independent of national context, and possibly highlight key differences to be expected related to specific national contexts.

The increased interest in monitoring the repository prior to closure to confirm the basis for the safety case and, in certain contexts, to provide data to re-evaluate options available for stepwise disposal process management, is consistent with a general consensus that the repository is not "done" after receipt of a license to construct and operate, and that the disposal process should proceed in a transparent manner. At the chore is a requirement to obtain confirmation from in-situ data that the basis for repository safety is adequate. Closure of a repository would not be authorized otherwise.

This is consistent with available socio-political feedback received on earlier disposal programme developments, many of which have effectively halted further progress towards implementing a repository, irrespective of their demonstrated technical and scientific soundness. From these, a consensus appears to have emerged, that an informed, stepwise approach provides an acceptable basis allowing to progress through a licensing stage, to progressive construction, operation and partial closure of a repository. The major decision to bring to repository to a post-closure configuration would be taken in a fairly distant future, according to current and then applicable regulations and guidelines.

Previous international collaborations (IAEA (2001), EC (2004)) and more recent international workshops held in preparation and within the framework of the MoDeRn project tend to confirm overarching agreement with a number of main monitoring objectives:

- Monitoring to verify/confirm the basis for expected/predicted behaviour of the repository system
    - Support the basis for the long term safety case
    - Support pre-closure management of the disposal process
- Operational safety
- Environmental impact
- Nuclear safeguards

All of these may contribute to decisions governing the stepwise disposal process and may contribute to enhance stakeholder confidence in the process. All of these should be addressed by repository monitoring. Only the first, however, is the focus of this project as it addresses development of monitoring activities specific to a geologic repository.

The progressive approach from construction to closure provides both an opportunity to verify the knowledge basis over extended periods of time (i.e. several decades up to a century), as well as an opportunity to further adapt the repository to its natural environment. This was formalized using various approaches in different countries, with possibly a more explicit requirement provided in the French context, where the reversible management approach calls for flexibility in available management options to respond to future demands and for a structured decision making process.

Arguably, the latter may stand out from other national contexts mostly by (i) the extent to which possible alternative routes, including potential waste retrieval, have to be considered from the outset, (ii) the extent to which provisions for such alternatives have to be included in the original design, and (iii) possibly the formalism that may be developed for decision making. Notwithstanding these hypotheses, it remains similar consistent with most national contexts, in as they seem to agree on a stepwise process based on informed decisions, where monitoring would provide useful information.

These call for a number of monitoring activities that need to respond to the main monitoring objectives of a radioactive waste repository and that need to be tailored to the specific national context in which the repository is developed.

6.1 Societal boundary conditions and potential influence on monitoring developments

When looking at the **legal and regulatory frameworks** described in the national context overviews, the levels of detail in which monitoring requirements and approaches are specified vary considerably. Even though some of these national frameworks provide a basis for what needs to be included in the monitoring programme, this tends to be described in relatively general terms, without too much (if any) specification on how the act of monitoring is defined. Mention may be made of a stepwise implementation process, but no details are available on how decisions at each step should be taken. Some regulations may include specific requirements for implementation strategies, e.g. the Swiss regulator calls for monitoring to be conducted in a pilot facility.

The French guidelines also address monitoring to inform reversible disposal management, especially as related to structural health providing for temporal flexibility and as related to waste disposal package and disposal cell conditions as related to the potential for waste retrieval.

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

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

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

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

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

The importance of developing a better understanding of such expectations is recognized by this project. Expert stakeholder, in particular the implementers' perception of Lay stakeholder expectations are currently based on written evidence from engagement activities involving lay stakeholders. Engagement events provide the opportunity for expert stakeholder to elicit lay stakeholder views directly, and to learn about their concerns. The enhanced understanding and experience gained by those experts involved in lay stakeholder engagement can be applied in subsequent discussions, and further contribute to clarifying how monitoring may contribute to confidence and acceptability of the disposal process. Of course, the degree to which such input is informed by direct engagement may vary, and opinions should be supported, where possible, by written evidence. Nevertheless, experts' perceptions of lay stakeholder expectations provide a valuable tool for informing others and sharing information, which can help to avoid "reinventing the wheel" in future planning and engagement activities.

6.2 Physcial boundary conditions and potential influence on monitoring developments

The properties and quantity of waste inventories, often conditioned in a primary waste matrix such as borosilicate glass and in a primary waste package, condition the search and design for a suitable natural and engineered environment for the repository system. In addition to overall volume and quantity of primary waste packages, their heat generation, radionuclide concentration as it pertains to the risk of criticality, content of e.g. organic materials and other properties such as e.g. potential to release radioactive gas or to produce hydrogen must be taken into account when selecting and evaluating favourable properties of a host formation and when designing the corresponding engineered system.

6.2.1 Natural environment

In disposal concepts designed for different types of host rock, the isolation of radioactive waste from the biosphere is based on different components of a combination of engineered and natural barriers. Monitoring prerogatives for each rock type vary as a function of waste and rock properties in concert with disposal concepts.

Monitoring efforts are generally intended to confirm that subsurface conditions and geotechnical parameters are as anticipated and that changes to these conditions are within limits applied in the design and licensing process. Monitoring objectives that might be further developed are likely related to:

- Confirmation that the hydrogeological environment is consistent with the licensing baseline;
- Verification that favourable rock properties taken into account in the safety case and characteristic of the undisturbed host rock are preserved, minimally altered, or understood sufficiently during construction and operation;
- The thermo-hydro-mechanical response in the near field to construction, operation and partial closure, both as related to the basis for the safety case and to support disposal process management prior to closure;

- Far field response, if any, due to construction, operation and closure.

In crystalline rock, the long-term integrity of the waste containers and the behaviour of the bentonite buffer are critical, so that the near-field groundwater flow and groundwater chemistry are emphasised. This type of formation is characterized by blocks of tight rock suitable for waste deposition surrounded by fractures or fracture zones. Monitoring may thus also contribute to the knowledge of host rock heterogeneities. In sedimentary or saline rock, the concept relies more on the homogeneity, sorption capability, and extremely low hydraulic conductivity of the host formation. In the latter case, therefore, the average hydraulic properties on larger scale, and of the backfilled and sealed access tunnels, ramps, and shafts, are vital. This may be associated with a monitoring activity confirming the self healing properties of clay that was fractured during construction and operation. Moreover, the impact on surface waters and shallow groundwater can be expected to be limited to the vicinity of the entrances to access shafts and ramps. This must, of course, be verified by hydrological monitoring, especially in the case of nearby surface waters and aquifers of environmental or economical value.

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

Particular aspects to be considered are the relation between structural health monitoring (geotechnical and ground support evolution) and (i) the conditions for nuclear transfer and operations, (ii) the conditions ensuring radioprotection such as operations of radioactive shields and nuclear ventilation (if required to extract air that may be contaminated).

6.2.2 Engineered system

It is first worth noting that **repository layout** and envisioned construction, operation and partial closure, may induce greater or lesser technical challenges to conduct monitoring. This is mostly related to the ability to access to the vicinity of the monitored component and/or its near-field, and the duration for which such access is possible.

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

Monitoring objectives for waste disposal packages (**WDP)** most likely address their longevity. These are typically measured with respect to water tightness in response to long term safety requirements and mechanical stability in response to both long term safety and operational/retrievability requirements. No clear picture emerges as of yet whether this is best done in situ on actual packages, whether representative long term tests (e.g. on metal corrosion samples can provide needed information, or whether prior quality assurance and monitoring in a transfer store can be considered to provide sufficient information to confirm their expected performances.

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

The repository **sealing system** which may include disposal unit plugs or seals, gallery seals and access shaft/ramp seals is emplaced to restrict water flow and radionuclide transport through the repository. Monitoring activities may consider the mechanical and hydraulic properties of such seals and possibly confirm an adequate chemical environment consistent with expected seal material swelling. Detailed considerations need to take into account the time scales at which natural seal resaturation may operate. It appears that, while for crystalline rock, the interception by seals of water bearing features may lead to a natural resaturation offering the potential for monitoring, this would at best be limited to the contact zone between seal material and an argillaceous host rock.

6.3 Several key issues

Above considerations are based on the assumption that detailed technical objectives for monitoring can be derived from an analysis of accepted main monitoring objectives and the associated expected performances of the repository and its components. From this preliminary overview, several key issues can be identified that require further developments. First is the issue of representativity of monitoring results. The other is dealing with time scales not accessible to direct monitoring. A particular issue is post closure monitoring. Finally, the use of monitoring information within the decisional process is addressed. Considerations of these highlight possible limitations to what monitoring can provide as well as potential paths to overcome such limitations. In particular, the need is recognized to reach a good balance between improving the disposal process by including some monitoring activities, and progressively reducing and ending such monitoring to move to a passive safety configuration.

6.3.1 Representativity of monitoring results

Although it is theoretically possible to perform monitoring exhaustively on all components of the repository, this approach is not realistic. Risk and/or Cost measured as added difficulty to civil engineering work, possible interference between monitoring and stepwise operations, and financial burden must be balanced with added value towards safe management of the operational phase, information for sound decisions in step wise construction, operation and closure, as well as any required or perceived needs of monitoring to confirm the scientific basis supporting the long term safety case.

Therefore monitoring can only be conducted in select areas and components of the repository. Monitoring activities have to be integrated with the engineered component design as well as with the disposal plan of progressive closure. Even when selected monitored components and/or monitored near field evolutions are distributed throughout the repository layout, the issue of representativity has to be addressed. For a given host formation and engineered system, an argument will need to be developed supporting that conducted monitoring provides required information that is representative for the overall repository. This will typically be based on considerations of homogeneity of the natural environment and of the controlled homogeneity of manufacture and construction of engineered components. The impact any heterogeneities may have on repository functions may be accounted for by addressing these when designing a monitoring system.

6.3.2 Overall monitoring time scale

Most national disposal programs assume that repository construction, operation and staged closure will span a representative time scale on the order of a century. In situ monitoring of the actual repository (after site characterisation, but including any test or pilot facility monitoring) is assumed to begin at construction and to accompany the disposal process at least until the decision to move to post-closure. It therefore provides the disposal process management with substantial added value through the in-situ data made available over such a time scale. This will typically exceed the time scale that had been previously available to conduct experiments whose results contribute to the basis of the safety case.

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

6.3.3 Post closure monitoring

The confirmation of the basis used to evaluate long term safety is a prerequisite to obtaining authorization to move to post-closure. Therefore, performance confirmation monitoring related to long term safety is conducted prior to closure of the repository. It is not clear at this stage whether additional confirmatory monitoring may be called for after closure.

Two arguments can be provided to suggest that this cannot reasonably be developed to a great level of detail at the present stage. First, the decision on closing a repository is on the order of a century away. It would be presumptuous to guess at what type of further monitoring requirements, if any, might be expressed at that time. Second, the decision to definitely close a repository – at least from today’s perspective – is preceded by (i) a century of experience with disposing waste, managing a repository and obtaining confirmatory information from in-situ monitoring and from a parallel long term science and technology programme, (ii) confirmation and re-evaluation of the safety case prior to closure. It might then be argued that, should additional residual questions remain concerning the long term safety of the repository, then the decision to close the repository would be postponed. Conversely, if all stakeholders agree on having confidence in the long term safety, it would be difficult to associate this view with a request for further monitoring.

An exception may be the case when repository closure would call for a near- or far-field response that can be monitored over reasonable time scales, and that was not already seen subsequent to partial closure of, say, disposal drifts. For instance, the hydrogeological response to closure in crystalline rock might deserve special attention. In that case, ongoing monitoring from distant boreholes may provide useful information over a time span beginning prior to construction, throughout operation and until the early post-closure phase.

It is noted that organizations are currently developing wireless, through rock transmission technology that may allow responding to some level of in-situ post-closure monitoring, to prepare for the eventuality of such a future requirement.

Finally, it is noted that the above does not concern surface based post-closure monitoring, as may e.g. be warranted during an institutional control period, and as may be related to non-intrusion and nuclear safeguards surveillance.

6.3.4 Decisional process

All monitoring is conducted to inform the decision process, either indirectly, e.g. by enhancing the science basis used to develop predictive models, or directly, e.g. by verifying in-situ evolutions do not exceed certain trigger values. Three major decision points in a disposal process are acknowledged:

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

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

A monitoring programme is designed to provide relevant data called for to inform such decision points. In particular, we focus attention on (i) the verification of the adequacy of the license basis for long term safety and on (ii) evaluation of options available to further conduct the disposal process prior to closure.

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

Somewhere in between physical and societal boundary conditions is the influence that the step wise decisions for repository management and closure (from individual cell or drift closure to complete closure of the repository) may have on the choice of monitoring approaches themselves. Indeed, such decisions rely in part on information provided by monitoring to decision makers (thus the "societal" influence) and condition the physical environment in which ongoing monitoring may need to be performed (e.g. if monitoring of a sealed drift is expected).

6.3.5 Recognized limitations of monitoring

A certain number of limitations of monitoring can be recognized. These are primarily due to five considerations:

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

For all of these, it is important to achieve a balance between the added value monitoring can bring to a transparent and informed management of the disposal process, and the potential risk to operational activities and to long term safety. The above identified limitations, however, should not be construed to diminish the potential for added value a monitoring programme holds. For each, arguments can be developed in view of finding an adequate balance:

- In-situ monitoring over a century scale provides an unprecedented opportunity to observe engineered barrier and natural environment evolutions; confirmatory activity related to very slow, long term evolutions may be conducted successfully using indirect means, e.g. by confirming that key intrinsic properties (e.g. geochemical conditions) are consistent with baseline data and/or that local environmental properties are consistent with model assumptions;
- A thorough understanding of the natural environment and quality control of produced and constructed engineered barriers, combined with adapted in-situ monitoring implementation strategies, can provide an adequate basis to confirm representativity of monitoring results;
- Monitoring implementation strategies can be developed to provide both required in-situ data and preserve required barrier performances, if necessary

by including wireless transmission systems, by providing for a partial dismantling of monitoring systems, or by allowing for waste retrieval of a monitored disposal unit whose performances can no longer be guaranteed;

- Monitoring in comparable environmental conditions of high temperature, pressure and water content has been conducted in URLs and available experience combined with a dedicated R&D programme allow to further enhance durability of available monitoring equipment;
- Implementation strategies may provide for long term, in-situ representative testing in a dedicated environment made accessible for sampling after several decades of evolution to compensate for the lack of technological ability for direct sensor-based in-situ monitoring, and an ongoing technology R&D programme may enhance the ability for direct monitoring of certain parameters.

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