EUROPEAN COMMISSION
Community research

Monitoring Developments for Safe Repository Operation and Staged Closure

**Contract Number: 232598**

# Technical requirements report

# DELIVERABLE (D-N°:2.1.1)

Author(s): **AITEMIN**

Reporting period: e.g. 01/05/2009 – 31/10/2010

Date of issue of this report: **03/01/2011**

Start date of project: **01/05/2009** Duration: 48 Months

| Project co-funded by the European Commission under the Seventh Euratom Framework Programme for Nuclear Research &Training Activities (2007-2011) | | |
|---|---|---|
| **Dissemination Level** | | |
| **PU** | Public | X |
| **RE** | Restricted to a group specified by the partners of the [MoDeRn] project | |
| **CO** | Confidential, only for partners of the [MoDeRn] project | |

**[MoDeRn]**

EURATOM

| History Chart | | | |
| --- | --- | --- | --- |
| **Type of revision** | **Document name** | **Partner** | **Date** |
| **Initial outline** | MoDeRn_M2111_TechReqInitial_v0d0.doc | Aitemin/Enresa | 14/12/2009 |
| **Contribution** | WP2 Technical Requirements - NDA RWMD Monitoring Table (ILW)final.doc | NDA | 17/12/2009 |
| **Contribution** | MoDeRn_M2111_TechReqInitial_v0d0_DBETEC.doc | DBETEC | 07/01/2010 |
| **Contribution** | MoDeRn_M2111_TechReqInitial_v0d0_posiva.doc | Posiva | 18/01/2010 |
| **Contribution** | MoDeRn_M2111_TechReqInitial_v0d0_RAWRA.doc | RAWRA | 22/01/2010 |
| **Contribution** | RWMC.xls | RWMC | 26/01/2010 |
| **Contribution** | MoDeRn WP2– Milestone 2.1.1.1Technical Requirements-v3.xlsx | Andra | 04/02/2010 |
| **First draft** | MoDeRn_M2111_TechReqInitial_v0d1.doc | Aitemin | 15/03/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d1_DBETEC.doc | DBETEC | 26/03/2010 |
| **Contribution** | Annex M2.1.1.1 NRG_v1.1.doc | NRG | 29/03/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d1_TJS.doc | NRG | 29/03/2010 |
| **Approval** | e-mail | Posiva | 30/03/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d1 Andra.doc | Andra | 31/03/2010 |
| **Second draft** | MoDeRn_M2111_TechReqInitial_v0d2.doc | Aitemin | 08/04/2010 |
| **Approval** | | DBETEC | 14/04/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d2 Andra.doc | Andra | 14/04/2010 |
| **Contribution** | Technical Requirements.docx | Sandia | 15/04/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d2 TJS.doc | NRG | 16/04/2010 |
| **Comments** | e-mail | NDA | 19/04/2010 |
| **Comments** | At the phone | ENRESA | 21/04/2010 |
| **Comments and new table for annex II** | e-mail and RWMC20100415.xls | RWMC | 22/04/2010 |
| **Comments and new table for annex II** | e-mail and Annex A-7.docx | Andra | 23/04/2010 |
| **Table for annex II** | MoDeRn_M2111_TechReqInitial_v0d0_EUR.doc | Euridice | 23/04/2010 |
| **Table for annex II** | MoDeRn_M2111_TechReqInitial_v0d2 - Blp.doc | Nagra | 26/04/2010 |
| **Comments** | e-mail | Euridice | 28/04/2010 |
| **Third draft** | MoDeRn_M2111_TechReqInitial_v0d3.doc | Aitemin | 29/04/2010 |
| **Comments and tables** | MoDeRn_M2111_TechReqInitial_v0d3_EUR.doc & Tables 1-2-3_EUR.xls | Euridice | 10/05/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d3_TJS.doc | NRG | 11/05/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d3_posiva.doc | Posiva | 12/05/2010 |
| **Comments and tables** | MoDeRn_M2111_TechReqInitial_v0d3_Andra.doc & MoDeRn WP2– Milestone 2.1.1.1Technical Requirements-v6.xlsx & Table1-2-3_Andra.xlsx | Andra | 12/05/2010 |
| **Fourth draft** | MoDeRn_M2111_TechReqInitial_v0d4.doc | Aitemin | 20/05/2010 |
| **Comments** | MoDeRn_M2111_TechReqInitial_v0d4_NRG.doc | NRG | 15/06/2010 |
| **Table for annex II** | MoDeRn_M2111_TechReqInitial_v0d0_RAWRA1.doc | RAWRA | 16/06/2010 |
| **Table for annex II** | Monitoring_SKB table.xls | SKB | 24/09/2010 |
| **Fifth draft** | MoDeRn_M2111_TechReqInitial_v0d5.doc | Aitemin | 30/09/2010 |

| | | | |
|---|---|---|---|
| **Comments and approval** | MoDeRn_M2111_TechReqInitial_v0d5_Andra.doc | Andra | 01/10/2010 |
| **Approvals** | MoDeRn_M2111_TechReqInitial_v0d5.doc | NRG, DBETEC, RWMC & EURIDICE | 7-12/10/2010 |
| **Minor Corrections** | MoDeRn_M2111_TechReqInitial_v0d5 - AC & BJB comments.doc | NDA | 25/11/2010 |
| **Final version** | MoDeRn_D-2.1.1_TechReq_v1.doc | AITEMIN | 29/11/2010 |

| Distribution lists of  the final version (email + acknowledgement of receipt) : DD.MM.YYYY | |
|---|---|
| **Steering Committee** | X |
| Contributors | X |
| **Project Officer** | |
| **Administrative and financial teams** | |

# Table of Content

# 1. Introduction

## 1.1 Background

Task 2.1 of the MoDeRn project aims to provide an overview of the technical requirements that will likely need to be addressed when developing, selecting and implementing monitoring technologies suitable for the geological disposal of radioactive waste. It is noted that “technical requirements” are not to be understood in the sense of “mandatory - obligation to implement”, but in the sense of “specifications that need to be addressed” when selecting monitoring technology best suited to respond to technical monitoring objectives. Both, objectives and requirements are closely interrelated, because obvious technical limitations of current hardware may lead either to the development of new equipment or a reconsideration of the objectives. There are many potential ways to meet the objectives: e.g. a certain parameter can be measured close to the radioactive waste, but if radiation and/or heat is too high, the sensor can also be placed further apart from the waste. It should also be noted that the requirements defined in this report can be multidimensional or even contradictory: e.g. if we place sensors further apart, this may increase the reliability but reduce the precision or sensitivity of the measurements, eventually leading to such a large uncertainty range which may no longer be convenient to support decision-making. Wireless techniques may be the best option with respect to the maintenance of the integrity of the barriers, but may be not the first choice if it comes to aspects such as reliability or durability. However, this report (Milestone 2.1.1.1) gives an overview of different requirements as defined for several national concepts in three different host rocks without analysing in which way requirements are related to each other.

The analysis leading to such an overview is based on an initial understanding of possible monitoring objectives and strategies (Task 1.2) and of the corresponding national contexts (Task 1.1). At this stage of the project, corresponding information is available in a preliminary, draft status. Indeed, The Site Plans and Monitoring Programmes Report (Deliverable 3.1.1.1) provides an overview of participating organizations’ programmes which have not yet developed to a great level of detail. However, an overall understanding of the type of monitoring activities that might be expected is available and a reasonable understanding of the environmental conditions and implementation constraints is also available. Indeed, the initial drafts for the first milestones of Tasks 1.1 and 1.2 provide enough information and context for this report to provide a first overview of technical requirements to be considered for development, selection and implementation of monitoring technologies.

Clearly, this report which provides an initial overview cannot be definitive as this would require all available details on repository design, safety strategy, and selection of precise emplacement of sensors, etc,. to be defined, which cannot be expected during the MoDeRn Project. It does, however, provide a good working basis to gain an appreciation of the technological specifications for monitoring systems in a repository. This basis will allow to evaluate whether available technologies are likely to respond to the needs of repository monitoring, where specific adaptations of available technologies (e.g. to enhance resistance to environmental conditions) are needed and where improvements or entirely new developments are necessary (e.g. to monitor without the risk of degrading performances of engineered barriers).

## 1.2 Scope and objectives

The scope of this document is focused on those aspects of technical requirements that are very specific to repository monitoring. Therefore, fairly classical monitoring activities related to occupational health and safety while working underground and in a radiologically-controlled environment are not developed further in this work programme. Indeed, some of the monitoring during the construction phase and the operational phase is not different from programmes applied in comparable underground constructions, e.g. mines or a few road and rail tunnels. A good part of the radiological monitoring programme is focused on aspects related to occupational health and safety and is comparable to programmes performed in other nuclear facilities. These radiological monitoring programmes are based on well defined (national) guidelines and regulations and carried out with conventional, commercially available equipment.

Therefore, the aim of this report is to determine the technical requirements, besides the aspects related to occupational health, for the development of a monitoring programme for a repository during the operational phase and the early[1] post-closure phase to give a general overview on what, where and when to measure within the different national programmes.

Specific consideration is given to monitoring as it relates to confirming the basis of the long term safety evaluation and as it can be used to support specific aspects of the disposal process management (i.e. information that might be needed in a stepwise decision process, information that might be needed with respect to retrievability or reversibility of the disposal process).

## 1.3 Rationale

The definition of technical requirements for the monitoring of a repository will be based on considerations on the potential objectives that must be achieved in a set of given environmental conditions, while respecting repository safety, both operational and post-closure. Such requirements may include the necessity to monitor over extended periods of time (decades) without any possibility to access, calibrate or renew monitoring equipment; the availability of components that enables the sampling of reliable data under more or less severe environmental conditions (radiation if inside a disposal vault, heat if inside or in the vicinity of a disposal vault, high lithostatic and hydrostatic pressures in almost all cases,…); challenging emplacement conditions for individual monitoring components and the potential need for miniaturisation and/or wireless techniques for the transmission of monitoring data within or outside a repository facility to avoid any impairment of relevant safety functions.

The initial draft report on monitoring objectives and strategies and the report regarding monitoring context combined with the monitoring requirements and constraints received by the different partners provides the basis for this overview on technical requirements. Thus, they should be considered as a list of requirements based on the best expert judgement of the different national programmes at this moment and the results of the study will identify *potential monitoring requirements* only.

---

[1] several decades to 100 years

## 1.4 Structure and content

This report compiles the inputs received from the contributing partners in order to provide an initial set of potential monitoring requirements and constraints for a repository during the operational phase.

Chapter 2 provides some basic considerations regarding the development of a monitoring programme. Chapter 3 analyses and synthesises the input received from the partners and Chapter 4 summarises the main conclusion extracted from this contribution. Tables with obtained measuring ranges by parameter and for the different monitoring areas are given in Annex I. The complete contributions are included as Annex II.

## 1.5 Applicable documents

- Grant Agreement nr. 232598, Annex I (Description of Work) stipulates
- Consortium Agreement for MoDeRn, V1 dated August 31, 2009
- Quality Plan, MoDeRn_M011_Quality Plan_v1, dated October 19, 2009.

## 1.6 Terms and abbreviations

| | |
|---|---|
| CA: | Consortium Agreement |
| CAP: | Communication Action Plan |
| CSH: | Calcium Silicate Hydrate gels |
| DMS: | Data Management System |
| EBS: | Engineered Barrier System |
| GA: | Grant Agreement |
| HLW: | High Level Waste |
| ILW: | Intermediate Level Waste |
| RTD: | Research and Technology Development |
| RH: | Relative Humidity |
| URL: | Underground Research Laboratory |
| WP: | Work package |
| TBD: | To Be Defined |

# 2. Basis of a monitoring programme

## 2.1 Introduction

The definition of a monitoring programme is a complex task that should consider many aspects. To initiate such a programme, it is necessary to answer the following questions:

- Why measure? (i.e. to comply with regulation, to inform operational and design decisions of the disposal process, to inform the step-wise decisions making process, in particular to confirm the basis of the safety case, to inform the potential for retrievability and/or to inform on the level of reversibility...)
- What to measure? (i.e. technical monitoring objectives and specific processes and parameters)
- Where to measure? (i.e. inside the actual facility or a pilot facility, inside a disposal cell, in a sealed off area…)
- When to measure? (i.e. from beginning of construction until closure or until a prior decision to seize monitoring, overall duration of information need…)
- How to measure? (available techniques, sufficient confidence)

Looking more into detail, it is clear that for many of these obvious questions the answers are not easy to define, as these questions are interrelated. Often, parameters that are identified in the second question ("what to measure") require knowing what the expected range of values is, or can not be measured in the preferred location or not with sufficient precision, sensitivity, etc. When deciding "where to measure" the expected environmental conditions can have a relevant influence in combination with the available commercial equipment or with the required long-term performance. In the context of complex projects like the disposal of nuclear waste, it may be useful to identify and define first the technical requirements.

All aspects of the above are further developed in Work Package 1 – Monitoring Objectives and Strategies and in Work Package 4 - Case Study of Monitoring at all Stages of the Disposal Process.

## 2.2 Components of a monitoring system

A monitoring system to be applied in a potential monitoring programme will be composed in general by the following main components/equipment:

- Sensors that transform physical or chemical properties into analogue signals.
- Data transmission media between different parts of the monitoring system, usually composed of cables, amplifiers, filters, signal converters (that transform sensor signals into digital data), hubs and other electronic devices including wireless data transmission units.
- Data management systems (DMS) to register, (pre)process, store and display the digital data from the converters.
- Power supply system to power up all the equipment

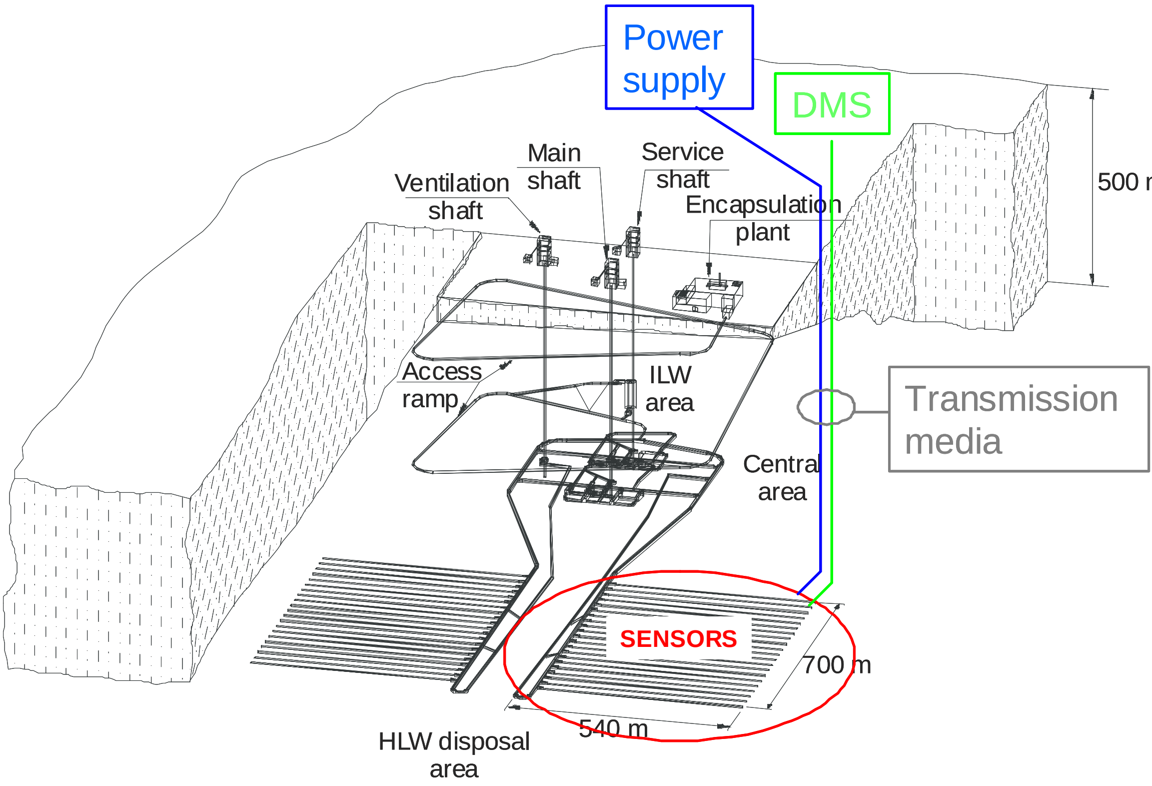


**Figure 1: Layout of a generic monitoring system**[2]

One objective of the MoDeRn Project is to define the technical/operational requirements that should be imposed to the repository monitoring equipment that will be specific to the geologic disposal of nuclear waste during the operational phase and in the (early) post-closure phase. Due to the specific challenges within this context, the requirements will apply mostly to the sensors, to the data transmission media and to the power supply system to be installed and that will remain in the areas to be isolated.

## 2.3 Requirements to be imposed on a monitoring system

Technical or operational requirements imposed on monitoring equipment may be attributed to several aspects:

- Requirements due to the individual national monitoring concepts and scopes
- Requirements due to essential safety functions, that should not be impaired, e.g. barrier performance (aspects that may need to be considered are e.g. wires i.e. no wire through barriers; small physical dimensions of equipment to avoid impairment of the structural integrity of barriers; retrievability of equipment after end of monitoring activities)
- Requirements due to the specific nature of the parameters that need to be measured (deformation and/or stress; positive or negative hydrostatic pressures, water content, relative humidity; temperature; chemical parameters such as pH or the concentration of a compound in the gas phase of a disposal cell…)

---

[2] This is a simplified example of a monitoring system. Note that the DMS or other components not necessarily needs to be centralized or surface-based.

- Requirements due to the necessary sensitivity of a method or the range of values that need to be measured
- Requirements due to necessary specificity of a method and the cross-sensitivity to other environmental variables (as for instance temperature)
- Requirements due to the necessary precision and long-term stability of a method - often without the possibility to access, maintain and/or recalibrate the sensor readings - to be able to measure accurately anticipated small slow time evolutions
- Requirements to be able to detect defective sensors and to identify erroneous readings
- Requirements due to the necessary long-term (decades) durability of the monitoring hardware against unfavourable environmental conditions present in the repository
- Requirement due to the necessary reliability of the system. Redundancy of critical system components (e.g. sensors, cables, data processing devices) allows limiting the loss of information in case of the failure of system components. Redundant sensors using complementary measuring technologies can also used to verify the coherence of the measurements.
- Requirements due to the influence of measurement equipment on the measured parameter
- Requirements due to an obligatory positioning of a sensor (for instance to compare measurements with model calculations)

A factor that will have a high influence on a potential monitoring programme for a repository is the specific concept on waste disposal and the defined process of a staged closure that is considered during the operational phase. Requirements could be less restrictive if the monitoring programme is applied to a pilot facility or a dedicated test disposal drift, than in case they are applied in the main part of the repository. As a general rule, pilot facilities or dedicated test disposal drifts may provide a greater tolerance in relation to requirements related to the long term safety (e.g. the use of cables instead of wireless technology) because they may provide the option of being dismantled at the end of the monitoring activity (the waste will be disposed elsewhere in the repository area). The conditions at pilot or dedicated test disposal facilities could be less stringent, too: for instance lower pressures and temperatures could be developed (depending on the context and concept) and the possible degradation of the barrier performance by the installed monitoring equipment would not be so critical with respect to the long term safety of the emplaced waste.

# 3. Potential technical requirements

## 3.1 Introduction

As only a few national waste management programmes have specific legal requirements for the monitoring of a repository and almost no one has already defined that beyond the repository construction phase. Therefore not all countries have defined yet a monitoring programme for the operational phase or the early post-closure phase.

A questionnaire (initial outline) was distributed to obtain an initial overview of such monitoring requirements and constraints from each project partner. Thus the contributions given here need to be placed within the context of the current phase of each national programme. Some of the contributions are based on a general “wish lists” of potential interesting parameters and techniques, while others are already the result of considerations with regard to feasibility aspects or the relevance within the overall context.

Inputs received consider different host rocks and therefore requirements are clearly influenced by that constraint. Four inputs consider a repository built in argillaceous rock (Andra, NRG, Euridice and Nagra), another two in salt rock (DBETEC and SANDIA), four in crystalline rock (Enresa, Posiva, Rawra and SKB), one more considers both argillaceous or crystalline rocks (RWMC) and finally one considers all available host rocks (NDA).

As result of the analysis of the input received the potential technical requirements have been structured in the following sections:

- Parameters of interest
- Potential monitoring areas
- Necessary transmission modes
- Environmental conditions
- Monitoring frequency and duration

## 3.2 Parameters of interest

A broad range of parameters is identified that is likely to be of interest in a few or most repository monitoring programs. The following is a first compilation of such a list of interest:

- Temperature
- Mechanical pressure
- Hydraulic pressure
- Water content/saturation
- Salinity
- Radiation
- Displacement
- Deformation
- Humidity
- Gas concentration (Oxygen, Carbon Dioxide, Hydrogen and Methane)
- Gas pressure
- pH
- Eh
- Concentration of colloidal particles
- Alkalinity

Given the variety of national contexts, not all parameters may be necessary or of interest for monitoring, while others related to a very specific objective, may need to be added

## 3.3 Potential monitoring areas

In principle five areas for potential monitoring were identified:

- Waste package and buffer (a specific buffer does not exist in some concepts or it is substituted by overpacks and liners),
- Near-field rock (and, if included in specific designs, structural elements of disposal cells and repository infrastructure such as shafts, ramps, tunnels),
- Backfill,
- Seals and
- Far-field rock

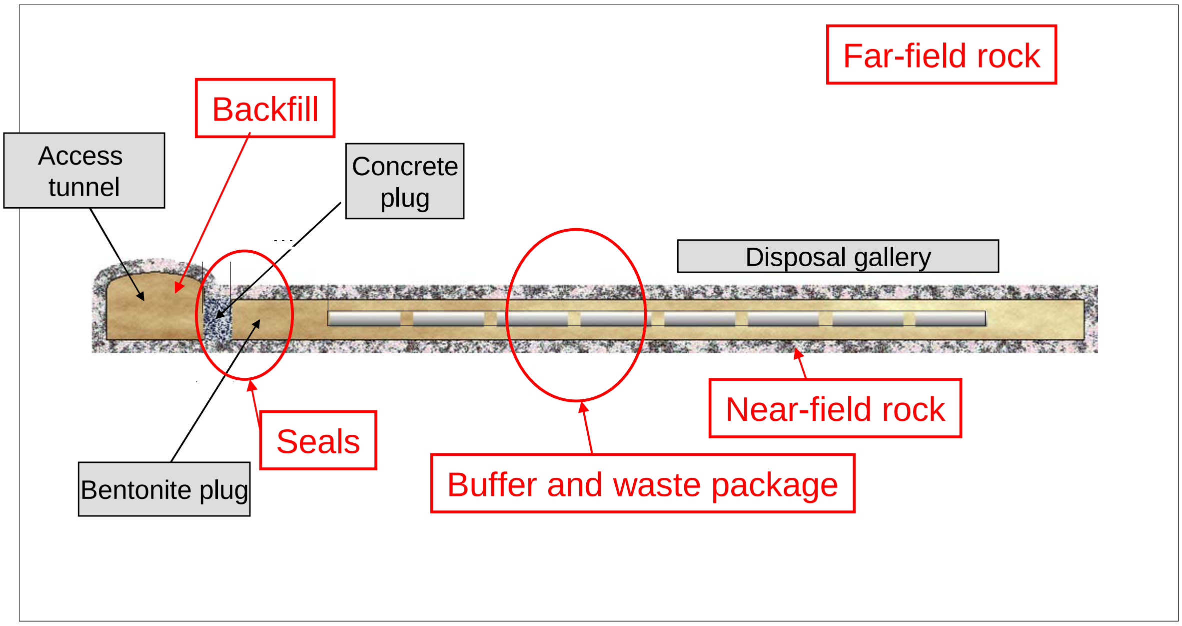


**Figure 2: Schematic of potential monitoring areas**

According to received inputs it will be necessary to monitor the far-field rock. Other potential monitoring areas that would be instituted are the backfill, the near-field rock and seals, but upon the monitoring concept to be applied the monitoring equipment could be modified or removed during the emplacement of the waste and the sealing processes. Finally, there are potential monitoring areas that could be established in some cases to confirm the design performance as the buffer and the waste package and certain structural elements of disposal cells and repository infrastructure, as may be necessary in certain concepts (e.g. in argillaceous rock).

As already anticipated at Section 2.1 there are clear interrelations between the potential monitoring areas (where to measure) and other technical requirements as for instance when and how to measure, especially taking into account the long term safety performance of the engineered barriers or with respect to the environmental conditions to withstand.

The answers on where to measure a certain parameter were diverse but they can be synthesised in the following tables by host rock type. When at least one participant considered a certain parameter as relevant this is indicated by a green box in the table. Note that only a few inputs were received for each host rock.

**Table 1: Considered monitoring parameters at different locations for repository concepts in crystalline rock (Green: considered as relevant; Empty: no statement made)**

| Parameters to measure | Waste package or Buffer | Near-field rock | Backfill | Seals | Far-field rock |
|---|---|---|---|---|---|
| Temperature | [green] | [green] | [green] | [green] | [green] |
| Mechanical pressure | [green] | [green] | [green] | [green] | |
| Hydraulic pressure | [green] | [green] | [green] | [green] | [green] |
| Water content/saturation | [green] | [green] | [green] | Bentonite [green] | |
| Radiation | | | | | |
| Displacements | [green] | [green] | [green] | [green] | |
| Deformation | | | | | |
| Humidity (vol) | | | | | |
| Gas concentration | | | | | |
| Gas pressure | | | | | |
| pH | | | | | |
| Eh | | | | | |
| Colloids | | | | | |
| Alkalinity | | | | | |
| Other | | Ground water flow/inflow [green] | | | Ground water chemistry [green] |

**Table 2: Considered monitoring parameters at different locations for repository concepts in argillaceous rock (Green: considered as relevant; Empty: no statement made)**

| Parameters to measure | Waste package or Buffer | Near-field rock | Backfill | Seals | Far-field rock |
|---|---|---|---|---|---|
| Temperature | [green] | [green] | [green] | [green] | [green] |
| Mechanical pressure | [green] | [green] | [green] | [green] | |
| Hydraulic pressure | [green] | [green] | [green] | [green] | [green] |
| Water content/saturation | [green] | [green] | [green] | [green] | |
| Radiation | [green] | [green] | [green] | [green] | |
| Displacements | [green] | [green] | [green] | [green] | |
| Deformation | [green] | [green] | | [green] | |
| Humidity (vol) | | [green] | | | |
| Gas concentration | [green] | [green] | | | |
| Gas pressure | | | | | |
| pH | | [green] | | [green] | |
| Eh | | | | | |
| Colloids | | | | | |
| Alkalinity | | | | | |
| Other | | | | | |

**Table 3: Considered monitoring parameters at different locations for repository concepts in salt rock (Green: considered as relevant; Empty: no statement made)**

| Parameters to measure | Waste package or Buffer | Near-field rock | Backfill | Seals | Far-field rock |
|---|---|---|---|---|---|
| Temperature | | | | | |
| Mechanical pressure | | | | | |
| Hydraulic pressure | | | | | |
| Water content/saturation | | | | | |
| Radiation | | | | | |
| Displacements | | | | | |
| Deformation | | | | | |
| Humidity (vol) | | | | | |
| Gas concentration | | | | | |
| Gas pressure | | | | | |
| pH | | | | | |
| Eh | | | | | |
| Colloids | | | | | |
| Alkalinity | | | | | |
| Other | | | | | |

## 3.4 Necessary data transmission modes

The long term safety of a nuclear waste repository is a key issue and therefore the components of the monitoring system must not degrade the performance of the engineered and natural barriers.

Based on received inputs, the presence of cables, antennas or other data transmission media that could increase the permeability of the EBS and the rock should be avoided in the surroundings of the waste package, especially at the buffer and the seals. Such devices may be implemented in actual disposal drifts only if evidence can be provided that they will not degrade the expected long term safety performance. Depending on the monitoring concept to be applied, the absence of cables and antennas was not identified as a requirement in pilot facilities or dedicated test disposal drifts. On the contrary, wireless devices could be allowed almost everywhere and independently of the selected monitoring concept.

It should be noted, that the use of wireless techniques will lead to new technical requirements: when using wireless devices, the sensors need to have their own, localized power supply, realized either by long term batteries, local power generation devices or the use of remote wireless power transmission techniques.

## 3.5 Environmental conditions

The often harsh environmental conditions present in a facility deep below the surface are a major issue for the design of reliable, long-life equipment. Expected environmental conditions in each of the identified potential monitoring areas are mainly defined by seven parameters: temperature, mechanical pressure, hydraulic pressure, water saturation, salinity, radiation and displacement.

It should be noted that the indicated ranges for possible displacements are closely related to the:

1. Elasto-plastic properties of the host rock,
2. Design of any structural elements,
3. Design and emplacement of backfill, buffer or seal material.

The main information is that displacements can become relatively large over time and, if their monitoring is envisioned, then adequate measurement ranges should be considered.

The ranges of such environmental conditions of interest are as follows[3], depending on the potential monitoring area and specific parameter to consider:

- Buffer and waste package (close to):
  - Temperature: in general the maximum temperature expected will be between 90 ºC to 130 ºC. For salt rock, temperatures close to the waste package can reach values up to 200 ºC. For ILW cells in argillaceous rock, raised temperatures up to 50 ºC are exceptional (normally less than 30 ºC). Peak values are reached gradually within a few months to a few years after waste emplacement. After that, the temperature close to the waste package will decrease with time and from the vicinity of the waste package to the near-field rock, values of around 15 ºC to 25 ºC will be reached, depending on the host rock and concept. The characteristic time for this decrease may far exceed the duration of the pre closure phase.
  - Mechanical pressure: maximum estimated values are closely related with the host rock type and the proposed depth of the repository, being up to 40 MPa for salt rock, between 12 MPa to 15.5 MPa in argillaceous rock[4] and from 6 MPa to 40 MPa in crystalline rock.
  - Hydraulic pressure: as opposed to the temperatures and due to the slow resaturation process, the expected hydraulic pressures will increase[5] with time both for crystalline and argillaceous rocks (for overconsolidated formations resaturation will take hundreds of years[6]). Values up to 9 MPa are expected to be reached (usually up to 5 MPa), except for salt rock where no hydraulic pressure is expected because of the complete hydraulic isolation of the waste cells in this concept.
  - Saturation: as for the hydraulic pressure, the saturation will increase with time in the buffer until it is fully saturated, but for overconsolidated argillaceous formations resaturation will take hundreds or thousands of years[6]. In a repository in salt rock no humidity is expected.
  - Salinity: the salinity commonly present ranges from 1 g/l to 70 g/l and it is strongly dependent on the ground water composition. Again, for repository concept in salt rock, no water is present. However, chemical interactions of equipment with the pure salt must be considered.

[3] As already shown by tables 1 to 3 the ranges provided hereafter for some environmental parameters do not mean that they are wanted/needed to be monitored.
[4] For the Belgium and French concepts the use of a structural lining is envisaged so the mechanical pressure in the buffer-waste area is uncoupled from the host rock until degradation and failure of structural elements, which are only expected after closure of the repository.
[5] Due to the evolution from dry to saturated condition
[6] For Boom Clay the resaturation is expected to be shorter (years)

- Radiation: as for the temperature case, the values will decrease with time and received values are estimations. At the very beginning it can be as high as 10 Gy/h[7] at the surface of the waste package. The average radiation in the buffer in most concepts is estimated between 10-60 mGy/h[8].
- Displacement: ranging from 10 mm to 100 mm, being up to 1000 mm for salt rock.

- Near-field rock and structural elements:
  - Temperature: depends on the host rock and concept, the maximum expected temperature close to the waste will be between 55 ºC to 100 ºC for argillaceous rock, 70 ºC for crystalline rock and up to 200 ºC for salt rock. With time the temperature of the waste will decrease reducing the temperatures in the vicinity of the waste package and in the far-field rock, and values between 15 ºC and 25 ºC will be reached, depending on the host rock and disposal concept.
  - Mechanical pressure: maximum values are closely related with the host rock type and the proposed depth of the repository, being up to 40 MPa for salt rock, between 12 MPa to 30 MPa in argillaceous rock and from 10 MPa to 42 MPa in crystalline rock.
  - Hydraulic pressure (formation water pressure): the expected hydraulic pressures will depend on the depth of the repository ranging from 3 MPa to 9.5 MPa, except for salt rock where no hydraulic pressure is expected.
  - Saturation: full saturation except for salt rock where no humidity is expected.
  - Salinity (formation water): salinity ranging from 1 g/l to 70 g/l except for salt rock where no free water exists.
  - Radiation: radiation at the very beginning can be up to 0.02 mGy/h at the surface of galleries close to the waste package, except for argillaceous rock where the expected values could be higher for some concepts, ranging from 1 mGy/h to 1 Gy/h[9].
  - Displacement: ranging from 10 mm to 50 mm, being up to 1000 mm for salt rock

- Backfill:
  - Temperature: the maximum temperature expected is much lower than in the buffer being between 25 ºC and 80 ºC. With time the temperature will decrease to reach values of around 15 ºC to 25 ºC, depending on the host rock and disposal concept.
  - Mechanical pressure: again, maximum values are closely related with the host rock type and the proposed depth of the repository, being up to 30 MPa for salt rock, up to 13 MPa in argillaceous rock and from 2 to 3 MPa in crystalline rock.

---

[7] The physical unit (Gy) is used here because the interest is related to effects on electronic devices; the otherwise commonly used unit (Sv) includes a measure of biological effects in human beings. 1 Gy/h is the maximum at the canister surface according to Swedish concept.

[8] Radiation at 1 m away from Supercontainer surface will be lower than 25 µGy/h in the Belgian concept.

[9] No significant radiation is expected in the Belgian concept.

- Hydraulic pressure: the expected hydraulic pressures will increase with time both for crystalline and argillaceous rocks (for overconsolidated clay formations resaturation will take hundreds of years[10]). Values of up to 5 MPa are expected to be reached (in exceptional cases they could reach 9 MPa), except for salt rock where no hydraulic pressure is expected because of the complete hydraulic isolation of the waste cells in this concept.
- Saturation: as for the hydraulic pressure, the saturation will increase with time until the backfill is fully saturated, but for overconsolidated argillaceous formation resaturation will take hundreds or thousands of years[10]. In a repository in salt rock no humidity is expected.
- Salinity: the salinity commonly present ranges from 1 g/l to 70 g/l and it is strongly dependent on the ground water composition. Again, for repository concept in salt rock, no water is present. However, chemical interactions of equipment with the pure salt must be considered.
- Radiation: radiation at the very beginning can be up to 0.02 mGy/h at the closest locations with regard the waste package except for argillaceous rock where the expected values could be higher for some concepts, ranging from 1 mGy/h to 1 Gy/h[11].
- Displacement: ranging from 10 mm to 120 mm in crystalline rock, being up to 1500 mm for salt rock and up to 30 mm in argillaceous rocks.

- Seals:
  - Temperature: the maximum expected temperature is between 16 ºC and 80 ºC, decreasing with time to reach values of around 15 ºC to 25 ºC, depending on the host rock and disposal concept.
  - Mechanical pressure: maximum expected values for salt rock are 25 MPa, 12-13 MPa in argillaceous rock and 6 MPa in crystalline rock.
  - Hydraulic pressure: hydraulic pressures will increase with time both for crystalline and argillaceous rocks (for overconsolidated formations resaturation will take hundreds of years[10]) to reach values up to 9 MPa (usually up to 5 MPa), except for salt rock where no hydraulic pressure is expected.
  - Saturation: the saturation will increase with time until reach fully saturation, but for overconsolidated argillaceous formations resaturation will take hundreds of years[10]. No humidity is expected in salt rock concept.
  - Salinity: salinity commonly present and ranging from 1 g/l to 70 g/l, being strongly dependent on the ground water composition. For salt rock concept the environment is pure dry salt.
  - Radiation: radiation at the very beginning can be up to 0.02 mGy/h at the closest locations with regard the waste package, except for argillaceous rock where the

[10] For Boom Clay the resaturation is expected to be shorter  (years)
[11] Radiation at 1 m away from supercontainer surface will be lower than 25 μGy/h in the Belgian concept.

expected values could be higher for some concepts, ranging from 1 mGy/h to 1 Gy/h[12].

- Displacement: ranging from 5 mm to 10 mm in crystalline rock, up to 30 mm in or argillaceous rocks. No value is defined for salt rock yet.

- Far-field rock: Not fully defined at this stage but some proposed parameters to measure/control are as follows:
  - Surface subsidence
  - Changes in groundwater flow or pressure
  - Changes in groundwater composition.
  - Temperature

Besides, some partners pointed out the necessity of measuring additional parameters which are indicated below with the suggested ranges when available:

- Moisture content (%vol) to be measured in buffer, backfill and seals for repository in salt rock.
- pH (expected values above 12.4[13]) and Eh (expected values up to 450 mV[14]) to be measured in buffer/waste package and backfill solutions in a repository in argillaceous rock and in the seals of a repository in salt rock.
- Radioactive gases to be measured in the backfilled areas of the repository in salt rock[15]
- Hydrogen, oxygen, carbon dioxide and methane concentrations in the gas phase (%vol) to be measured in buffer/waste package area in argillaceous overconsolidated rock.
- Gas pressure derived from the production of hydrogen and methane (expected values of up to 6.3 MPa).
- Colloidal particle concentrations (expected values of up to $10^{11}$ to $10^{12}$ particles/litre from CSH phases).
- Alkalinity concentrations by precipitation of calcite and CSH.
- Ground-water inflow and humidity in the repository for mass balance calculation.
- Monitoring sea and stream levels.
- Meteorological parameters.

These host rock specific data were synthesised at the tables given in Annex I. Note that the indicated ranges are the maximum values for each potential monitoring area. For some parameters these values will decrease when moving away from the waste package locations as is the case for temperature or radiation. In many cases, measurement may therefore be performed in larger distances to the waste packages.

[12] Radiation at 1 m away from supercontainer surface will be lower than 25 μGy/h in the Belgian concept

[13] This is for deposition concepts using cementitious materials

[14] Eh will increase at the beginning due to the intrusion of oxygen (oxidised conditions) and after closure it will decrease again to reach anoxic conditions.

[15] This is closely related with the type of waste to be emplaced.

### 3.6 Monitoring frequency and duration

The typical overall duration for a monitoring programme has been established on the order of several decades (ranging from a minimum of 20 years to a maximum of 100 years). Typically, such a programme is considered to begin prior to construction and to end after closure of the repository.

Specific technical objectives of the monitoring programme may be addressed from the construction of the related structures and either end upon a specific decision to do so (e.g. when the decision is based on the evaluation that a given evolution has been monitored for a sufficient time), upon reaching a regulatory requirement (e.g. after the completion of an expected performance confirmation period), or upon deciding to close part or all of the repository (where such a decision would be linked to the decision to seize monitoring).

Regardless, the initial expected duration provides requirements on durability of emplaced monitoring equipment and/or on the need to maintain or update such equipment.

The measurement frequency was established from several measurements per day to 1 measure per day or month in function of the stage of the waste emplacement programme and of the expected evolution of the parameters to be measured (rate of change or signal noise). This parameter could be easily modified during the operational phase but it is clear that it will decrease with time.

# 4. Conclusions

Given that at the current stage no complete monitoring programme is available, with detailed technical objectives addressing all relevant aspects in the operational and post-closure phase, the overview on technical requirements presented here cannot be regarded as complete. Rather, this first inventory gives an overview of the parameters and their tentative ranges, that are currently considered, and that should be included in a potential monitoring programme.

Currently there are no conclusive arguments as to why to monitor a certain parameter and not to monitor another, and in this sense the presented overview on technical requirements may be incomplete. The contributions and the obtained results are based on expert judgement on the relevance of a monitoring parameter for the safety of the repository and on what is feasible, based on the analysis of existence and characteristics of available technology. It should, however, be noted that the designs and the safety cases would not rely upon monitoring to achieve safety and in many cases current monitoring programmes related to long-term safety are focused on providing information on the performance to engineered barrier design after isolation of waste. These monitoring programmes thus focus on gaining information on the early stages of evolution following disposal.

A first description of the expected range of relevant environmental conditions in the different parts of several repository concepts has been established and can be used to define the technical requirements on the used equipment. The environmental conditions in some areas of the repository will lead to severe design demands for the equipments to be used: high temperatures, mechanical pressures, the presence of saline water, coupled with the effects of radiation and the expected long duration of the monitoring programmes will make it, in some cases, impossible[16] to find commercial equipment capable of fulfilling such requirements. If a high precision and long-term stability of the sensor readings are envisaged, the development of suitable equipment can be very challenging as it has been already demonstrated in several tests carried out in URLs around the world.

There is a general agreement that the use of cables for data transmission or energy supply can affect the behaviour of the engineered barriers and therefore they will be only acceptable where it can be demonstrated that the use of cables will not degrade the long term safety, as it could be the case in particular for the monitoring of pilot facilities or a dedicated test disposal drifts. The use of wireless sensors is accepted almost everywhere in the repository. If cables can not be used and the use of wireless techniques is mandatory, new technological requirements can be defined with regard to the reliable transmission of sensor readings through the isolated areas of a repository without affecting the engineered barriers performance and with regard to the energy supply for the measuring equipments over long periods.

These are the reasons why Task 2.2 seeks to update the state of art of the monitoring technologies that could be applicable in nuclear waste repositories, and why Task 2.3 pursues to develop RTD on promising monitoring technologies that will be demonstrated afterwards in WP3. In this sense, wireless technology is not mature yet for the repository conditions during the operational and post-closure phase but the benefits of having such technology available are clearly recognised. This is one of the technologies proposed for further RTD development and demonstration within MoDeRn project.

---

[16] For some parameters or measuring conditions the required equipment does not yet exist.

Taking into account the technical requirements discussed above, future monitoring programmes need to find a good compromise between monitoring requirements and the constraints of available technologies capable of fulfilling the requirements; this was stated in previous workshops held in Oxford [1] and Madrid [2].

## 5. References


[1] P.J. Hooker, M.J. White, E.J. Harvey and D.A. Galson SCIENCES LTD. MoDeRn WP1 Workshop “Monitoring Objectives and Strategies”.Oxford 27-28 February 2008: Detailed Workshop Report.

[2] M.J. White and E.J. Harvey. Galson SCIENCES LTD. Record of Discussion at the Second MoDeRn Internal Project Workshop: Madrid, Spain,18-19 November 2009.

**Annex I:** Tables of measuring ranges by parameter and monitoring area

**Crystalline rock**

| Expected ranges | Waste package and Buffer | Near-field rock | Backfill | Seals | Far-field rock |
|---|---|---|---|---|---|
| Temperature (ºC) | 0-100 | 0-70 | 0-60 | 0-50 | ND |
| Mechanical pressure (MPa) | 0-40 | 0-42 | 0-3 | 0-6 | ND |
| Hydraulic pressure (MPa) | 0-7 | 0-9.5 | 0-7 | 0-7 | ND |
| Humidity/saturation (% HR) | 0-100 | 0-100 | 0-100 | 0-100 | ND |
| Salinity (g/l) | 0-70 | 0-70 | 0-70 | 0-70 | ND |
| Radiation (Gy/hr) | 0-60 | 0-0,02 | 0-0,02 | 0-0,02 | ND |
| Displacements (mm) | 0-100 | 0-50 | 0-120 | 0-10 | ND |
| Water Content (%vol) | | | | | ND |
| pH | | | | | ND |
| Eh (mV) | | | | | ND |
| Radioactive gases | | | | | ND |
| Hydrogen | | | | | ND |
| Methane | | | | | ND |
| Gas pressure (MPa) | 0-6 | 0-6 | 0-6 | 0-6 | ND |
| Colloids (part./l) | $0\text{-}10^{12}$ | $0\text{-}10^{12}$ | $0\text{-}10^{12}$ | $0\text{-}10^{12}$ | ND |
| Alkalis | ND | ND | ND | ND | ND |
| Other | | | | | |

ND: Not defined N/A: Not Applicable An empty box means that nobody showed interest in measuring such parameter.

**Argillaceous rock**

| Expected ranges | Waste package and Buffer | Near-field rock | Backfill | Seals | Far-field rock |
|---|---|---|---|---|---|
| Temperature (ºC) | 0-130 | 0-100 | 0-80 | 0-80 | ND |
| Mechanical pressure (MPa) | 0-15,5 | 0-30 | 0-13 | 0-13 | ND |
| Hydraulic pressure (MPa)* | 0-9 | 0-9 | 0-9 | 0-9 | ND |
| Humidity/saturation (% HR) | 0-100 | 0-100 | 0-100 | 0-100 | ND |
| Salinity (g/l) | 0-70 | 0-70 | 0-70 | 0-70 | ND |
| Radiation (Gy/hr) | 0-10000 | 0-1000 | 0-1000 | 0-1000 | ND |
| Displacements (mm) | 0-100 | 0-50 | 0-30 | 0-30 | ND |
| Water Content (%vol) | | | | | ND |
| pH | 0-14 | | 0-14 | | ND |
| Eh (mV) | 0-450 | | 0-450 | | ND |
| Radioactive gases | | | | | ND |
| Hydrogen | ND | | | | ND |
| Methane | ND | | | | ND |
| Oxygen | ND | | | | |
| Carbon Dioxyde | ND | | | | |
| Gas pressure (MPa) | 0-6 | 0-6 | 0-6 | 0-6 | ND |
| Colloids (part./l) | $0\text{-}10^{12}$ | $0\text{-}10^{12}$ | $0\text{-}10^{12}$ | $0\text{-}10^{12}$ | ND |
| Alkalis | ND | ND | ND | ND | ND |
| Other | | | | | |

*Resaturation in over consolidated formations will take hundreds or thousands of years

ND: Not defined N/A: Not Applicable An empty box means that nobody showed interest in measuring such parameter.

**Salt rock**

| Expected ranges | Waste package and Buffer | Near-field rock | Backfill | Seals | Far-field rock |
|---|---|---|---|---|---|
| Temperature (ºC) | 0-200 | 0-200 | 0-60 | 0-50 | ND |
| Mechanical pressure (MPa) | 0-40 | 0-40 | 0-30 | 0-25 | ND |
| Hydraulic pressure (MPa) | N/A | N/A | N/A | N/A | ND |
| Humidity/saturation (% HR) | N/A | N/A | N/A | N/A | ND |
| Salinity (g/l) | pure salt | pure salt | pure salt | pure salt | ND |
| Radiation (Gy/hr) | 0-60 | 0-0,02 | 0-0,02 | 0-0,02 | ND |
| Displacements (mm) | 0-1000 | 0-1000 | 0-1500 | ND | ND |
| Water Content (%vol) | ND | | ND | ND | ND |
| pH | 0-14 | | 0-14 | | ND |
| Eh (mV) | 0-450 | | 0-450 | | ND |
| Radioactive gases | | | ND | | ND |
| Hydrogen | | | | | ND |
| Methane | | | | | ND |
| Gas pressure (MPa) | | | | | ND |
| Colloids (part./l) | | | | | ND |
| Alkalis | | | | | ND |
| Other | | | | | |

ND: Not defined    N/A: Not Applicable    An empty box means that nobody showed interest in measuring such parameter.

**Annex II:** Input received from contributing partners

## A-1. ENRESA

| **Monitoring when closing** | **Buffer** | **Rock*[1]** | **Backfill** | **Seals** |
|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | Yes*[2] | Yes*[2] | Yes*[2] | Yes*[2] |
| Continuous or discontinuous monitoring | Continuous | Continuous | Continuous | Continuous |
| Minimum frequency of measurement | 1 per day | 1 per day | 1 per day | 1 per month |
| Minimum duration of monitoring (sealed) | 20 years | 20 years | 20 years | 50 years |
| Cables allowed (yes/no) | No | No | Yes | No |
| Wireless allowed (yes/no) | Yes | Yes | Yes | Yes |
| Antenas allowed (yes/no) | Yes | Yes | Yes | No |
| **Expected environment conditions*[2]** | **Buffer** | **Rock*[1]** | **Backfill** | **Seals** |
| Temperature | 70-100 ºC | 70-16 ºC | 16-25 ºC | 16 ºC |
| Mechanical pressure | 0-6 MPa | 10-12 MPa | 0-2 MPa | 0-6 MPa |
| Hydraulic pressure | 0-5 MPa | 0-5 MPa | 0-5 MPa | 0-5 MPa |
| Water content/saturation | 80-100% | 100% | 80-100% | 80-100% |
| Displacements | 0-10 mm | 0-10 mm | 0-10 mm | 0-5 mm |
| Salinity | Increasing | No | Increasing | Increasing |
| Radiation | 60-15 mGy/hr | 0,02-0 mGy/hr | 0,02-0 mGy/hr | 0,02-0 mGy/hr |
| Material/composition | Compacted bentonite | Crystalline rock | Sand-bentonite mixture | Bentonite/concrete |
| Thickness | 0,75 m | 500 m | 5-7 m | 6+3 m |

*[1] Close to openings *[2] First 100 years

| Parameters to measure | Buffer | Rock*[1] | Backfill | Seals |
|---|---|---|---|---|
| Temperature | X | X | | |
| Mechanical pressure | X | X | X | X |
| Hydraulic pressure | X | X | X | X |
| Water content/saturation | X | | X | |
| Displacements | | X | | X |
| Other (specify) | | | | |
| | | | | |
| | | | | |
| | | | | |

*[1] Close to openings *[2] First 100 years

## A-2. NDA

| Technical Requirements – Initial (NDA) | | | | | | |
|---|---|---|---|---|---|---|
| The UK programme for radioactive waste disposal has not identified a site or specific geological environment for a disposal facility. The following list of technical requirements for geological disposal have therefore been developed recognizing this position. They therefore reflect more the generic approach to monitoring and indicate the key areas of monitoring interest rather than provide a categoric list of requirements. For spent fuel disposal, NDA propose to develop a disposal solution based on site-specific information (e.g. on the geological environment). NDA has, in the absence of a site and site-specific geological environment, adopted design solutions for HLW and spent fuel disposal from partner organisations, therefore the information below focuses on the requirements for ILW disposal, recognising that the partners will address repository monitoring technical requirements appropriate to their disposal concept. | | | | | | |
| **Aspect** | **Waste Package** | **Buffer** | **Local Backfill** | **Seals** | **Near-field Rock** | **Far-field Rock** |
| Basis for monitoring | If feasible this could be considered and early pilot studies may be provided, but not viewed as a necessity to support post-closure safety assessment. | Monitoring could be instituted to confirm the design performance. Not necessary to support the environmental safety case but could be of value depending on decisions made by future generations. | Monitoring could be instituted to confirm the design performance. Not necessary to support the environmental safety case but could be of value depending on decisions made by future generations. | Monitoring could be instituted to confirm the design performance. Not necessary to support the environmental safety case but could be of value depending on decisions made by future generations. | Monitoring would be instituted and sustained during construction and operation. As emplacement, backfilling and sealing progresses the level of monitoring and areas being monitored will be modified. | Will be necessary to monitor the far-field from the early stages of site investigation (baseline monitoring) through construction, operation and closure in order to support development of safety cases. |

| Aspect | Waste Package | Buffer | Local Backfill | Seals | Near-field Rock | Far-field Rock |
|---|---|---|---|---|---|---|
| Typical Frequency | From continuous to monthly or annually depending on the parameter and the stage in the programme. | From continuous to monthly or annually depending on the parameter and the stage in the programme. | From continuous to monthly or annually depending on the parameter and the stage in the programme. | From continuous to monthly or annually depending on the parameter and the stage in the programme.. | From continuous to monthly or annually depending on the parameter and the stage in the programme. | From continuous to monthly or annually depending on the parameter and the stage in the programme. |
| Possible Duration | Unlikely to monitor following backfilling – therefore decades. | For the duration of operations. Potentially 100 years plus. | For the duration of operations. Potentially 100 years plus. | Until final closure decision. Could be decades or longer. | For the duration of operations and sealing. Potentially 100 years plus. | Throughout site investigation, construction operations and closure. Monitoring could be sustained by future generations after closure. Possibly '00's of years. |
| Cables Allowed | No – not once backfill emplaced | No | No | No | No | No |
| Sensors Allowed | No | Possibly remote | Possibly remote | Possibly remote | Possibly remote | Possibly in a maintained |
| Wireless Allowed | Yes | Yes | Yes | Yes | Yes | Yes |
| Antennas and Waveguides Allowed | No | Possibly | Possibly | No | Possibly in specific locations | No |

| Aspect | Waste Package | Buffer | Local Backfill | Seals | Near-field Rock | Far-field Rock |
|---|---|---|---|---|---|---|
| Peak Temperature | 65°C within 0.3 years of backfilling | 65°C within 0.3 years of backfilling | 65°C within 0.3 years of backfilling | 65°C within 0.3 years of backfilling | 65°C within 0.3 years of backfilling | |
| Stress | Maximum vertical thermal stress of 12 MPa, maximum horizontal thermal stress of 18 MPa | Maximum vertical thermal stress of 12 MPa, maximum horizontal thermal stress of 18 MPa | Maximum vertical thermal stress of 12 MPa, maximum horizontal thermal stress of 18 MPa | Maximum vertical thermal stress of 12 MPa, maximum horizontal thermal stress of 18 MPa | Maximum vertical thermal stress of 12 MPa, maximum horizontal thermal stress of 18 MPa | ? |
| Hydraulic Pressure | Atmospheric at closure rising to hydrostatic ~5 MPa after 200 years | Atmospheric at closure rising to hydrostatic ~5 MPa after 50 years | Atmospheric at closure rising to hydrostatic ~5 MPa after 50 years | Atmospheric at closure rising to hydrostatic ~5 MPa after 50 years | Atmospheric at closure rising to hydrostatic ~5 MPa after 50 years | ? |
| Redox | Anaerobic conditions 5 years after saturation, -450 mV 1,500 years after closure | Anaerobic conditions 5 years after saturation, -450 mV 1,500 years after closure | Anaerobic conditions 5 years after saturation, -450 mV 1,500 years after closure | Anaerobic conditions 5 years after saturation, -450 mV 1,500 years after closure | Anaerobic conditions 5 years after saturation, -450 mV 1,500 years after closure | ? |
| pH | >12.4 local to waste package for 10s of thousands of years | >12.4 local to waste package for 10s of thousands of years | >12.4 local to waste package for 10s of thousands of years | Not applicable | | ? |
| Alkaline Disturbed Zone | Precipitation of calcite and CSH phase on a scale of metres to 100s of metres | Precipitation of calcite and CSH phase on a scale of metres to 100s of metres | Precipitation of calcite and CSH phase on a scale of metres to 100s of metres | Precipitation of calcite and CSH phase on a scale of metres to 100s of metres | Precipitation of calcite and CSH phase on a scale of metres to 100s of metres | Precipitation of calcite and CSH phase on a scale of metres to 100s of metres |

| Aspect | Waste Package | Buffer | Local Backfill | Seals | Near-field Rock | Far-field Rock |
|---|---|---|---|---|---|---|
| Colloid Populations | $10^{11}$-$10^{12}$ particles/litre from CSH phases | $10^{11}$-$10^{12}$ particles/litre from CSH phases | $10^{11}$-$10^{12}$ particles/litre from CSH phases | $10^{11}$-$10^{12}$ particles/litre from CSH phases | $10^{11}$-$10^{12}$ particles/litre from CSH phases | ? |
| Repository-derived Gases | Peak generation rate for carbon-14 bearing methane 1030 TBq/y 100 years after closure | Maximum flux hydrogen 0.101 m/y, maximum flux methane 0.0166 m/y. | | | | |
| Gas Pressures | 6.3 MPa 7 years after closure | 6.3 MPa 7 years after closure | 6.3 MPa 7 years after closure | 6.3 MPa 7 years after closure | 6.3 MPa 7 years after closure | |
| Radiation | | | ? | ? | ? | ? |
| Material Composition | Steel and grouted waste (cement- or polymer- based grout) | Alkaline Cement-based | Alkaline Cement-based | Cement-based plus low-permeability materials | Depends on site selected. | Depend on site selected. |
| Thickness | ~1-2 m | ~1-22 m | ~1-22 m | ~1-5 m | ~1-100 m | 200m – 1000m |

## A-3. DBETEC

| Monitoring when closing | Buffer | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | yes | yes | yes | yes | |
| Continuous or discontinuous monitoring (C/D) | C | C | C | C | |
| Minimum frequency of measurement (per day, week or month) | 1 per day | 1 per day | 1 per day | 1 per day | user change option at any time |
| Minimum duration of monitoring (sealed) in years | 30 | 30 | 30 | 30 | |
| Cables allowed (yes/no) | no | yes | no | no | |
| Wireless allowed (yes/no) | yes | yes | yes | yes | |
| Antenas/waveguides allowed (yes/no) | no | yes | no | no | |
| **Expected environment conditions*[2] (ranges)** | **Buffer** | **Rock*[1]** | **Backfill** | **Seals** | **Comments** |
| Temperature (ºC) | 25 - 200 | 35 - 200 | 25 - 40 | 25 - 40 | |
| Mechanical pressure (MPa) | 0 - 40 | 0 - 40 | 0 - 30 | 0 - 25 | |
| Hydraulic pressure (MPa) | 0 | 0 | 0 | 0 | |
| Water content/saturation (%) | 0 | 0 | 0 | 0 | |
| Displacements (mm) | 0 -1000 | 0 - 1000 | 0 - 1500 | not yet clear | no seal developed yet for HLW |
| Salinity | 100% | 100% | 100% | 100% | |
| Radiation (msv/hr) | 60 - 15 | 0.02 - 0 | 0.02 - 0 | 0.02 - 0 | |
| Material/composition | crushed salt | rocksalt | crushed salt | salt-concrete | |
| Thickness (m) | 0.1 - 3 | 800 | 02-abr | 100 - 150 | for drift seals: the length is ment |
| **Parameters to measure** | **Buffer** | **Rock*[1]** | **Backfill** | **Seals** | **Comments** |
| Temperature (yes/no) | yes | yes | yes | yes | |
| Mechanical pressure (yes/no) | yes | yes | yes | yes | |
| Hydraulic pressure (yes/no) | no | no | yes | yes | |
| Water content/saturation (yes/no) | no | no | yes | yes | |
| Displacements (yes/no) | yes | yes | yes | yes | |
| **Humidity (Vol%)** | yes | yes | yes | yes | |
| **Radiation** | yes | no | no | no | |
| **Radioactive gases** | yes | no | yes | no | |
| **pH and Eh values** | yes | no | yes | yes | |
| *[1] Close to openings *[2] First 100 years | | | | | |

## Additional information

1. In the German concept we do not use a real “buffer”. There is no difference between buffer and backfill. We intend to use crushed rocksalt (as “buffer”) to fill the space between the casks and the vertical boreholes, in case of borehole disposal, or between the cask and the drift contours in case of drift disposal. At the same time we will use crushed rocksalt to “backfill” all other remaining openings.

2. The following questions are currently discussed at our authority:

   How to monitor **humidity** (not pore pressure) in buffer, backfilled areas and seals ?
   How to monitor **radiation** in the vicinity of casks ?
   How to monitor **radioactive gases** in backfilled areas ?
   How to <u>continuously</u> monitor **pH- and Eh-values** (important for the sealing constructions with salt-concrete)

   I suggest to take all these measurements as an “requirement” and see if and how we can meet them ! So I added them to “parameters to be measured” in the table.

## A-4. POSIVA

| Monitoring when closing | Buffer | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | Yes | Yes | Yes | Yes | |
| Continuous or discontinuous monitoring (C/D) | C /D | C /D | C /D | C /D | In demostration phase and just after closing to get ensurance for expected behaviour of system the monitoring is more like continuous but after a time the monitoring could be done in campaigns or the frequency is so low that it could be thought as discontinuous. |
| Minimum frequency of measurement (per day, week or month) | 1/hour => 1/week | 1/hour => 1/week | 1/hour => 1/week | 1/hour => 1/week | Frequency of measurement decreases during monitoring |
| Minimum duration of monitoring (sealed) in years | 100 | 100 | 100 | 100 | |
| Cables allowed (yes/no) | No | No | Yes | Yes | Backfill and seals yes, for limited areas and feed through has to be shut finally |
| Wireless allowed (yes/no) | Yes | Yes | Yes | Yes | Buffer yes, but not to the surface of canister or rock; Rock if needed yes, but not to the hydraulic active place |
| Antenas/waveguides allowed (yes/no) | Yes | Yes | Yes | Yes | Buffer yes, but not to the surface of canister or rock; seals yes, but feed through has to be shut finally |

| Expected environment conditions*[2] (ranges) | Buffer | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Temperature (ºC) | 100-15 °C | 70-15 °C | 60-15 °C | 50 °C | |
| Mechanical pressure (MPa) | 10-0 MPa | 33-10 MPa (*b) | 3-0 MPa | 6-0 MPa | (*b) In situ Rock Stress |
| Hydraulic pressure (MPa) | 4,5-0 MPa | 4,5-0 MPa | 4,5-0 MPa | 4,5-0 MPa | |
| Water content/saturation (%) | 100-50 % | 100 % | 100-50 % | 100-50 % | |
| Displacements (mm) | 100-0 mm | 10-0 mm | 120-0 mm | 10-0 mm | |
| Salinity | 70-10 g/l | 70-10 g/l | 70-10 g/l | 70-10 g/l | 70 g/l is upper limit of performance target for groundwater salinity, 10 g/l is lower limit of observed salinities in Olkiluoto (depth 400 m). |
| Radiation (msv/hr) | 325 msv/h * | | | | *Maximum at the surface of the canister (F |
| Material/composition | bentonite | crystalline rock | bentonite or bentonite+crushed stone | concrete | |
| Thickness (m) | up 2,2 m, down 0,8 m and both side 0,35 m | 420 m | 4,4-3,5 m | 6 m | |

| Parameters to measure | Buffer | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Temperature (yes/no) | y | y | y | | |
| Mechanical pressure (yes/no) | y | y | y | y | |
| Hydraulic pressure (yes/no) | y | y | y | y | |
| Water content/saturation (yes/no) | y | | y | | |
| Displacements (yes/no) | y | y | y | y | |
| Other (specify) | | | | | |

*[1] Close to openings *[2] First 100 years

## Additional information

- The table above concerns only monitoring activities in special monitoring tunnels.
- The decision about monitoring activities in actual deposition tunnels will be made in 2018.

## A-5. RAWRA

| Monitoring when closing | Buffer | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Monitoring needed/desired | yes | yes | yes | yes | nice-to-have for whole this section |
| Continuous or discontinuous monitoring | c | c | c | c | |
| Minimum frequency of measurement (per day, week or month) | 1 per week | 1 per week | 1 per week | 1 per month | |
| Minimum duration of monitoring (sealed) in years | 20 years | 20 years | 20 years | 20 years | |
| Cables allowed | no | no | yes | no | |
| Wireless allowed | yes | yes | yes | yes | |
| Antennas/waveguides allowed | yes | yes | yes | no | |
| **Expected environment conditions*[2] (ranges)** | **Buffer** | **Rock*[1]** | **Backfill** | **Seals** | **Comments** |
| Temperature (ºC) | less than 100ºC | 10ºC | N/A | N/A | values in this section were given by old design project from 1999, update will be finished in 2011 |
| Mechanical pressure (MPa) | 20MPa | 20MPa | N/A | N/A | |
| Hydraulic pressure (MPa) | N/A | 5MPa | N/A | N/A | |
| Water content/saturation (%) | N/A | 100% | N/A | N/A | |
| Displacements (mm) | N/A | 0-2mm | N/A | N/A | |
| Salinity | N/A | 200-500mg/l | N/A | N/A | |
| Radiation (msv/hr) | 2-10mSv/hr | <2,5microSv/hr | <2,5microSv/hr | <2,5microSv/hr | dose rate limits for controlled area |
| Material/composition | compacted bentonite | crystalline rock | sand/bentonite/crushed rock mixture; | concrete | |
| Thickness (m) | 0,325m | 500m | 5,5-10m | 0,5m | |
| **Parameters to measure** | **Buffer** | **Rock*[1]** | **Backfill** | **Seals** | **Comments** |
| Temperature | yes | yes | no | no | |
| Mechanical pressure | yes | yes | yes | yes | |
| Hydraulic pressure | yes | yes | no | no | |
| Water content/saturation | yes | yes | yes | no | |
| Displacements | no | yes | no | no | |
| Other | | | | | |

*[1] Close to openings *[2] First 100 years

## A-6. RWMC

| Monitoring when closing | Buffer | Near-field*[1] | Backfill | Seals | Far-field | Comments |
|---|---|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | NDT | NDT | NDT | NDT | NDT | NDT: Not determined yet in Japan |
| Monitoring needed/desired (yes/No) | (No) | (No) | (No) | (No) | (Yes) | (From RWMC's monitoring strategy in disposal panels (Suyama, Y., et al, 2010)) |
| Continuous or discontinuous monitoring (C/D) | | | | | | |
| Minimum frequency of measurement (per day, week or month) | | | | | | |
| Minimum duration of monitoring (sealed) in years | | | | | | |
| Cables allowed (yes/no) | | | | | | |
| Wireless allowed (yes/no) | | | | | | |
| Antenas/waveguides allowed (yes/no) | | | | | | |
| **Expected environment conditions*[2] (ranges)** | **Buffer** | **Near-field*[1]** | **Backfill** | **Seals** | **Far-field** | **Comments** |
| Temperature (ºC) | -100 | | | | | From JNC H12 project report (JNC, 2000) |
| Mechanical pressure (MPa) | -1 Swelling pressure | 7- Overburden pressure | | | | From JNC H12 project report (JNC, 2000) |
| Hydraulic pressure (MPa) | 3- After re-saturation | 3- After re-saturation | 3- After re-saturation | 3- After re-saturation | | HLW shall be disposed of more than 300m below the groudn surface (Final Disposal Act). |
| Water content/saturation (%) | -100 | -100 | -100 | -100 | | From JNC H12 project report (JNC, 2000) |
| Displacements (mm) | | | | | | |
| Salinity | | Saline or brackish, fresh water | | | Saline or brackish, fresh water | From JNC H12 project report (JNC, 2000) |
| Radiation (msv/hr) | | | | | | |
| Material/composition | Sand-Bentonite mixture | Crystalline rock or Sedimentary rock | Sand-Bentonite mixture | Sand-Bentonite mixture | Crystalline rock or Sedimentary rock | From JNC H12 project report (JNC, 2000) |
| Thickness (m) | 0,7 | 300- | 5 | 7 | | From JNC H12 project report (JNC, 2000) |

| Parameters to measure | Buffer | Near-field*[1] | Backfill | Seals | Far-field | Comments |
|---|---|---|---|---|---|---|
| Temperature (yes/no) | | | | | Yes | |
| Mechanical pressure (yes/no) | | | | | No | |
| Hydraulic pressure (yes/no) | | | | | Yes | |
| Water content/saturation (yes/no) | | | | | No | |
| Displacements (yes/no) | | | | | No | |
| Other (specify) | | | | | groundwater chemistry | |
| *[1] Close to openings *[2] First 100 years | | | | | | |

JNC, 2000. H12 Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, JNC TN1410 2000-001.

## A-7. ANDRA

| Monitoring when closing | Buffer | HLW cell | ILW cell | galerie | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | N/A | Andra concept | | | yes | not decided - potential need to verify residual voids and settling after backfill emplacement | yes for disposal cell and access galery seals; no formal decision, but negative working assumption for shaft seal | Monitoring needs/desires not finalized- working assumptions at this stage - will be reevaluated |
| Continuous or discontinuous monitoring (C/D) | N/A | | | | c | ? | c | Discontinuous measurement, from my point of view should be considered just to reduce power consumption. It is shown that continuous measurements provide a better estimation of the damage. |
| Minimum frequency of measurement (per day, week or month) | N/A | | | | If influenced by diurnal ventilation variations, at lest 2 measurement/days<br>In general, frequency adapted to evolution (several per hour after construction, towards one per day or less as evolutions slow) | ? | Adapted to time scale of phenomenon (fast or slow evolutions) and to potential influence/minor variations induced by other nearby activities.<br>The latter suggests using at lest 2 measurement/days | Feedback from structural monitoring applications suggests that a higher frequency (at least ten times higher than apparent need) help to filter perturbations form an other external source. |
| Minimum duration of monitoring (sealed) in years | N/A | | | | Not defined for sealed area - assumption that at least some representative, sealed structure will be monitored<br>Order of decades? | ? | order of several decades - decision to stop may depend on decision to further close the repository | |
| Cables allowed (yes/no) | N/A | | | | yes - this only applies to the near field, with cables that will not create an added risk of flow/transfer | yes | yes - however a remedial action to the seal is envisioned when monitoring done, to ensure compliance with long term safety considerations | |
| Wireless allowed (yes/no) | N/A | | | | yes | yes | yes | |
| Antenas/waveguides allowed (yes/no) | N/A | | | | yes - cf. "cables", only if no additional transfer or chemical byproduct risk created | yes | yes | |

| Expected environment conditions*[2] (ranges) | Buffer | HLW cell | ILW cell | galerie | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|---|---|---|
| Temperature (ºC) | No buffer in Andra conception (EBS limited to waste overpacks, liners and seals) | ~90°C | less than 30°C for most; 55°C in exceptional context | 22°C to 50°C near HLW cells; close to ambient (23°C) elsewhere | 90°C (max, short time) | ambient near ILW cell; rise of several 10 °C near HLW cell | ambiant in galleries and shafts; slightly higher near ILW cell | |
| Mechanical pressure (MPa) | | from 0 to 12 MPA | from 0 to 12 MPA | from 0 to 12MPA | from 0 to 12MPA | compaction pressure TBD | 1-12MPa in distant future once bentonite resaturated | intimate contact with the rock |
| Hydraulic pressure (MPa) | | 5 MPA | 5 MPA | 5 MPA | 5 MPA | no resaturation until several thousand years later | no resaturation until several thousand years later | |
| Water content/saturation (%) | | 95-100% (operating time) | 40%(operating time) | 30-40% | in close field 90% in far field 97-100% | ambient hygrometry after closure rises to 100%; resaturation in distant future | ~ 70% water content at installation | hydric saturation |
| Displacements (mm) | | needs to be established with future URL tests | ? | ? | | | ? | |
| Salinity | | 2-3g/L | 2-3g/L | 2-3g/L | 2-3g/L | 2-3g/L | 2-3g/L | water at MHM URL |
| Radiation (sv/hr) | | max radiation (in wastepackage pseudo-contact) =10 sv/h; on the surface of the liner= 1sv/h | max radiation (in wastepackage pseudo-contact) 1 sv/h; on the surface of the liner 0,01sv/h | workers protection: < 5mSv/year | 0,01 or 1 sv/h | | ? | Table 2.4.2 dossier 2005 |
| Material/composition | | Non-alloy steel liner and waste overpack | concrete liner | concrete liner | Argilite | Argilite | Bentonite of Wyoming MX 80, European bentonite, Backfill | |
| Thickness (m) | | 25-35mm cell liner thickness | ~1m | ~1m | 500m depth; min 60 m argilite cover above structures | 150m | several 10s of m for swelling clay, plus concrete support | |
| core Permeability (water) m/s | | bentonite plug at cell head | | | unperturbed rock: 1E-12 to 1E-14 m/s; EDZ: 1E-7 to 1E-9 m/s | | target: 1E-12m/s | |
| **Parameters to measure** | **Buffer** | **HLW cell** | **ILW cell** | **galerie** | **Rock*[1]** | **Backfill** | **Seals** | **Comments** |
| Temperature (yes/no) | N/A | yes | yes | yes | yes | | yes | |
| Mechanical pressure (yes/no) | N/A | yes | yes | yes | yes | | yes | |
| Hydraulic pressure (yes/no) | N/A | yes | yes | yes | yes | | ? | |
| Water content/saturation (yes/no) | N/A | yes | yes | yes | rock close to structure and seal= yes | | yes | |
| Displacements (yes/no) | N/A | yes | yes | ? | yes | No input for the moment | ? | |
| Other: deformation | N/A | yes | yes | yes | yes | | yes | |
| Other: hydrogen content in air | N/A | yes | yes | ? | ? | | no | |
| other: pH | N/A | Probable | Probable | Probable | yes | | yes | |
| | | | | | | | | |
| Other (specify) | N/A | | | | | | | |

Note: The above table reflects current knowledge and includes several working assumptions concerning monitoring objectives. These are likely to evolve in the next four years, prior to submission a license application in 2014.

## A-8. NRG

| **Monitoring when closing** | **Buffer** | **Rock[*1]** | **Backfill[+]** | **Seals** |
|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | Yes | Yes | Yes | Yes |
| Continuous or discontinuous monitoring | Continuous | Continuous | Continuous | Continuous |
| Minimum frequency of measurement | week - month | week - month | week - month | week - month |
| Minimum duration of monitoring (sealed) | 50 years | 50 years | 50 years | 50 years |
| Cables allowed (yes/no) | No | No | Yes | No |
| Wireless allowed (yes/no) | Yes | Yes | Yes | Yes |
| Antenas allowed (yes/no) | Yes | Yes | Yes | No |
| **Expected environment conditions for the first 100 years** | **Buffer** | **Rock*[1]** | **Backfill[+]** | **Seals** |
| Temperature | 20-90 ºC | 20-55 ºC | 20-50[#] ºC | 20-50[#] ºC |
| Mechanical pressure | 0-13 MPa | 13 MPa | 0-13 MPa | 0-13 MPa |
| Hydraulic pressure | 0-5 MPa | 0-5 MPa | 0-5 MPa | 0-5 MPa |
| Water content/saturation | 0-100% | 100% | 0-100% | 0-100% |
| Displacements | < 6 cm | 1.5 – 2 cm | ? | ? |
| Salinity | 2 - 20 mS/cm | 2 - 20 mS/cm | 2 - 20 mS/cm | 2 - 20 mS/cm |
| Radiation | <40 mGy/hr[#] | <1 mGy/hr[#] | <1 mGy/hr[#] | < 1 mGy/hr[#] |
| Material/composition | cement (OPC) | Boom Clay | shotcrete/grout/? | bentonite/concrete |
| Thickness | 0,75 m | 100 m | ? | 3-10 m |
| **Parameters to measure** | **Buffer** | **Rock*[1]** | **Backfill[+]** | **Seals** |
| Temperature | X | X | | X |
| Mechanical pressure | X | X | X | X |
| Hydraulic pressure | X | X | X | X |
| Water content/saturation | X | X | X | X |
| Displacements | X | X | X | X |
| Radiation | X | | X | |

[*1] Close to openings [+]in connecting galleries, backfill in disposal cell see ‘Buffer’ [#]estimated values

## A-9. SANDIA

| Monitoring when closing | Buffer | Rock | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Monitoring needed/desired (yes/no) | No | Yes | No | Yes | |
| Continuous or discontinuous monitoring (C/D) | N/A | C&D | N/A | QA[1] | Quality control monitoring |
| Minimum frequency of measurement (per day, week, or month) | N/A | Week | N/A | | During construction |
| Minimum duration of monitoring (sealed) in years | N/A | 30 | N/A | N/A | Operational period |
| Cables allowed (yes/no) | N/A | Yes | No | No | |
| Wireless allowed (yes/no) | Yes | Yes | Yes | Yes | If applicable |
| Antennas/waveguides allowed (yes/no) | TBD | TBD | TBD | TBD | |
| **Expected environment conditions** | **Buffer** | **Rock** | **Backfill** | **Seals** | **Comments** |
| Temperature (°C)[2] | <250 | <250 | <250 | 25 – 40 | |
| Mechanical pressure (MPa) | 0 - 40 | 0 – 40 | 0 – 30 | 0 – 25 | |
| Hydraulic pressure (MPa) | 0 | 0 | 0 | 0 | |
| Water content/saturation (%) | 0 | 0 | 0 | TBD | Clay seal density specifications |
| Displacements (mm) | 0 – 1000 | 0 – 1000 | 0 – 1500 | N/A | |
| Salinity | 100% | 100% | 100% | 100% | |
| Radiation (msv/hr) | TBD | TBD | TBD | TBD | |
| Material/composition | MgO | Rocksalt | Crushed salt[2] | Salt concrete, crushed salt, compacted clay and asphalt | |
| Thickness (m) | 1 | 300 | 4 | 300 | |
| **Parameters to measure[2]** | **Buffer** | **Rock** | **Backfill** | **Seals** | **Comments** |
| Temperature (yes/no) | Yes | Yes | Yes | TBD | |
| Mechanical pressure (yes/no) | TBD | Yes | Yes | Yes | |
| Hydraulic pressure (yes/no) | No | No | TBD | Yes | |
| Water content/saturation (yes/no) | No | No | Yes | Yes | |
| Displacements (yes/no) | Yes | Yes | Yes | Yes | |
| Humidity (Vol%) | No | No | No | No | |
| Radiation | No | No | No | No | |

TBD: to be defined

## Additional information

[1, 2] considerations for WIPP:

1. Seal performance confirmation is ensured by redundant design, multiple off-the-shelf materials, and construction quality control.
2. WIPP is an ambient repository. Temperature ranges entered into this table are predicated on external work on a HLW repository in salt.

Further comments:

WIPP is an operating nuclear waste repository in salt. The transuranic inventory does not impart a thermal load. Therefore, temperature measurement at WIPP is not important to performance confirmation, but would be important for HLW repository in salt.

The ten parameters measured at WIPP for confirmation purposes are:

1. Drilling Rate
2. Probability of Encountering a Castile Brine Reservoir
3. Waste Activity
4. Subsidence
5. Changes in Culebra Groundwater Flow
6. Change in Culebra Groundwater Composition
7. Creep Closure
8. Extent of Deformation
9. Initiation of Brittle Deformation
10. Displacement of Deformation Features

These monitoring parameters are actual requirements for an operating, licensed salt repository for long-lived transuranic radioactive waste.

## A-10. EURIDICE

| Monitoring when closing | Buffer | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | NO (quality control during manufacturing) | YES (mainly thermal and hydro conditions) | YES (lining integrity) | YES (seal performance) | preliminary |
| Continuous or discontinuous monitoring (C/D) | | c | c | c | "continuous" in the sense of unattended monitoring |
| Minimum frequency of measurement (per day, week or month) | | typically a few times a day | | | |
| Minimum duration of monitoring (sealed) in years | | 100 (longer in far field | 50 | 50 | |
| Cables allowed (yes/no) | | YES | YES | YES (based in current seal) | to be limited, but no fundamental objection |
| Wireless allowed (yes/no) | | YES | | | no conceptual restrictions |
| Antenas/waveguides allowed (yes/no) | | YES | | | no conceptual restrictions |
| **Expected environment conditions*[2] (ranges)** | **Buffer** | **Rock*[1]** | **Backfill** | **Seals** | **Comments** |
| Temperature (ºC) | 15 - 110 | 15 -70 | 15-80 | 15-80 | temperature in HADES 15 °C; increases a few °C with each 100 m depth |
| Mechanical pressure (MPa) | | 3 - 5 | 3 - 5 | 4 - 8 | litostatic pressure about 2 MPa/100 m depth |
| Hydraulic pressure (MPa) | | 2.5 - 3.5 | | | long term equilibrium value is hydrostatic column |
| Water content/**saturation** (%) | | 100% | 100% | 80 - 100 % | long term (after 10 y): fully saturated |
| Displacements (mm) | | 5 cm | 1 - 2 cm (deformation) | | mainly thermally related (expansion/contraction) |
| Salinity | alkaline | 1 g/l $NaHCO_3$ | alkaline | depends on bentonite | corrosivie species (due to e.g. pyrite oxidation) in the near-field (1 m around excavations) in host rock. |
| Radiation (msv/hr) | | natural background | <0.1 mSv/hr | | Supercontainer has been designed such that radiation at 1 m from the surface < 25 µSv/h |
| Material/composition | OPC (low hydration / low temperature) | Boom Clay | grout (low cement / low strenght) | concrete / stainless steel | |
| Thickness (m) | 0.75 m | 50 m (effective cover) | 40 - 100 cm | 3 - 10 m | |

| Parameters to measure | Buffer | Rock*[1] | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Temperature (yes/no) | | yes | yes | yes | |
| Mechanical pressure (yes/no) | | no | yes (load in lining / pressure on lining) | no | |
| Hydraulic pressure (yes/no) | | yes | yes | yes | |
| Water content/saturation (yes/no) | | no | yes | yes | in clay we expect full saturation (to be confirmed) |
| Displacements (yes/no) | | yes | yes | no | |
| Other (specify) | | | | | |
| *[1] Close to openings *[2] First 100 years | | | | | |

## A-11. NAGRA

| **Monitoring when closing** | **Buffer** | **Rock[*1]** | **Backfill[+]** | **Seals** | **Comments** |
|---|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | yes | yes | yes | desired | |
| Continuous or discontinuous monitoring | C | C | C | C | |
| Minimum frequency of measurement | | | | | Depends on parameter, noise etc.; will be selected to minimize data set and to avoid aliasing |
| Minimum duration of monitoring (years) | 50 | 50 | 50 | 50 | Monitoring time starts after closure of pilot repository |
| Cables allowed (yes/no) | (yes) | (yes) | yes | No | (yes) = allowed only in pilot facility if no other adequate technique is possible |
| Wireless allowed (yes/no) | yes | yes | yes | yes | |
| Antennas allowed (yes/no) | (yes) | yes | yes | yes | (yes) = Depends on size of antenna |
| **Expected environment conditions for the first 100 years** | **Buffer** | **Rock*[1]** | **Backfill[+]** | **Seals** | **Comments** |
| Temperature (°C) | 130 - 100 | 100 - 35 | 60 - 35 | 60 - 35 | Depends partly on repository depth and undisturbed in-situ temperature |
| Mechanical pressure (MPa) | 0 - 6 | 0 - 30 | 0 - 2 | 0 - 10 | Depends partly on repository depth and far field stresses |
| Hydraulic pressure (MPa) | 0 - 9 | 0 - 9 | 0 - 9 | 0 - 9 | Depends on depth and undisturbed pore pressure at the site |
| Water content/saturation (%) | 20 - 100 | 20 - 100 | 20 - 100 | 20 - 100 | |
| Displacements (mm) | 0 - 30 | 0 - 30 | 0 - 30 | 0 -30 | |
| Salinity (g/l) | 10 - 15 | 10 - 15 | 10 - 15 | 10 - 15 | |
| Radiation (mSv/h) | <1000* (40 -60) | < | < 1 | < 1 | * max value at canister surface according to regulation (expected value) |
| Material/composition | bentonite | Opalinus Clay | Crushed rock or sand / bentonite | bentonite or sand / bentonite | |
| Thickness (m) | approx. 0.75 | 100 | Depend on tunnel size | Depend on tunnel size | |

| Parameters to measure | Buffer | Rock*[1] | Backfill[+] | Seals | Comments |
|---|---|---|---|---|---|
| Temperature | X | X | | | |
| Mechanical pressure | X | X | X | X | |
| Hydraulic pressure | X | X | X | X | |
| Water content/saturation | (X) | (X) | | (X) | Not decided |
| Displacements | (X) | X | X | X | |
| Others | Loss of containment | | | | Required by authority, possibly gas monitoring (Xe and / or Kr) in pilot repository |
| | | | | | |

*[1] Close to openings [+]in connecting galleries, backfill in disposal cell see ‘Buffer’ [#]estimated values

## A-12. SKB

| Monitoring when closing | Buffer | Rock*1 | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Monitoring needed/desired (yes/No) | No | Yes | No | Yes | Monitoring will be performed only during operation. No monitoring of closed tunnel will be done. |
| Continuous or discontinuous monitoring (C/D) | N/A | C /D | N/A | C /D | |
| Minimum frequency of measurement (per day, week or month) | N/A | month --> year | N/A | month --> year | Frequency of measurement depends on measured parameter |
| Minimum duration of monitoring (sealed) in years | N/A | see comment | N/A | see comment | Monitoring during operation until final closure of the repository. |
| Cables allowed (yes/no) | N/A | Yes | N/A | Yes | |
| Wireless allowed (yes/no) | N/A | Yes | N/A | Yes | |
| Antenas/waveguides allowed (yes/no) | N/A | Yes | N/A | Yes | |
| **Expected environment conditions*2 (ranges)** | **Buffer** | **Rock*1** | **Backfill** | **Seals** | **Comments** |
| Temperature (ºC) | 100-15 °C | 50-15 °C | 60-15 °C | 50 °C | |
| Mechanical pressure (MPa) | 40-0 MPa | 42-10 MPa (*) | 3-0 MPa | 6-0 MPa | (*) Major horizontal *in situ stress*. Pressure from creep of the rock is considered negligible, i.e. 0 |
| Hydraulic pressure (MPa) | 5-0 MPa | 9.5-0 Mpa (*) | N/A | 5-0 MPa | (*) We expect to monitor below deposition level |
| Water content/saturation (%) | 100-50 % | 100 | 100-50 % | 100-50 % | |
| Displacements (mm) | 50-0 mm | 50-0 mm | N/I | N/I | Establish base line depending on lower limit of the seismic activity. Displacement of the backfill or the seals would have no safety implication |
| Salinity | 10-7 g/l | 24-7 g/l | 10-7 g/l | 10-7 g/l | 10-7 g/l (measured at deposition level, 470 m)<br>24 g/l (highest salinity measured in Forsmark). |
| Radiation (msv/hr) | 1 Gy/h | | | | The radiation dose rate at the surface of the canister must not exceed 1 Gy/h |
| Material/composition | bentonite | crystalline rock | bentonite | bentonite seal + concrete plug | |
| Thickness (m) | up 1.5 m, down 0,5 m and both side 0,35 m | 470 m | 4,2-4,8 m (*) | 1.7 m | (*) Minimum 60% bentonite blocks and remaining space pellets<br>(**) Thickness of the concrete plug |

| Parameters to measure | Buffer | Rock | Backfill | Seals | Comments |
|---|---|---|---|---|---|
| Temperature (yes/no) | N/A | y | N/A | y | |
| Mechanical pressure (yes/no) | N/A | No | N/A | y | Pressure from creep of the rock is considered negligible in crystalline rock. Rock stress is not a monitoring parameter |
| Hydraulic pressure (yes/no) | N/A | y | N/A | y | |
| Water content/saturation (yes/no) | y* | No | y* | Yes | The saturation of the bentonite seal in the plugg will be monitored - since this is needed to ensure that the plug works as intended. In principle, it could be of interest to monitor saturation of the clay barriers, but we have no plans and the saturation may take very long time (up to several 1000 years - so monitoring is not meaningful. |
| Displacements (yes/no) | N/A | No* | N/A | y | (*) Displacement - if any - are only expected in relation to major earthquakes - having extremely low probability over any foreseeable monitoring period. Not meaningful to monitor |
| Other (specify) | | | | | |

| | |
|---|---|
| **Additional information** | |
| No decision is made regarding post closure monitoring | |
| The table content reflects potential monitoring program of sealed tunnels and their enviroment during operation | |
| No decision is made regarding mock-up solution | |
| Monitoring ground-water flow | |
| Monitoring ground-water inflow in the repository (and humidity for mass balance calculations) | |
| Monitoring sea and stream levels, as well as stream flow are included in the monitoring program | |
| Monitoring meteorological parameters are included in the monitoring program | |