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Reliability and qualification of components

Work Package 3, Task 6

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Abstract

This study summarizes the progress made by entities (implementers, regulators and scientific researchers) on a common multi-stage methodology for qualifying monitoring components of the measurement chain (sensor, connecting cable and/or wireless system/controller) at a Deep Geological Repository (DGR). It results from a multi-stage analysis including: i) the study of transferable experience gained from other industry fields, ii) the analysis of case studies operating in conditions close to those expected in repositories, iii) the initiatives for the development of a qualification process for selecting and testing the monitoring components and at last iv) the proposal for a global protocol appropriate to all monitoring contexts.

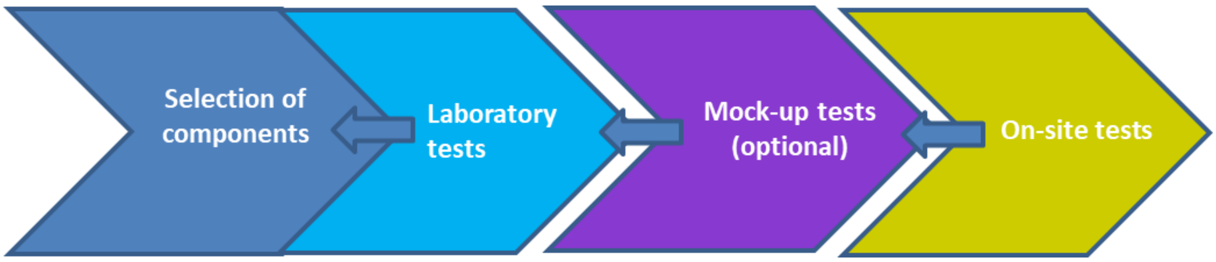
The analysis of transferable experience from other fields aimed at summarizing the different protocols used by other industries with respect to the monitoring components to deliberately accelerate their ageing and qualify their use. The analysis was done through a bibliographic research made around two major companies EDF and ESA involved in the energy and the space field, respectively. The outcomes obtained from EDF (French Electricity producer) indicate a selection and qualification process implemented through three main tasks including: i) a selection of material and suppliers further to a permanent watch on technologies, ii) a laboratory qualification with the verification of metrological characteristics, tests for sensitivity to influence quantities, verification of functional and ergonomic features, verification of compliance with the standards in force, robustness and ageing tests, iii) an on-site qualification performed either on real structures or at a large scale mock-up. The former is generally operated in parallel with devices already in place and qualification pronounced after a satisfactory exploitation time lasting at least one year. The use of large-scale mock-up aims at verifying the behaviour of components at a larger time scale and at conditions similar to real ones or even better controlled. One example is that of the Vercors experiment developed for verifying the behaviour of components associated to a reactor structure. Concerning the space field, Europe has created its own European "organism" for space qualification, namely ESCC. It is shown that despite different influencing parameters, due to the rocket take-off (vibrations) or the space conditions (vacuum, temperature, radiations), the qualification process is rather similar to that developed in the energy field. The selection of components is a complex process that alone accredited companies (SAFT, TRAD, IAS) are able to perform. It includes the analysis of performances, design, operation, environment, manufacturing and testing. The testing of components requires qualification campaigns in space simulators, controlled clean environments, thermal vacuum space cycling, vibration pot and irradiation facilities and is considered as achieved when the Part Approval Document (PAD) is fully filled up and signed. It shows the strong synergy existing between energy and space fields with needs for a DGR facility such as robustness, long-life power supply, and optimization of communications. Their qualification process for monitoring components always considers three stages: i) Selection of components, ii) The laboratory qualification and iii) On-site qualification.

The second part of this study concerned the analysis of case studies of monitoring components operating in conditions close to those expected in repositories. The main idea was to obtain information about ageing, accuracy, possible drift over time and robustness of sensors installed. This was done through a selection of in situ and long-term or demonstration experiments performed at URLs or in large mock-ups (GCR, FEBEX, SEALEX, POPLU, PROTOTYPE). Each selected experiment was summarized through an experiment form detailing the type (long-term or demonstrator), present status (dismantled or on-going), goals, means and main results with respect to survival rate of sensors, the failure origin, if any, and the possible improvements. Lessons learned from this analysis are various. The first observation is that experiments only lasted a few years (less than a decade) which is far below the time of the operation phase for a DGR. The second finding is that despite a strict selection of the best technical solution of the moment, the analysis of the different long-term and demonstrator experiments suggest improvements on monitoring components: 1) For wired sensors, preference was given to passive measuring methods such as the vibrating wire technique and the optical fiber distributed sensing for which an extension of

recording time is required to demonstrate the absence of water pathways along the cables. In case of potential leakage, wireless technologies should be used and the size and number of cables should be limited; cables should also be more armored and resistant to corrosion to prolong their service life. 2) For wireless sensors many problems occurred during swelling of the bentonite-based seal under wetting. Improvements mostly concern a better isolation between transmitters and sensors for avoiding electrical short circuit with free water and the extension of batteries' lifetime.

The third part was dedicated to initiatives for the development of a qualification process and aimed at putting forward a protocol for selecting and testing of components potentially used in the repository monitoring system. The first step concerns the selection of components for which the proposed protocol is largely inspired from the space and the energy fields. The selection process should verify: i) the metrological characteristics and performances, ii) the functional, operating and ergonomic characteristics, iii) the design, compliance with current standards, iv) the sensitivity to influence parameters, v) the minimum required value of the Technology Readiness Level (TRL), vi) the quality and product assurance and at last vii) the testing conditions with the evaluation and qualification plan, the test methods and the screening definition. The second step of the qualification process concerns the testing of components under laboratory or real conditions of use. The laboratory tests must allow the equipment to be tested from a metrological and functional point of view in reproducible conditions and on extended measurement ranges in relation to the requirements set out in the specifications. A test form was sent to partners with the goal of having their feedback from laboratory testing methodologies. The result is that two categories of laboratory tests were identified: Tests of robustness and ageing tests. In both cases tests seek to estimate the degree to which a system or component can function correctly in the presence or stressful environmental conditions but ageing tests alone look at the normal degradation with time of use by accelerating artificially the process. This is especially the case for irradiation tests performed on new sensors developed in the framework of Modern2020 at the IRSN (IRMA) and CEN-SCK (RITA) facilities with Total Ionizing Dose (TID) of less than 0.1MGy and of 1 MGy, respectively. Most of the tests concerned Optical fibers and provided very promising results in view of their integration in a DGR. However, a lot of work remains to do to quantify precisely the Radiation Induced Attenuation on the fiber itself with the necessity to use a dopant or to evaluate the coupled impact of influence parameters (temperature, radiation, hydrogen...) on the sensing cable. Contrary to laboratory tests, on-field tests may allow testing the complete measurement chain metrologically and functionally under real conditions of use. But for the moment, only demonstrators in underground, long-term experiments at on-site/off-site laboratories or at large mock-up can serve as dummy on-site tests. Monitoring strategies like that proposed by Andra also suggests using some “sacrificial”, “surveillance” or “witness” structure exhaustively equipped to fulfil the monitoring goals at the future repository.

Finally the multi-stage qualification methodology applicable to each component of the monitoring system can be summarized by the global sketch given in the figure below.



Global sketch for the qualification of monitoring components in **DGR**s

The proposed global qualification protocol combines the same three successive steps proposed by other fields with optional large-scale mock-up stage and a retrofit process in case of dissatisfaction of one of the three/four major steps.

The first step concerns the strict selection of component candidates with the aim of measuring influence parameters and to define the list of tests to be carried out. The goal of the second step is to proceed on the laboratory testing of components/combined components under adverse conditions. The last step is linked to testing under real conditions of use. To package this methodology, a document model named ADOC is proposed to cover all the envisaged repository contexts. The document fully completed would help validating the installation of a monitoring component at the DGR.

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Glossary

ADOC: Approval DOCument for a monitoring component qualification

Ageing: Process to accelerate artificially the normal degradation of a monitoring component (MC) with time of use. The process may be artificially accelerated with Temperature, Radiation, Chemistry, Humidity, Strain... It is meant to be representative for DGR service conditions, but with higher intensity of stresses, in order to reduce the duration of experiments.

CSM: Polymer - Chlorosufonated Polyethylene (Hypalon)

CYTOP: Polymer - Amorphous fluoropolymer

Dummy sensors: materials made to reassemble the shape, piping and tighness of the selected sensors

DGR: Deep Geological Repository

DAS: Data Acquisition System

DAWE: Drainage, Artificial Watering and Emptying of air

D-LVDT: Linear Variable Differential Transformer Displacement

D-VW: Vibrating Wire Extensometer

EBS: Engineered Barrier System

EDZ: Excavation Damaged Zone

EMC: Electro Magnetic Compatibility

EMS: Extensometer Multi-points Single-rod

ESCC: European Space Components Coordination

FBG: Fiber Bragg Grating

FE: Full-scale Emplacement

FM: Flowmeter

FO Brillouin: Distributed Brillouin scattering within monomode optical fiber

FPM: Polymer - fluoro-elastomer materials

GP Gas pressure sensor

GPS: Global Positioning System

Gray (Gy): The gray is a derivative unit of ionizing radiation dose in the international system unit. It is defined as the absorption of one joule of radiation energy per kilogram of matter.

GTS: Grimsel Test Site

HA/HLW: High Activity / High Level radioactive Wastes

Hardening: Continuous and dynamic process for the demonstration of the resistance of a MC to stresses applied during ageing tests.

IB: Inclinometer

IIR: Polymer - Isobutylene-isoprene

ILW: Intermediate Level radioactive Wastes

LTO: Long Term Operation

LTRBM: Long-Term Rock Buffer Monitoring

MC: Monitoring Component

mINT: Mini interrogator for fiber Bragg gratings

MPT: Multi Purpose test

MTTF: Mean Time To Failure

Multimode OFS: Optical Fibers Sensors for strain and temperature measurements based on multimode fibers

OFS: Optical Fiber Sensors

NPP: Nuclear Power Plant

PMMA: Polymer - Poly(Methyl MethAcrylate)

POF: Polymer Optical Fiber

PP-P: Pore Pressure Piezo-resistive sensors

PP-VWE: Pore pressure Vibrating WirE

TP-P: Total Pressure Piezo-resistive sensors

TP-VW: Total pressure vibrating wire

PAD: Part Approval Document

PT: Resistance thermometer Platinum probes (100 or 1000)

Qualification: Demonstration through testing, analysis or experience of the capability of a MC to function within acceptance criteria during specified operating conditions while retaining the ability to perform its safety functions under normal or degraded scenarios.

QPL: Qualified Parts List

R&D: Research and Development

Reliability : The quality of being trustworthy or of performing consistently well.

Robustness: It is the degree to which a system or component can function correctly in the presence or stressful environmental conditions

SG: Strain gauge

SI-POF-PMMA : Step Index PMMA Plastic Optical Fibre

T: Thermocouple wire gauge, Platinum temperature transducer, thermistors

TID: Total ionizing Dose, expressed in Gray unit (Gy)

T-H-M-C-B-R: Thermal-Hydraulic-Mechanic-Chemical-Bacterial-Radiation

T-VW: Vibrating Wire Extensometer thermistor

TRL: Technology Readiness Level

URL: Underground Research Laboratory

WC: Water content capacitive

WP: Water content psychrometric

WT: Water content Time Domain Reflectometry

WF: Water content Frequency Domain Reflectometry

WMO: Waste Management Organization

WP: Work Package

1. Introduction

1.1. Background

The EU H2020 project Modern2020 deals with the Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal and is jointly funded by the Euratom research and training programme 2014-2018 and European nuclear waste management organizations (**WMO**s). The Project is running from June 2015 to May 2019, and a total of 28 **WMO**s and research and consultancy organisations from 12 countries are participating.

The overall aim of the Modern2020 Project is to provide the means for developing and implementing an effective and efficient repository monitoring programme, taking into account requirements of specific national programmes on geological disposal. The Project is divided into six Work Packages (WPs):

- WP1: Coordination and project management.
- WP2: Monitoring programme design basis, monitoring strategies and decision making. This WP aims to define the requirements of monitoring systems in terms of the parameters to be monitored in repository monitoring programmes with explicit links to the safety case and the wider scientific programme (see below).
- WP3: Research and development of relevant monitoring technologies, including wireless data transmission systems, new sensors, and geophysical methods. This WP will also assess the readiness levels of relevant technologies, and establish a common methodology for qualifying the elements of the monitoring system intended for repository use.
- WP4: Demonstration of implementing monitoring programmes, and related technologies and systems in repository-like conditions. The intended demonstrators, each addressing a range of monitoring-related objectives, are the Full-scale in situ System Test in Finland, the Highly-Active (**HA**) Industrial Pilot Experiment in France, the Long-Term Rock Buffer Monitoring (**LTRBM**) Experiment in France, and the Full-scale Emplacement (**FE**) Experiment in Switzerland. An assessment and synthesis of a number of other tests and demonstrators will also be undertaken.
- WP5: Effectively engaging local citizen stakeholders in Research and Development (**R&D**) and research, development and demonstration (RD&D) on monitoring for geological disposal.
- WP6: Communication and dissemination, including an international conference, a training school, and the Modern2020 Synthesis Report.

This report summarizes the work performed in Task 3.6 of Work Package 3 of the Modern2020 Project. It integrates contributions of Amberg, Andra, EURIDICE, IRSN, SKB and VTT and is prepared and compiled by IRSN.

1.2. Objectives of this report

This report addresses the following objectives of the task 3.6:

1. To gather and analyse the transferable experience from other industries on the performance of relevant sensors and other monitoring equipment that could be used in a repository context.
2. To search and analyse case studies of long lived electronic components and fibre-optics components that have been in operation for as many years as possible in applications worldwide and in conditions similar to those expected in repositories.
3. To develop a methodology for selecting monitoring components to be tested on testing benches.
4. To test the selected components and equipment using different techniques with the aim of producing robustness tests and accelerated ageing under the conditions to be found in a repository: temperature, humidity and pressure, chemical attack/corrosion and radiation.
5. To analyse the results and proposal of most adequate techniques and equipment through the proposal of a general methodology assumed convenient to all **WMO**s.

1.3. Scope of this Report

To reach the goals listed above it appeared necessary to gather transferable experience by other industries (Energy, Space…) by summarizing the different protocols used with respect to the monitoring components to deliberately accelerate their ageing and qualify their use.

Next, as there is currently no **DGR**, it is important to get the feedback of components that worked under conditions as close as possible of a repository that is in **URL**s or in large off-site mock-ups although similar lifetime and radiation conditions with respect to **DGR** are unlikely.

The selection of components potentially useful in the repository monitoring system represents the first stage of the qualification process as the selected components should next undergo a series of tests to be considered qualified.

The second stage of the qualification process considers the testing of the selected components. Testing should be performed at the laboratory and on-site when possible as laboratory and field tests are essential and complementary.

Whatever the monitoring context is, all the items aforementioned should help to propose a general protocol for the qualifying the monitoring components. Hence, Task 3.6 was split into five subtasks:

1. Gathering of transferable experiences from other fields
2. Searching and analysing components that worked under similar conditions
3. Selection of representative components
4. Testing of selected components
5. Analysis of results and proposal of components and techniques

1.4. Report Structure

The structure of the document was set in agreement with these substasks:

- Chapter 2 raises the problem and issues about monitoring system dedicated to Deep Geological Disposal (**DGR**) of radioactive wastes. It starts with the description of the monitoring contexts in France, Belgium and Sweden for host rocks in clayrock and granite, respectively. Then the technological and operational issues associated with the monitoring system in **DGR**s are highlighted through the performance measurement challenges on monitoring equipment.
- Chapter 3 is dedicated to in-situ monitoring and development of the qualification process. The approach consists in comparing experiences gained from the energy and space fields to that proposed by Andra for Cigeo. A Part Approval Document required for qualifying components in the space field is reported in **Appendix 1**.
- Chapter 4 provides lessons learned through Monitoring Components (**MC**) used in long-term and demonstration experiments conducted at Underground Research Laboratories (**URL**) for **DGR** purpose. The main proposed conclusions are extracted from dedicated experimental forms reported in **Appendix 2**.
- Chapter 5 summarizes the Initiatives for the development of a qualification process. It starts with the proposed methodology for selecting monitoring components. Next are given the proposed methodologies for testing and evaluating monitoring compound and include robustness, ageing and on-field tests. This chapter has a link to ageing test forms at **Appendix 3** and with details on irradiation tests at **Appendix 4**.
- Chapter 6 concludes with the proposal of a general protocol appropriate to all monitoring contexts. It includes the selection of components, [1] the laboratory and on-site qualification processes. Its starts with the guidelines to elaborate a qualification process for monitoring component in the context of monitoring geological disposal. And finishes with the proposal of Approval DOCument for a monitoring component qualification, namely **ADOC**.

Note that the glossary provides the definitions of the words or acronyms highlighted in bold in the text.

2. Issues about monitoring system dedicated to geological disposal

2.1. Monitoring DGR context

With regards to nuclear waste management, the IAEA prescribes that “Monitoring and surveillance programmes are important elements in providing assurance that a disposal facility for radioactive waste performs at the required level of safety during the operational and post-closure phases”.

Monitoring may also be carried out to enhance confidence in, and therefore acceptance of, the disposal process [1]. This confidence building does not only refer to the confidence of scientists, but also of the broader public. It is believed that increasing transparency of the ongoing processes during the operational phase (and perhaps the early parts of the post-closure phase) could play a part in stakeholder engagement and dialogue.

In the context of geological disposal of **HL** radioactive wastes there are various possible strategies of monitoring and different interpretations of their purpose.

France – Andra [2] **– Cigeo project**

The French concept of high and intermediate level & long-lived waste repository is made of two types of disposal cells: small tunnels (around 100 m of length and less than a meter of diameter) with a metallic liner for high level waste (Figure 2-1) and long tunnels (several hundreds of meter of length and around 10 m diameter) with a concrete liner for intermediate level wastes. Besides the verification that the installation remains in the operational area as in the general operating rules, monitoring aims at identifying possible deviations which may bring the system out of the normal evolution field in the absence of corrective measures and at checking the packages removing capacity. The observation aspect involves investigating an element or a process in order to better understand it and gives way to improvement of the monitoring program itself or of the disposal concept. The selection of the parameters to be monitored is based on the respect of safety functions and requirements, for each of them are defined the main parameters to follow. The approach allows the identification of the needs of monitoring and observation. For Andra there are two kinds of parameters to monitor (see Tables 2 and 3 in [3]): those of the repository as a whole especially during the construction phase up to the final sealing of the section utilized by workers and those to be monitored in the harsh environment in galleries and disposal cells over a period of about 100 years.

Only the galleries distributing the disposal cells will be accessible for maintenance and visual monitoring. Inside the disposal cells, monitoring will mainly rely on *in situ* instrumentation and observation that can be made during retrievability tests. Instrumented tests will be performed regarding the backfills and the seals during the pilot phase and the results will help optimize the design of the backfilling and seal components to be implemented later (not before 2050).

The monitoring strategy in the French case takes into account that despite the use of qualified technology to design the monitoring system, a risk of providing misleading information remains. Therefore, redundancy in sensing chains will be provided in number and in approach (various technologies). Amongst monitoring units, the sensors would be placed in surplus on the one hand and associated according to their complementarities on the other hand: proven technologies next to innovative sensors, localized measurements associated with devices providing distributed measurements. Finally, metrological references will be placed nearby to evaluate whether sensing chains are subject to long-term drifts. However, the consequences of extensive instrumentation – costs, invasiveness, construction slow-down – call for reaching a good equilibrium between instrumenting every structure and only instrumenting a single prototype.

For this purpose, in the French concept, the global design will take advantage of the complementarities of different technical approaches available by putting progressively more emphasis on visual inspections and on non-destructive tests, while decreasing the number of embedded sensors. It entails optimizing the arrangement of sensing means in order to spread the instrumentation in a largely inhomogeneous way by taking advantage of the similarity between structures, in particular the kilometres of access tunnels and the thousands of disposal cells for long-lived high-level waste (2000 cells currently foreseen). By taking advantage of the similarity of some expected phenomenological evolutions, the monitoring strategy suggests to follow a sequence of structures, referred to as “surveillance cells”, current and non-instrumented, whose density of embedded instrumentation is progressively decreased. If necessary, this could be complemented by a “sacrificial structure”. The “surveillance” structure is chosen amongst the first structures built. It must be exhaustively equipped to fulfil the monitoring goals. Beside the first constructions, the surveillance structures will be chosen for specific locations that ensure a representative monitoring area. The “current” structure is less instrumented, monitored by comparison with a “witness” structure. The standard cell is generally not instrumented. It would only contain essential equipment for the operational safety and would be the target of occasional inspection and control.

When there is a lack of qualified technology, in other words when monitoring of real structures is not possible, the use of dummy structures is planned. This could be the case for corrosion monitoring in high level repository cells where at this stage, the only qualified technique is weighing material coupons. For example, providing one or more “sacrificial cells” similar to a demonstrator structure and containing real containers, since temperature and dose rates influence the speed of corrosion, is envisioned. The monitoring strategy for **HL** waste cells anticipates the integration of an initial module constructed from witness cells respectively distributed (i) in the core of the module and at its edge (ii) along the length of the access gallery (air intake and air return) and (iii) along the module (first cells loaded against the last cells loaded). For ILW disposal cells, several witness structures are envisioned to be selected, depending on the type of wastes that they host.

Belgium - ONDRAF [4]- ***geological disposal project***

The underground repository is designed for **ILW** and **HLW** as co-location. Depending on the scenario chosen to manage the spent fuel (reprocessing or not, political decision which is still pending in Belgium), the amounts of waste to be disposed of will vary. The waste packages (i.e. supercontainers or monoliths), will be emplaced horizontally one after the other (no distance in-between) in the centre of the disposal galleries. These galleries are drifts about 1,000 m long, which are lined with concrete wedge blocks (gallery liners). Since there is no site yet, requirements related to monitoring are very limited for the moment.

The monitoring strategy will evolve as the repository design concept and the regulations mature, and therefore, the strategy was designed with flexibility in mind. Activities undertaken for site characterization might well become a testing and monitoring function later on. Thus, the testing and monitoring program begins during site characterization and continues until permanent closure and post-closure. The breadth of the program includes in situ monitoring, laboratory and field testing, and in situ experiments.

The initial set of requirements for the monitoring includes:

- confirm that subsurface conditions, geotechnical and design parameters are as anticipated and that changes to these parameters are within the limits assumed in the safety case,

- evaluate whether natural and engineered barriers are functioning as intended,

- evaluate the effectiveness of design features intended to perform a post-closure safety function during repository operation and development,

- monitor waste package conditions.

Sweden/Finland – SKB [5]- ***KBS-3V***

The Swedish concept of spent-fuel repository is “KBS-3V-type” (i.e. copper canisters containing the spent fuel emplaced in vertical deposition holes surrounded by a high-compacted bentonite buffer), in crystalline basement rock (granite) at about -500 m level (Figure 2-1). The overlying deposition tunnel will be backfilled with bentonite. A concrete plug will be installed at the entrance of each deposition tunnel to control the amount of water seeping out into the main tunnels and to ensure that the backfill stays in place. Eventually the entire repository will be backfilled with clay material, which need to be tight up to about 100 m above the deposition areas. Some illustrations of this concept can be found in Figure 2-1.

The safety case is built on the assessment of post closure safety and on the ability to guarantee the initial state of the EBS. The assessment of post closure safety is based on more than 30 years research including various laboratory tests, modelling, in-situ tests, natural analogies etc. The conclusion from the post closure assessment is that the KBS-3V in Forsmark fulfils the ambitious requirements and is safe. No need for monitoring of the EBS or the repository has been identified.

The objectives of SKB monitoring programme are:

1. Further increase the confidence in SKB’s handling and understanding of repository evolution.
2. Contribute to the search for earlier unknown features, events and processes

SKB do not intend to apply monitoring that could disturb or jeopardize the EBS function. Hence neither emplaced waste nor **EBS** components (canister, buffer and backfill) will be directly monitored.

Some long-term tests in the repository to monitor the evolution of EBS components will be carried out. The design and planning for such test has recently been initiated. The water flow past the deposition tunnel plugs will be monitored. Full scale test is a key part of the technology development and experiences from such tests forms the basis for the quality control programme to be established. As for the far-field host rock, monitoring activities at Forsmark within the geologic discipline are handled in following three categories: Hydrology, geochemistry together with mechanical and thermal behaviour of the host rock.

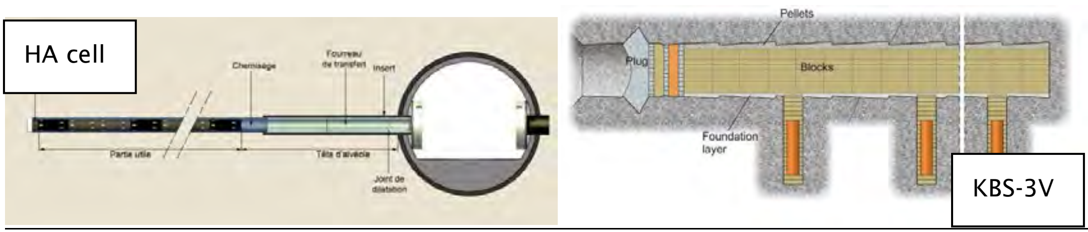

Figure 2-1: French (HA cell) and Swedish/Finnish (KBS-3V) concepts for High Level wastes discussed in this section

2.2. Technological issues associated with the monitoring system in the context of geological disposal

2.2.1. Performance measurement challenges

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

- Individual national monitoring concepts and scopes;
- 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);
- 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…);
- Necessary sensitivity of a method or the range of values that need to be measured;
- Necessary specificity of a method and the cross-sensitivity to other environmental variables (as for instance temperature);
- 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;
- Ability to detect defective sensors and to identify erroneous readings
- Necessary long-term (decades) resistance of the used hardware against unfavorable environmental conditions present in the repository;
- 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 use to verify the coherence of the measurements;
- Influence of measurement equipment on the measured parameter;
- Mandatory positioning of a sensor (for instance to compare measurements with model calculations).

Many of the performance measurement issues that **WMO** face could be extremely challenging.A generic list of typical parameters to be monitored in the repository EBS, host rock and other elements of the repository with relevant measurement intervals is reported in Table 2-1.

Table 2-1: Example of parameters that could be monitored for specific compounds of DGR with relevant measurement intervals (this study)

Compounds	Parameters	Typical value [reference]/Measurement range
Host rock	Temperature, °C	20 - 90 [3] / 0 – 150
	Hydrogen, % or ppm	[0-4%] sensitivity of 5OO ±100 ppm [3] [4-10%] sensitivity of 1% ±<1% [3]
	Water pressure, MPa	4 – 5 / 0 - 6
	Displacements, mm/m	-2.5 - +0.5 [3] / -5 - +5
EBS	Swelling pressure, MPa	0 -10 /0 - 15
	at pseudo-contact of canister γ Dose rate, Gy/h γ TID, MGy	(ILW,F) 0.2 to 25 Gy/h; 0.5 < TID < 0.9(100years) [3] (HLW,F)10 to 240 Gy/h; TID=10MGy(100years) [3]
Concrete	Strain, µm/m	10µm/m [3]
	crack, µm	Threshold for openings: 200 µm
Cell	Gap evolution inside, mm	10 (in 100 years)

2.2.2. Expected harsh environment

At the cell scale, the monitoring devices and installed equipment must further resist to the severe environmental conditions existing in a repository, which may include high temperatures, high pressures, humidity and/or submersion, chemically aggressive environments, and levels of radiation that may degrade electrical and optical cables performances.

Typical requirements also include the longevity (several decades) of expected monitoring (without real possibility of accessibility to maintain equipment, except by robotized devices), the high level of needed confidence in signal reliability, and the absence of interference with barrier performances, in particular as pertaining to long term safety. This is a key requirement of the monitoring system not to degrade the favourable conditions and expected performances for long-term safety of the repository.

The harsh environmental conditions present in a facility deep below the surface are a major issue for the design of reliable, long-living equipment. Typical conditions expected in a **DGR** will differ from the location of the monitoring components as for example for the Cigeo project (Table 2-2).

Table 2-2: Typical conditions expected in different localizations at Cigeo

Parameter	Gallery	ILW cell	HLW cell	Comment
Life time	100 years			
Humidity	30-40%	30%	0 to 100%	
Atmospheric Pressure	1bar	1bar	0.8 to 1 bar	
hydraulic Pressure	5 to 6.3 MPa	5 to 6.3 MPa	5 to 6.3 MPa	
Lithostatic pressure	12 MPa	12 Mpa	12 MPa	
Pressure due to temperature	3 MPa	3 MPa	3 MPa	
Ventilation	3 m^3/s	10 m^3/s to $3m^3/s$	0	
Salinity	2-3 g/l	2-3 g/l	2-3 g/l	
[H_2]	~ppm	10L/package/year	140mol/package/ year	
[O_2]	21%	21%	21%-->0 %	
Chemical phenomena	Bacterial activity	Radiolysis, bacteria activity,	Anoxic corrosion, Radiolysis, bacterial activity	Ongoing research
pH	7 to 12	8 to 13	7 to 12	
Vibration	Construction machinery	Construction machinery	Introduction of the nuclear packages	Gear features is not known
Dose rate		0.1Gy/h (γ)	1 Gy /h (Neutron)	
Total Integrated Dose		0.5-0,9 MGy(γ)	8 MGy (Neutron)	
Dust	Abundant	Need to be characterized	Need to be characterized	

2.2.3. Requirements

In view of the challenging conditions expected for the components of the future monitoring system intended for DGR the development of a robust procedure for their proper qualification is a must.

3. In-situ monitoring and development of qualification process

3.1. Introduction

The ability to ensure reliable and durable monitoring system with repeatable quality through the time life is critical for **DGR** implementation. However, as there is still no **DGR** implemented existing analogies can also be a way for qualifying the **MC**s and obtain reliable equipment over the long term. This can be done taking into account the feedback from industries working in harsh environments such as the energy and space fields. Furthermore, the approach proposed by Andra is also presented and discussed. Finally, it is acknowledged that another way for qualification and reliability of monitoring components is to take into account the lessons learned through long-term experiments conducted at underground research laboratory.

3.2. State of art: gathering of transferable experiences from other fields

The goal of this task is to summarize the different protocols used by other industries (Energy, Space…) with respect to the monitoring components to deliberately accelerate their ageing and qualify their use. To answer this question bibliographic searches have done for the two following fields:

- Energy field: EDF, electricity producer
- Space field: European Spatial Agency (ESA) and other space industries involved in space instrumentation

3.2.1. Experience from the energy industry field

Results reported in this subchapter are mainly taken from public references produced by the French Energy supplier EDF [6]. Innovations (eg. new design of the hydraulics at Marèges), accidentology (eg. Malpasset) and pathologies of works at dams (alkali-reaction concrete at Chambon) fueled a need for remote long-term quality monitoring. This especially concerned reliability of data transmission as dams are no longer easily accessible in winter. Nuclear power was inspired by these practices by using similar sensors and telemetry systems [7].

The field of civil engineering is distinguished from other industrial environments by the durations of life of devices that are particularly long, a large geographical dispersion of the civil engineering works, disparate environments, sometimes severe atmospheric conditions, a culture of measurement and metrology rather weak and limited external supply in terms of solution.

Companies that manufacture sensors and other measurement systems are few in number, produce small quantities of equipment and perform few **R & D** actions. The offer must therefore always be examined with caution and requires significant qualification actions before their operational implementation on the works.

In order to take into account these different characteristics as well as the large number of sensors involved in hydraulic and nuclear power plants (around 20,000 sensors in 600 civil engineering works), EDF has defined and implemented an industrial policy for the choice, the qualification and the maintenance in operational conditions of auscultation equipment [8] [9]. It is based on the following three main principles:

- Use of a limited number of types of equipment,
- Development of a selection and qualification process for materials,
- Sustainability of qualified materials.

Alone the second item is discussed hereafter but the two others are accessible at [6]. Those two items are directly linked to risks in material obsolescence or the disappearance of suppliers, monopoly risk of a supplier…, all problems that require developing contracts of maintenance and management of obsolescence with suppliers.

The selection and qualification process such as performed at EDF is implemented through the three following tasks.

3.2.1.1. Permanent watch on new methods of sensor measurements and technologies

In parallel with qualifications, a permanent watch on the new measurement, data transmission methods and sensor technologies is realized. For example, the following projects can be mentioned:

. Development of optical fiber leakage measurements for dike monitoring

. New topographic methods: **GPS** monitoring, radar interferometry.

3.2.1.2. Selection of materials and suppliers

The main features expected of auscultation equipment are:

- Accuracy, fidelity, absence of drift over time;
- Insensitivity to environmental conditions (temperature, humidity, surges);
- Reliability, longevity (sometimes inaccessible device, continuity of measurements very important);
- Robustness (hostile environment: humidity, cold, lightning, ...);
- Easy to use and maintain, maintainability;

The materials are selected according to their manufacturer characteristics.

EDF is preferably looking for "close" (European) suppliers who are well represented in the area to benefit from a better after sales service and easier dialogue as part of a partnership. The cost aspect of the material is obviously considered.

However, this criterion is weighted against the others (in particular the reliability and the robustness) because the recurrent failures of a hardware installed on an isolated site become very quickly expensive.

3.2.1.3. Laboratory Qualification

The selected materials are then subject of a substantial program of verifications and tests in metrology and testing laboratories:

- Verification of metrological characteristics (compliance with "business requirements")
- Tests for sensitivity to influence quantities (temperature, hygrometry, **EMC**, ...)
- Verification of functional and ergonomic features
- Verification of compliance with the standards in force (safety, CE marking, etc.)
- Robustness tests (temperature, hygrometry, **EMC**, shocks...)
- Ageing tests

This phase of the qualification can last from a few weeks to several months in case of nonconformities to the requirements. If these are not prohibitive, corrections can be made by the manufacturer so that the equipment meets the needs.

3.2.1.4. On-site qualification

At the end of the laboratory qualifications, the equipment is installed on a structure and operated in parallel with the devices already in place.

This essential step makes it possible to verify, under real conditions, the suitability of the equipment with respect to initial needs. The qualification of a material is pronounced, in general, after a satisfactory exploitation on site during one year.

3.2.1.5. Qualification at experimental mock-up

As part of EDF's continuous effort for the management of Long Term Operation (**LTO**) of its fleet of Nuclear Power Plants, an experimental mock-up of a reactor containment building at 1/3 scale has been built at Moret sur Loing, near Paris with the aim of having an operational system of monitoring components very close to the one designed with a high rate of survival. Named VeRCoRs (French acronym: Vérification Réaliste du Confinement des Réacteurs), this mock-up has been completed in 2015 [10]. It has been fit with a dedicated instrumentation system so that its behavior has been monitored from the beginning of the construction (Figure 3-1). More than 500 sensors and 2 km of fiber optic cables have been embedded into the prestressed concrete.

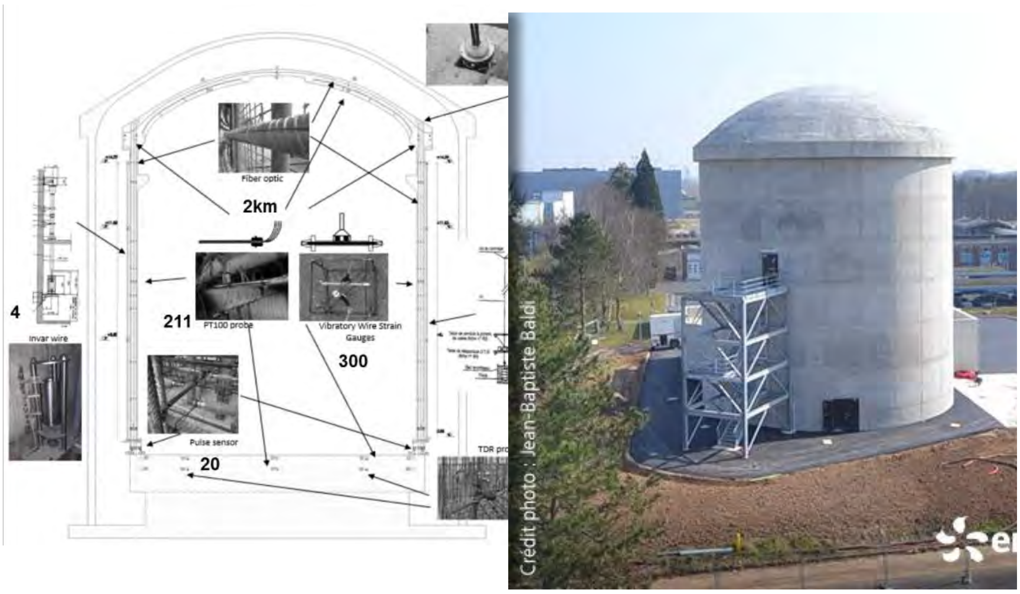

Figure 3-1: The VeRCoRs 1/3 scale-Mock Up: Comprehensive Monitoring System for Reduced Scale Containment Model – after an EDF conference paper 2016

From the first concreting up to the end of the research program, measurements will be collected every day on each sensor: temperature, strain, water content of the concrete.

The monitoring system of the mock up has been thought and designed to answer to several needs around the project:

- Being able to compare results on the mock-up with those on EDF's fleet
- Putting sensors in areas which are not usually equipped in order to have complementary information for models
- Trying out some new technologies

Table 3-1 compares the Monitoring system of the mock-up to that of the regular one on EDF's fleet.

Table 3-1: Monitoring system of VeRCoRs compared to the regular one on EDF's fleet

Physical variables	VeRCoRs	EDF's fleet
Temperature	> 200 Pt100 probes 2 km of fiber optic cables	~ 30 thermocouples
Diameter variations	4 pendulums with 3 reading tables each 12	12 pendulums with 1 reading table each
Height variations	4 INVAR wires	4 INVAR wires
Strain	> 300 strain gauges 2 km of fiber optic cables	~ 50 strain gauges
Prestressing	4 dynamometers	4 dynamometers
Steel bar strain	80 strain gauges	-
Water content	~20 TDR and 20 pulse sensors	-

Regarding the first point, EDF has chosen to use historical brand sensors and technologies already installed on its fleet, respecting the usual establishment plan.

3.2.2. Experience from the space field

To some extent, the main influence parameters or stresses on measuring instruments in space exploration are different from those of the Energy and Disposal fields as they include:

- Vibrations (strong at the takeoff of the rocket)
- Radiations (different from those of the nuclear sector)
- Large temperature range (-40°C to +80°C)
- High vacuum

For the European Space Agency (ESA) the term Qualification of components used in the space industry is commonly used in many situations [11]. You can find components that get:

- Approval on a case by case basis which is an individual and limited authorisation for one (or a few) specific project applications, based on a given mission profile
- A full European Space Components Coordination (ESCC) Qualification which is a general and long term authorisation for use in space and independent of the type of mission
- Components are part of the ESCC **QPL** (Qualified Parts List)
- Components are available at manufacturer as space grade
- For some specific missions (e.g. radiation, cryogenic applications …) extra reliability assessment may be necessary
- ESCC is the European "organism" for space qualification, others space agencies provide qualification with their standards, see for instance http://www.landandmaritime.dla.mil/Programs/QmlQpl/

The procurement specification will define all aspects of the component. Advices for the selection of components include:

- Performances: spectral characteristics, noise, stability
- Design: chips, package, add-on, fibre if any, interface definition
- Operation: input/output power, operating temperatures, wavelength, modulation, consumption, etc end of life
- Environment: specify the lifetime, radiations levels, mechanical stress, thermal stress, humidity exposure on ground, and storage duration to assess the hermeticity
- Manufacturing: single batch approach for all sub parts, screening definition for chips, add-on, fibre, define the allowed reworks, low outgassing materials
- Testing: evaluation and qualification plan, test methods, screening definition,

- Quality and Product Assurance: focus on reliability and traceability, define the customers reviews as early as possible, the list of documents to be delivered, how the hardware is accepted for delivery, criteria for batch rejection

Alone accredited companies are chosen to perform such qualification, testing and calibration tests. Some examples are listed below such as:

- SAFT (100% subsidiary of the Total group), a specialized company, leader of advanced-technology batteries for industry
- TRAD (Test & Radiations, Toulouse, Fr) For Radiation testing, modelling and design of test benches
- IAS (Institut d'Astrophysique Spatiale, a mixed research entity of CNRS and University of Orsay, Fr), has its own calibration station for testing and calibrating, in the space environment, embedded instruments or space equipment.

ESCC Qualification includes testing at:

- Qualification campaigns in space simulators for the calibration of instruments and space environment tests in a controlled cleanliness environment
- Thermal vacuum space cycling (10^{-7} mbar)
- Vibration tests with a vibrating pot
- Irradiations Tests at qualified facilities (US, UK, Italy, Ganil, ONERA, EADS, ...)
- Subcontracting of component testing such as Hirex Engineering

Qualification requires a Part Approval Document (**PAD**) such as the **PAD** sheet reported in Figure 3-2 and in Appendix 1 and must be signed to be approved.

PROJECT:................ Doc n°:.................. Prepared by: .... Issue:...................... Date:....................
Approval requested by:............................... Family:.................... Fcode [ ] Group:................. Gcode [ ] Component Number:.. Commercial Equivalent Designation:...................... Manufacturer/ Country:............................... Technology/Characteristics (value or range of values with tolerance, voltage, package etc): .... Pure tin free (Y/N) [ ] Generic specification:..................... Detail specification:...................... Issue:..... Rev.:..... variant:....... Specification amendment: .... Issue:..... Rev.:..... variant:....... Quality level:.......................... Procurement by:.............................
APPROVAL STATUS EPPL Part 1/2 listed (1/2/N) [ ] ESCC QPL or EQML listed. (Y/N) [ ] MIL QPL or QML listed (Y/N) [ ] If yes: QPL/QML Reference:............................... Other approvals/former usage .... Evaluation programme required (Y/N) [ ] If yes reference of the Evaluation Programme:..............................
PROCUREMENT INSPECTIONS and TESTS Precap (Y/N) [ ] Lot acceptance: ESCC LAT/LVT level or subgroup [ ] MIL QCI/TCI group [ ] Buy-off (Y/N) [ ] DPA (Y/N) [ ] if yes: sample size .... Complementary tests ....
RADIATION HARDNESS DATA Radiation Hardness Assurance Plan applicable (Y/N)[ ] Doc. Ref.: .... Total Dose Effects: Evaluation Test Data (report) reference: .... Single Event Effects: SEL/SEU/SET/SEFI/SEB/SEGR/others: *(cross out when non applicable)* Evaluation Test Data (report) reference: .... RVT required (Y/N)[ ]
REMARKS
Approval customer .... Date ....

Figure 3-2: Part Approval Document required qualifying components in the Space field (full page view in Appendix 1)

3.3. Andra's approach for DGR

An overview of typical environmental conditions, expected operating performances such as durability and precision, and other specific constraints imposed by the repository safety requirements were presented in the MoDeRn Technical Requirements Report [Deliverable 2.1, [12]]. It is recommended that available state-of-the-art monitoring technology is adapted and qualified to meet these requirements, and where necessary innovative technology is developed and qualified as well.

To illustrate this recommended approach, a succinct description of the qualification process that Andra has set up is provided. It entails testing and qualifying the complete measurement chain, by progressive steps, knowing, to be able to anticipate them, the failure rates and mastering the possible long term drifts. The overall process is inspired from the qualification guide for non-destructive methods. Global test sequence includes four stages such as in Figure 3-3:

· Stage one consists in acquiring in-depth knowledge of the sensing technology, engineering solutions, practical implementation constraints. It aims at selecting the technologies best suited to the specific requirements of monitoring the geological repositories for long-lived nuclear wastes. When commercially-available sensing chain performances do not fulfil requirements, research programs will be initiated.

· Stage two consists in carrying out laboratory tests, under fully supervised and/or controlled environmental conditions, to qualify the sensitive component and assess the complete measurement chain performances. Sensors are tested in air, and embedded in host material of interest.

· Stage three consists in outdoor tests, to evaluated field implementation influence. At this stage, the sensing chain is preserved from hazardous conditions, extreme temperature or gamma rays. Unexpected influence parameters might thus be revealed.

· Fourth stage involves **hardening** in view of the application environmental conditions. In the envisioned French geological repository, temperature would range from 25°C to 90°C. Gamma radiation rates reach Gy/h, total dose 10MGy. Hydrogen release is also expected; its maximum levels could approach 100% hydrogen content in the atmosphere.

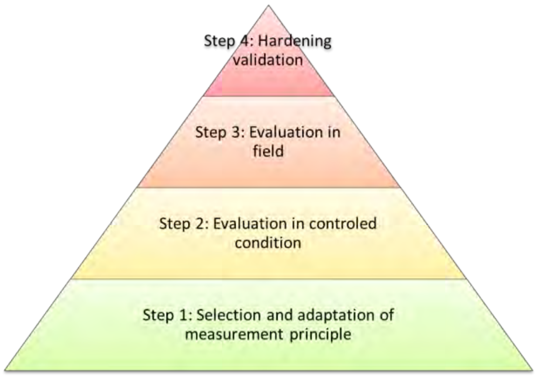

Figure 3-3: Qualification process for technology implementation in the Cigeo projet

Presently, **T-H-M** sensors are finishing qualification process while **C-R-** sensors are still at the laboratory stage. More precisely, Andra monitoring system will rely on platinum probes (T), VWS (vibrating wire extensometers - M), strain and temperature distributed optical fiber sensor based on Raman and Brillouin scatterings (T, M)), water content sensors based on Time Domain Reflectometry probes (H), interstitial pressure cells based on VWS (M), long-based-field-extensometer

3.4. Discussion

Results indicate that there is a strong synergy of DGR with other fields (Energy, Space,) concerning the needs such as robustness, long-life power supply, and optimization of communications…

The qualification process of Energy Space and DGR fields considers at least three stages:

- Selection of components
- Laboratory qualification
- On-site qualification

By combining the presented approaches the following list for the three items can be proposed.

The selection of components includes:

- o Verification of metrological characteristics and performances (compliance with environment requirements including lifetime, radiations levels, mechanical stress, thermal stress, humidity exposure, and storage duration…),
- o Sensitivity to influence parameters (Temperature, Humidity, ElectroMagnetic Compatibility, ...),
- o Verification of functional and ergonomic characteristics and design
- o Verification of compliance with current standards (safety, CE marking, **PAD**, approved at accredited labs...),
- o Operation: input/output power, operating temperatures, wavelength, modulation, consumption, etc end of life,
- o Testing: evaluation and qualification plan, test methods, screening definition,
- o Quality and Product Assurance: focus on reliability and traceability, define the customers reviews as early as possible, the list of documents to be delivered, how the hardware is accepted for delivery, criteria for batch rejection.

The Laboratory qualification includes:

- o Tests of robustness (Temperature, Hygrometry, shock, vibration, thermal vacuum, Irradiation…),
- o Tests of calibration (space simulators in a controlled cleanliness environment, …),
- o Ageing tests - Testing programs performed at accredited external laboratories (humid atmosphere, temperature, **EMC**, radiations…).

The on-site qualification considers:

- o Tests under real use conditions, qualification of the complete measurement chain (sensor, connecting cable and transmitter/controller),
- o Large Mock-up tests,
- o Direct experiments on existing devices (**NPP**, Dams, Spacelab and rockets, satellites…).

4. Lessons learned from existing long term experiments

The goal of this task is to get feedbacks on the components of the monitoring systems that worked under conditions close as the repository one that is in **URL**s or in large off-site mock-ups although similar lifetime and radiation conditions with respect to **DGR** are unlikely. The main idea is to obtain information about ageing, accuracy, possible drift over time and robustness of sensors installed. It concerns case studies of long lived monitoring components under **T-H-M-C-R** conditions. A special attention was paid on partly-dismantled and long-term experiments with the aim of analysing components that worked correctly or not and if not to detail the reasons of the failure or dysfunction.

4.1. Selection of long-term experiments

A selection of experiments based on these criteria was proposed by partners and listed in Table 4-1. Preference was given to experimentations containing a significant variety of components supposed either to measure the key parameters useful to the monitoring of a disposal cell/gallery or to contain wired & wireless components potentially useful in the context of a future **DGR**. Most of the proposed experiments have a limited lifetime either due to the need to dismantle them for analysing the evolution of the materials under real conditions, or more simply to limit acquisitions to the lifetime of dedicated project support. None of the experiment permits a visibility beyond 20 years of monitoring.

Table 4-1: Overview of Long-term experiments in **URL**s selected for their monitoring components with indication of duration.

Partner **URL/LAB (country)**	**ANDRA** LMHM(F)	**NAGRA AMBERG** GTS(CH)	**EURIDICE** Hades(B)	**IRSN** (F) Tournemire	**SKB** Äspö(S)	**VTT** Onkalo(FIN)	**SKB** Äspö(S)
Dismantled long-term and demonstrator experiments	GCR	FEBEX In situ					
Long-term experiments			CLIPEX	SEALEX	MPT	POPLU	Prototype
Duration (y)	6	18	18	6	5	5	8

Experiments listed in are detailed in **Appendix 2** by a specific dedicated *Experiment Test Form*. The experimental sheets detail the type (long-term or demonstrator and its present state dismantled or on-going), the experimental goals, means and main results with respect to survival rate of sensors, the failure origin, if any, and the possible improvements.

Those experiments can be shared into two categories: demonstrator and long-term. In demonstrators the general rule was to use high Technology Readiness Level (**TRL)** monitoring components essentially wired connected sensors such as in GCR and FEBEX. However, for the sake of redundancy and also for qualifying new or low TRL instruments, more innovative components including wireless sensors were applied in long-term experiments such as in POPLU, MPT or in SEALEX. Goals and Means utilized in the different experiments are given hereafter.

4.2. Lessons learned

A synthesis of sensors used in the selected experiment is reported in Table 4-2 with sensor types detailed in the Glossary. In this table values refer to the Total number of sensors / Sensors out of order at the experiment time given in Table 4-1.

Table 4-2: Long-term experiments performed in **URL** and selected for their monitoring components with indications of duration, number of sensors wired and wireless and of their survival rate at the experiment duration reported in Table 4-1

Sensors/Experiment	**GCR**	**FEBEX**	**SEALEX**	**MPT**	**POPLU**	**Prototype**
Strain & Displacement						
SG				32/23	32/12	
D-LVDT					12/0	
D-VW	21/0	11/9				
FO Brillouin	4/3					
Temperature						
T	42/1	54/14			58/4	80/15
T-VW	22/0					
Multimode OFS	7/2					
Moisture & Humidity						
WC		34/34	54/54	34/19	7/4	67/?
WP		24/19		32/2		67/59
Volumetric Water Content						
WT	14/0	10/7				
WF				13/13		
Pore Pressure						
PP-P	6/0		54/40	50/20		18/15
PP-VW		28/23			11/0	26/7
Total Pressure						
TP-P	3/1		41/19	43/13		31/22
TP-VW		6/3			11/0	39/7
Gas Pressure						
GP				3/0		
Convergence						
EMS	15/0					
Inclination						
IB				6/2		
Flow & leakage						
FM				1/0	1/0	
Wired/Wireless		**176/0**	**149/105**	**194/33**	**132/0**	**328/0**
Total sensors **% survival rate**	**134/9** **93%**	**176/108** **39%**	**149/113** **24%**	**227/99** **56%**	**132/20** **85%**	**328/125?** **61%?**

The following conclusions are directly extracted from individual experiment tests forms reported in **Appendix 2**.

For each experiment, main feedback can be summarized as follows:

- <u>GCR</u>

The survival rate of sensors of this monitoring system test six years after installation is about 93%. This has shown the robustness of selected technologies, even for most innovative and recent ones.

This real-scale experiment shows that optical fiber distributed sensing are well suited for underground tunnel monitoring. It also appears that the optical fiber cables chosen were sufficiently robust to tolerate construction conditions. When dealing with distributed data, a major difficulty is accurate event localization. This was solved by creating artificial events, as thermal excitation, during construction steps and after reparations when breaks occur to provide an accurate map.

Sensors tested provided data which allowed improving models and confirming the potential suitability between measurement's need and qualified sensors. As an example, the inductive extensometer in borehole allowed to characterize the evolution of the **EDZ** and was able to provide the same level of information as the other systems, well known and approved, like Invar wire.

Data will be acquired for several years in order to obtain information about ageing, accuracy, possible drift over time and robustness of sensors installed. In addition, measurements will be compared with different non-destructive methods in order to obtain the required level of reliable performances.

- **<u>FEBEX "in situ" GTS URL – Long-term dismantled</u>**

The use of high TRL sensors using passive measuring methods (as the vibrating wire technique) demonstrated to be the best choice. The failure rate for the low **TRL** sensors could be minimized for future applications by improving the mechanical protection, using corrosion resistant metals and avoiding weak plastic parts. The cables, if not avoided (i.e. by using wireless devices), should be armorer, built with long lasting materials and routed to provide flexibility when pulled due to bentonite swelling/movements appear. The sensor bodies shouldn't be too long and the joints between the bentonite blocks/layers should be avoided as much as possible to minimise mechanical deformations largely resulting from shearing, which could lead to fatal damages on the sensors' functionality. The checking and re-scaling of the survived sensors indicated that the accuracy of the data generated by these sensors remained rather unchanged, they showed negligible or very low drift for most of them (not for all parameters), and that the obtained data were trustworthy.

- <u>SEALEX</u>

The monitoring components likely suffered three kinds of losses linked to:

i) Breaks during installation works and/or under resaturation process of the bentonite-based seal.
ii) Sensitivity of capacitive humidity sensors at ~100% RH* conditions (~ free water),
iii) Life-time of the component itself.

The first causes of loss could be easily improved by: i) reinforcing cables and boxes or ii) excluding any cables and working wirelessly.

The second cause is in favour of a different technique (eg TDR, FDR, Tensiometer, GMS, OF humidity sensors) for measuring humidity, if there is no way to improve it. The third cause can only be discussed after the experiment dismantling. However, at this stage one can already claim that a two-years operation seems very insufficient for monitoring a DGR. For this reason a full qualification of components must be achieved especially through making of ageing tests.

- **MPT in situ**

The MPT installation was the first full scale KBS-3H installation and given how many new and novel solutions that had to be developed for sensor installation and cabling the outcome is deemed reasonable and the sensors are providing information about the buffer development.

A thorough assessment should be done on the sensors when the test is dismantled in order to better determine origins of failure.

The KBS-3H project gained a lot of experiences from the MPT and methodologies are now available for both component assembly and installation including sensors.

- **POPLU**

Monitoring systems were designed to assess plug performance based on properties of temperature, relative humidity, total pressure, pore pressure, strain and displacement of the concrete, clay and rock. The monitoring system was composed of sensors, wires and shielding, data collection systems, pressurization systems and near field monitoring including leakage assessment. In general, the monitoring systems of POPLU have performed well, and have been used to evaluate the performance of the experiment with respect to design specifications. The systems were designed and installed based on past experiences, including improvements to aspects especially related to watertightness for the extreme environment associated with pressurization. Monitoring results have fed back to the design basis and form an integral part of repository safety demonstration. The POPLU monitoring system design and experience can also be utilized in various other applications when evaluating material performance in challenging environments.

- **Prototype repository, partially dismantled**

Many of the installed sensors failed probably due to large forces on the housing of the sensors or on the tubing for the wires. It is favourable if the sensors could be tested mechanically before installation. One way to avoid sensor failures might be to separate the mechanical protection of the cable from the protection from high water pressure i.e the cabling could take the water pressure, and the piping could take the mechanical loads.

Many of installed sensors for measuring pore pressure and total pressure of type Geokon were tested afterwards with good results. They showed a maximum deviation from the applied pressure of ±2%. The judgment is thereby that all the Geokon sensors installed in the test have given reliable readings until failure or termination of the experiment.

The main results with respect to the behaviour of the monitoring components since installation are summarized for all experiments in Table 4-2 where it is shown that despite the precautions taken, none of the experiment concludes to a survival rate of 100%. Reasons of this defect are detailed in the next section. Note that the survival rate obtained in table 4.2 cannot easily be used to compare the success of the instrumentation used between experiments because the duration and THMC conditions are different. Furthermore, the "failure" of moisture & humidity sensors is often caused by reaching the full range (saturation) and thus should not be considered as a real dysfunction (performed well). The experiments having a relative high number of these sensors could get low survival rates for this reason.

4.3. Global feedback from currently-used monitoring components

The overall analysis of experiments has enabled us to propose a synthesis of failures for components currently used in long-term experiments at **URL**s as function of the sensor type (Table 4-3). For each sensor, possible improvements are proposed by the different partners involved in this task.

Table 4-3: failure origin and possible improvements as a function of the sensor type

Sensor type/**MC** (see Glossary)	Failure origin	Possible improvements
Water content capacitive **WC (suction)**	Very sensitive to free water (they become damaged when flooded, however in such case they reached the maximum range and they are not needed anymore), sometimes poor performance at higher degree of saturation (not water condensing)	Use of alternative sensors in parallel (volumetric water content) Improve the sensor cable connection Install them properly to avoid quick flooding (location and orientation) Need for more accurate measures in media close to full saturation
Psychrometric Water content **WP (suction)**	Cables pulled up during bentonite swelling & mechanical deformations from shearing. Also very sensitive to corrosion by salt	Use of alternative sensors in parallel (volumetric water content) Improve body and cables armoring, extend lifetime with long lasting materials and properly route the cables to provide flexibility when pulled up due to bentonite swelling
TDR Water content **WT (Volumetric)**	Cables pulled up during bentonite swelling & mechanical deformations from shearing and sensitive to salt corrosion	Avoid blocks junctions and cable stress due to bentonite swelling, use better plastics. Properly route the cables to provide flexibility when pulled up due to bentonite swelling
Temperature **T**, **TP**	Sensitive to corrosion from exchange with fluids (saline waters, air) under oxidizing or anoxic conditions. Drift in accuracy over time	Use of corrosion resistant metals (eg Titanium) or plastic covers or consider special metal coatings to improve resistance. Avoid galvanic corrosion due to di-metal
Distributed Optical Fibers General	Breaks during installation works	Improve cables armouring. Use protection at specific locations
Pore pressure **PP-P**, **PP-VWE**	Sensitive to corrosive attack by saline fluid (**PP-P**)	Use of better thermistors and cables (**PP-VWE**)
Deformation Virating Wire **D-VW**	Corrosion at the anchoring pieces Cable damages	Use of corrosion resistant metals (eg Titanium) or plastic covers Improve cables armouring Avoid stress differences along the body
Crackmeter	Flooding inducing a dysfunction of electronics	Avoid using very low TRL sensors without a minimal previous testing Protect electronic from water inflow

Most of the monitoring components were installed based on past experiences with the goal of giving a reliable result at the termination of the experiment. Besides, majority of monitoring components were designed for a different field and conditions (underground civil facilities) were the combination of T-H-M-C-R conditions of the DGR or URLs was not taken into consideration and thus many times the components required an extra hardening as additional protection for the sensors body or metal tubings for the cables. In this respect they could be considered as novel solutions. Furthermore the experiment time is different from that of the exploitation phase in the conditions of a **DGR**. For instance, none of those sensors have experienced conditions like those expected in a repository like radiation, H_2 production. Consequently, all the monitoring components would need robustness tests and ageing tests under potential stresses capable of simulating actual DGR conditions. This would help to obtain information about ageing, accuracy, possible drift over time and robustness of sensors installed.

For all sensors, including wireless one, most of the breaks and failures occurred during installation works and during resaturation processes of the bentonite-based seal. Many of the installed sensors failed probably due to large forces on the housing of the sensors or on the shielding for the wires. Thus, the monitoring components (eg cables, sensors…) should be sufficiently robust to tolerate construction conditions. The monitoring components should also be resistant to a full resaturation of the bentonite core either because of the total stress pressure induced by swelling or due to the presence of free water in contact of the sensing part of the MC. This suggests that the sensors should be tested at least mechanically and hydraulically before installation.

It is noteworthy that some sensors functioned well like specific gas sensor (**GP**) in MPT but their large size restricting their use to an acquisition at an accessible location would also lead to some required improvement. Other monitoring components like pH sensors were not accessible through this analysis.

For wired sensors, preference was given to passive measuring methods such as the vibrating wire technique and the optical fiber distributed sensing. Despite a strict selection of the best technical solution of the moment, the analysis of the different long-term and demonstrator experiments suggest the following improvements:

- The experiments should be time extended to demonstrate the absence of water short circuits along the cables. In case of leakage along the cables, wireless technologies should be used and the size and number of cables should be limited;
- Cables should be armoured, built with long lasting materials and routed to provide flexibility when pulled up due to bentonite swelling/movements during hydration process;
- For other wired sensors, use of corrosion resistant metals (eg Titanium) or plastic covers to avoid corrosion issues and improve cable-sensor connexions (eg **WT** in GCR).

For wireless sensors other problems occurred during swelling of the bentonite-based seal under waterflow. Wireless devices need to be improved to become an alternative to wired sensors. As for wired sensors some improvements are proposed:

- Isolation between transmitters and sensors should be improved for avoiding any electrical short circuit in between in contact with free water;
- Lifetime of batteries must be extended to respond to the needs of the monitoring time in the **DGR** context or to avoid any interrogation problems between the emitter and the receiver as observed in the SEALEX experiment.

5. Initiatives for the development of a qualification process

5.1. Introduction

This task aims at developing a protocol for selecting components potentially used in the repository monitoring system. It represents the first stage of the qualification process as the selected components should next undergo a series of laboratory and on-site tests to be considered qualified.

5.2. Methodology for selecting monitoring components

The selection must first consider the list of influence parameters which are DGR context and site specific. As for monitoring contexts in other fields the selection must include the following requirements:

- Verification of metrological characteristics and performances (compliance with environment requirements including lifetime, radiations levels, mechanical stress, thermal stress, humidity exposure, and storage duration…).
- Sensitivity to influence parameters (Temperature, Humidity, Stress, Strain, Corrosion under in situ conditions, Hydrogen,...).
- Verification of functional and ergonomic characteristics and design.
- Verification of compliance with current standards (safety, CE marking, **PAD**, approved at accredited labs...).
- Operation: input/output power, operating temperatures, wavelength, modulation, consumption, end of life, etc.
- Testing: evaluation and qualification plan, test methods, screening definition.
- Quality and Product Assurance: focus on reliability and traceability, define the customers' reviews as early as possible, the list of documents to be delivered, how the hardware is accepted for delivery, and criteria for batch rejection.
- Verification of the Technology Readiness Level (**TRL**).

The highest **TRL** value is preferred for each component. Only **TRL**'s above 7 could be parameter and **DGR** specific as discussed in the WP 3.1 of Modern2020.

5.3. Methods for testing and evaluating monitoring compound

This chapter aims at proposing a testing protocol to be applied to the selected components. Testing should be performed at the laboratory and on-site when possible as laboratory and field tests are essential and complementary. They are to be defined on a case-by-case basis, in proportion to the risks and challenges of the qualification.

It is recommended that laboratory tests be conducted prior to field testing. Indeed, in the case of a qualification among a panel of materials for example, laboratory tests can lead to detect relatively early materials that do not meet the requirements of the specifications and thus reduce the number of materials to test on site. However, these two types of tests can also be performed in parallel if necessary (time saving, planning constraints ...) and depending on the case (existing equipment on the market...). The realization of these tests requires upstream to:

1. Define the list of physical quantities to be tested in the laboratory as well as those to be tested on-site. It also requires defining the main influence parameters.
2. Define the list of functionalities to be tested: same as above but with respect to the functional aspect of the operator interface, the dialogue with the PC or the central datalogger, the associated software. Note that such functionalities could require joining part of the measuring chain as some compounds could not provide this kind of functionalities alone. For instance a VW sensor or any other passive one (FO) needs a reading device (another piece of the chain) to provide data.

3. List the tests to be carried out at off-site and at on-site laboratories and their numbers: ageing, humid atmosphere, influence of temperature, strain and stress (mechanical and chemical)
4. Select the off-site laboratories, preferentially accredited, that could perform the tests.
5. Establish the measurement ranges to be tested, the number of measurements to be made, the conditions of test with reference to the associated standards and propose a list of the norms of the domain.
6. Define a prioritization in the realization of tests (laboratory or on-site) in order to be able to dismiss as soon as possible material that would be subject to non-compliance.

5.3.1. Laboratory testing proposition

The laboratory tests must allow the equipment to be tested from a metrological and functional point of view in reproducible conditions and on extended measurement ranges (boundary conditions) in relation to the requirements set out in the specifications. The tests to be carried out by external laboratories are the subject of particular specifications. Among these specifications there is the assessment of the measurement uncertainty. This must take into account all the factors of influence of the result of the measurement from the five components of Manpower, Method, Means, Medium and Matter. Another important specification is the necessity to produce detailed test reports recalling the tests, test conditions, associated standards and test results for judging conformity or non-compliance.

As in Chapter 6 a test form was sent to partners with the goal of having their feedback from laboratory testing methodologies applied to the components selected according to the methodology proposed in chapter 7. Answers from the University of Mons, Andra, Amberg and VTT are detailed in Appendix 3 and can be split into two categories corresponding to the two following chapters:

- Tests of robustness and sensitivity to influence parameters (Temperature, Hygrometry, shock, vibration, Oxygen, Irradiation...),
- Ageing tests (Temperature, Radiations, Hydrogen...).

5.3.1.1. Robustness tests

Robustness is the degree to which a system or component can function correctly in the presence or stressful environmental conditions. Contrary to ageing tests, it is not intended to accelerate the normal degradation over the full time of use. They are a first stage of qualification to be done prior in situ testing.

As illustration of robustness tests, it may be mentioned a specific study to investigate the durability of the sensing cable embedded in concrete in a context close to that expected at **DGR** [13] that is under alkali chemical attack (solution at pH 13.5), thermal fatigue (20, 40, 60°C) and mechanical solicitations (compressive creep) as illustrated in

Figure 5-1.

Figure 5-1: Non irradiated robustness tests for a cable embedded in concrete at (left) 20, 40 or 60°C oven controlled temperature, (centre) alkaline solution tank at room temperature, (right) compressive creep bench and associated instrumentation

In this study, the immersion of the cable in an alkaline solution representative of the concrete medium has demonstrated a deterioration of the outer casing of the cable, the effect being amplified by temperature. This result led the manufacturer to the production of a new cable. For the cable embedded in concrete and under constant compression loading (creep), the strain profile measured along the optical fiber has oscillations, the period of which corresponds to the winding pitch of the fiber around the central core of the cable, and of increasing amplitude as a function of the ageing time.

A proposal of **robustness** test from VTT for the Nordic repository case is to develop a procedure to simulate long-term conditions in **EBS** environment. VTT proposes to test some selected measurement system components that are considered to be used for EBS monitoring (Appendix 3). **Robustness** tests are planned to be done in cycles so that it will give provisional results already during the test program. Test plan will consist of selected sensors and dummy sensors made to mimic the shape and having the same piping and tightness as the real ones and manufactured from different materials. Idea is to test sensor enclosure and sensor cable armouring/sheltering pipe with the dummy sensors.

A test would consist of 20 iterative steps as illustrated in Figure 5-2:

- Selected specimens will be exposed 1 month to salinity in neutral salt spray chamber that is expected to simulate 5 years exposure.
- Specimens will be exposed to 15-20MPa pressure that is consider to be hydrostatic pressure 500m below sea-level (5MPa) + swelling pressure of saturated bentonite (10-20MPa). The pressure is applied in a pressure chamber being equipped with heating elements and heated to a temperature of 85°C that simulates temperature close to canister.

The test plan is concentrated only on wired sensors that have proven their functionality in POPLU test. Tests are planned to be done mainly with dummy sensors with temperature and leakage detection. Sensor housing's and piping are made from three different alloys: stainless steel 316L, titanium Gr2, Inconel 600. Metallic pipe connections made from same materials are used in the tests to exclude galvanic corrosion. O-ring pipe connections are also tested with dummy sensors from three different polymers: **IIR**, **FPM** and **CSM**. After each salt spray test iteration each test sample is dried and weighted for mass loss and photographed for visual inspection.

After weighing and visual inspection starts the pressure phase where the sensor or dummy is attached to a hydraulic accumulator filled with water. The accumulator is heated outside to 85°C and decreased by 3.5°C per iteration. Temperature decrease is simulating heat flux change within 100 years. Pressure is raised to 15-20MPa inside accumulator gradually during a day. Sensor is detached from accumulator after 5 steps and detected if any leakage or visual changes have occurred to housing, piping connection or o-rings. These steps will be repeated to reach 20 iterations and then all connections and sensors will be opened and inspected from inside to make final conclusions. These cyclic corrosive and pressure tests in elevated temperature would provide some insights how well sensors made from different materials and joints would survive in harsh repository conditions during operational phase.

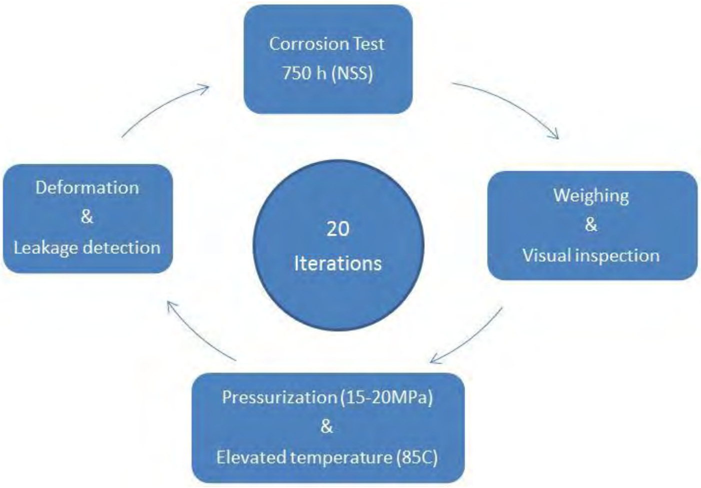

Figure 5-2: Cyclic robustness test concept diagram

This concept of cyclic robustness test developed for the Scandinavian context must be extended to other repository contexts such as those envisaged in clay host rocks in Western Europe.

5.3.1.2. Ageing tests

Ageing is a testing process to accelerate artificially the normal degradation of a monitoring component (**MC**) with time of use. The process may be artificially accelerated with Temperature, Radiation, Chemistry, Humidity, Strain... It is meant to be representative for **DGR** service conditions, but with higher intensity of stresses, in order to reduce the duration of experiments. Goals in ageing tests are therefore different as function of the repository context (see Chapter 2) and of available laboratories.

Some examples of ageing tests performed in the framework of the Modern 2020 especially developed in the different contexts of **DGR**s are reported in **Appendix 3**.

A special attention was paid on components for which impact of influence parameters (gamma hydrogen, temperature displacement …) was not enough document at the time of Modern2020 application and for which testing was done as first assessment of their **TRL** as in

Table 5-1.

Table 5-1: Sensors selected for ageing tests - Framed in light blue for those developed in Modern2020

	Sensor	Environment/monitoring context	Measurement type
Andra 1	Doped silica fibers designed to be radiation-hard (F, Ge)	Radiation + Temperature (80/100/120) / French	Strain and Temperature - Distributed Rayleigh and Brillouin, RIA
Andra 2	Doped silica fibers designed to be radiation-sensitive (Al, GeP …)		Radiation measurement
Andra 3	Brugg V9-IXblue sensing cable	Radiation + T measured / French	Strain and Temperature - Distributed Rayleigh and Brillouin

Mons1/2/3	Functionalised Silica sensor, **PMMA FBG** and **CYTOP FBG**	Radiation + H_2 with Controlled: T, Humidity, / Belgian	Various (H_2...) - H_2 was planned but was not done for security reason
CEN 1/2/3	mINT photonic chip	Radiation + H_2 + Controlled: T, H / Belgian	Various (H_2...)
CEN 4/5/6	Optical fibres	Radiation + H_2 + Controlled: T, H / Belgian	Temperature and Strain

1) Ageing test goals

Andra, has chosen as a testing to consider Optical Fiber Sensors (**OFS**) to obtain distributed measurements over the entire structure instead of being limited to local data through the use of traditional sensors whose utilization could be limited to redundancy purpose or to localized acquisition in case of bad OF testing results. The ageing tests aimed at evaluating possible coupled influence of temperature and gamma rays on Brillouin and Rayleigh scattering properties in silica optical fibers, envisioned for mechanical and temperature sensing in underground repositories. This was performed on a “radiation hard” fiber, based on F-dopants.

A reference Ge-doped optical fiber was collocated to enhance performances of the optical fiber designed within the MODERN2020 project. Another goal was to evaluate whether the strain transfer function of optical fiber strain sensing cables (=the function that links the concrete host material to the optical fiber core through the coatings and sheaths of the cable) might change after gamma exposure.

UMONS also considered performing ageing tests on optical fibers (silica and polymer) by studying the shift in the Bragg wavelength of **FBG**s inscribed in various fibers, by qualifying the stability of hydrogen layer for transport and irradiation. For all tests performed by UMONS, the following guidelines have been applied:

- Fibers are installed in an oven for temperature control, immersed into a pool and irradiated with a known and characterized source of gamma radiation.
- Interrogators are shielded 15 metres away from the pool and linked via waterproof cable to a container with the oven inside.
- Thermocouples are placed inside the container and the output logged in real time.
- Fibers are irradiated using ’RITA’ at SCK-CEN with specific doses attribuable to given fiber placement heights.
- Tests were designed to attain a total dose of 10 kGy and 100 kGy.

Samples were prepared by UMONS as described in the following list:

- Silica **FBG**s: uniform **FBG**s are inscribed at UMONS in different types of silica fibers, with different inscription lasers (continuous, femtosecond pulses, wavelength, ...) and with two different techniques (phase mask and Lloyd mirror interferometry).
- Hygrogen sensors: A Pt/WO_3 layer was deposited on two photosensitive fiber FBGs (PS1250), three standard fiber **FBG**s (SM28) and three pure silica **FBG**s (SM1500). For each fiber, two **FBG**s were present at a suitable distance. The chemical layer was produced at UMONS and deposited on a single **FBG**s in each fiber so as to allow a reference FBGs in each case, thus abstracting **FBG**s effects from those of the chemical deposition during the campaign.
- Microstructured **PMMA FBG**s (**m-POF-PMMA**): fibers were fabricated from raw materials at Denmark Technical University and **FBG**s were inscribed at UMONS using a HeCd laser and the phase mask inscription method. The samples were connectorized using the UV curing method.
- Step-index **PMMA FBG**s (**SI-POF**-PMMA): PMMA fibers were fabricated from raw materials at the Polytechnic University of Hong Kong and FBGs inscribed at UMONS using a HeCd laser and the phase mask inscription method. The samples were connectorized using the UV curing method.
- CYTOP **FBG**s: (**POF-CYTOP**) uniform **FBG**s are inscribed at Cyprus University of Technology using the point by point method. Connectorization of the CYTOP fibers is challenging and for

the first campaign, was carried out on site at SCK-CEN to avoid stability concerns. By the second campaign, the process was carried out at UMONS.

The monitoring components selected (

Table 5-1) have undergone a series of irradiation tests at two different locations (IRMA at the IRSN facility, Saclay - France; RITA at CEN-SCK facility, Mol, Belgium). A full information about the laboratory conditions and of the first results are given in the [Modern2020 milestone MS38].

Irradiation tests were performed in October 2017 and February 2018 at RITA/CEN and in November 2017 at IRMA/IRSN for γ-irradiations with dose rates at 0.41-0.66 kGy/h and 3 kGy/h, respectively. Tests lasted between one and two weeks for most expected components to reach the target of TID <10-100 kGy at RITA and of TID = 1 MGy at IRMA (Appendix 4). [Modern2020 milestone MS41].

2) Ageing tests main results

Main results are reported on individual forms in **Appendix 3** and can be summarized per partner involved as follows:

For Andra, this work has yielded very positive results in view of the integration of OFS in nuclear facilities such as deep geological repository for nuclear waste. Andra is confident distributed strain sensing based on optical fibers is possible for decades despite harsh conditions.

Coupled effects of temperature and radiation improve the sensing performances of strain distributed sensors exploiting the Stimulated Brillouin Scattering in Ge-doped and F-doped single-mode fibers. At 80 °C, 100 °C and 120 °C, compared to room temperature, the radiation induced attenuation is significantly reduced. However, the Brillouin frequency shift is not modified by coupled temperature influence, as it remains in the order of 4 MHz at 1 MGy (air) for the Ge-doped fiber and only 2MHz with the developed F-doped fiber, which approximately corresponds to 40µm/m maximal error in strain measurement.

Rayleigh scattering has proved to be a very promising solution for strain sensing. It is even less affected by radiation than Brillouin scattering. With the custom fiber based on F-dopants instead of Ge-dopants, the influence of radiation on Rayleigh frequency shifts is as small as -4GHz, or 2.5µm/m error, whatever the working temperature (80, 100 or 120°C). The influence of temperature is fully novel and should probably be published rapidly.

Further work is required to finalize data analysis, for all measurements acquired during the experimental campaign organized at IRMA facility (IRSN partner). Radiation Inducted Attenuation will be precisely quantified hence maximal distance range of distributed measurements will be determined.

The main difficulty is the degradation of carbon-coating hydrogen-hermiticity after 10 MGy dose. We must reproduce the test with the optical fiber we have developed within the project (the preliminary test was performed on a commercial fiber) and after several gamma doses.

Finally, Andra will evaluate the coupled impact of temperature and radiation on the external optical fiber coating (the sensing cable), whose influence might be important too for accurate strain sensing. Remaining perspective is to evaluate if sensing cable performances are similar with naked fiber ones. There remain to perform:

- Optical losses evaluation to quantify whether the encabling process has degraded the optical fiber performances
- Rayleigh and Brillouin strain sensitivities measurements will be measured and compared, on the fiber alone and the sensing cable (the fiber in the external sheath)

During Modern2020, Andra has also evaluated the ability to obtain distributed radiation sensing thanks to sensitive optical fibers. Three singlemode optical fibers were selected for their varied sensitivities towards radiation. Al-doped sample is clearly the most radiation-sensitive: it could provide distributed measurement until a dose of 470 Gy. Then the GeP-doped fiber should be favoured. It worked until 4 kGy. The Ge-doped could be measured till the end of the irradiation, despite lower sensitivity. The optical fiber lengths and the working wavelength are two other parameters to adjust to the application.

However, while obtaining these calibration curves, the strong dependence of curing effect and coupled temperature and radiation influences was demonstrated. As a consequence, this work must be reproduced taking into consideration many more parameters. We cannot conclude yet on the best solution for underground repository monitoring. TRL remains at 3.

For UMONS, the major findings for silica-based fibers and polymer optical fibers are that:

- Pure silica fibers (SM1500) are radiation resistant and there is no significant difference on the inscription laser wavelength used.
- Standard singlemode fiber (SM28) are radiation sensitive but FBGs written at a wavelength of 193 nm are less impacted. Writing wavelengths of 244 nm and 266 nm have the same effect.
- Photosensitive fibers (PS1250) are the most radiation sensitive. FBGs written at a wavelength of 193 nm and 244 nm have the same behaviour whereas the radiation sensitivity is the highest for the writing wavelength of 266 nm.
- For **SI-POF-PMMA** FBGs, after an initial transient (that lasts until 20h), the Bragg wavelength shifts linearly towards shorter wavelength at an approximate rate of −4.6 pm/kGy.
- For **m-POF-PMMA**, after an initial transient (that lasts until 20h), the Bragg wavelength shifts nonlinearly towards shorter wavelength but the radiation sensitivity is higher for the femtosecond laser writing technology (around −9.8 pm/kGy) than for HeCd writing technology (around −7.0 pm/kGy).
- **CYTOP-FBG**s present a complex behaviour with an approximate shift of -32.5 pm/kGy.
- Hydrogen sensors did not resist the test. After inspection, it appears that the main problem is the Pt/WO_3 layer stability. Layer adherence should be greatly improved.

The full results will be reported in the MS37 Internal Document.

5.4. On-field tests

They allow testing equipment metrologically and functionally under real conditions of use. In the case of a qualification of equipment to be integrated into an existing measuring system, the on-site tests contribute to the qualification of the complete measurement chain (from the sensor to the Information System through the acquisition and the transmission). For the moment, only demonstrators in underground or long-term experiments at on-site/off-site laboratories can serve as dummy or reference-on-site tests as no geological disposal exists to date. However, monitoring strategies like that proposed by Andra also suggests using some “sacrificial”, “surveillance” or “witness” structure exhaustively equipped to fulfil the monitoring goals at the future repository. Besides, other concepts incorporate a representative storage area, using real waste, fully monitored to serve as demonstration of the expected evolution of the repository, which will be dismantled long time after and that will provide insight on the performance of the monitoring components too.

To compensate this lack of real on-site test at present-day, Amberg proposes in its test form (Appendix 2) to reproduce stresses to cables and transducers such as those retrieved from FEBEX in-situ (18 years of operation for Vibrating wire transducers from geokon: pore pressure, total pressure & displacement Thermocouples type T) and determine how effective the procedure is. In other words the idea is to compare the results gathered by the ageing-tests for some monitoring components retrieved from long duration experiments as FEBEX or Prototype Repository, with those observed after dismantling the tests in order to evaluate how representative the ageing test are and to “calibrate” the degree of ageing that the tests could impose.

6. Conclusions

This document dedicated to the reliability and qualification of monitoring components for a **DGR** led to the conclusions that:

- Each country is asked to develop its own project that will necessarily require the development of a different monitoring system and equipment. For this reason, the proposal of a generalized qualification process must overwhelm differences between projects and focus on the essential.
- There is a strong synergy with respect to the monitoring components between energy and space fields with needs for a **DGR** facility such as robustness, long-life power supply, and optimization of communications. The qualification process of those different fields always consider at least three stages including i) Selection of components, ii) The laboratory qualification and iii) On-site qualification.
- Despite a strict selection of the best technical solution of the moment, in situ and long-term experiments performed at **URL**s or at large mock-ups suggest improvements that can only be checked in situ where conditions will be as close as possible of the real one at **DGR**s.
- The Initiatives for the development of a generalized qualification procedure must combine robustness, ageing and on-field tests.

This enables the different partners involved in this project to propose the following guideline.

6.1. Guidelines to elaborate a qualification process for monitoring component in the context of monitoring geological disposal

Those guidelines are the result of previous chapters and proposes a common (agreed by **WMO**s) multi-stage qualification methodology applicable to each component of the monitoring system. The qualification process of monitoring components can be summarized by the global sketch given in Figure 6-1. This global sketch denotes an increasing complexity that may require a retrofit process in case of dissatisfaction of one of the three/four major steps.

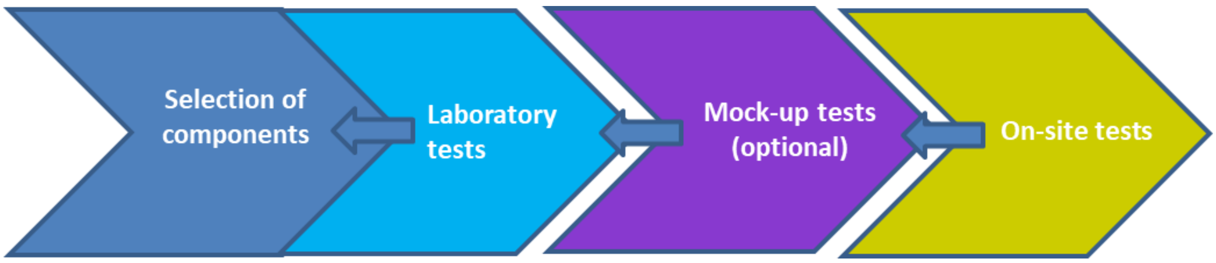

Figure 6-1: Global sketch for the qualification of monitoring components in **DGR**s

The first step concerns the selection of components (sensors, cables, housing, **DAS** etc.). It can be described as a desk exercise with lots of input from the manufacturers and from earlier tests for measuring influence parameters (Physical quantities and functionalities to be tested) very often performed at accredited laboratories. This selection first require preliminary steps such as: i) to set up the list of metrological and functional requirements in relation to the process to be measured, ii) to list influence factors and environmental constraints, iii) to perform a technological watch about devices and influence factors. The different steps linked to the selection of components are:

- ✓ Selection of components with the highest **TRL** (such as recommended in D31 of Modern220 task3 and rejection of components that do not fit the expected TRL value) and, if available, reliability features (**MTTF** of critical components).
- ✓ Verification of metrological characteristics (compliance with requirements).
- ✓ Sensitivity to influence parameters (Temperature, Humidity, Radiation, Stress, Strain, …).
- ✓ Verification of functional and ergonomic characteristics.
- ✓ Verification of compliance with current standards (safety, CE marking ...).

The second step is that of Laboratory Tests of the selected monitoring components. Its concerns testing of components/combined components under adverse conditions. This second step implies first to identify the devices (manufacturing date, software version, etc.) after verification of main functional and ergonomic characteristics and verification of compliance with current standards (safety, CE marking ...). Those tests are preferentially carried out in accredited/certified laboratories (need to develop new testing benches, independent control). Each test must be achieved by a report detailing the protocols and main results with estimates of parameters uncertainty, and main conclusions about strength and weaknesses of the component. They include the succession of three kinds of steps:

- ✓ 1) Tests of robustness (Temperature, Hygrometry, Elongation, Crash….). They first include a calibration and verification of compliance with the target of use (nominal / degraded measurement range, maximal errors in the nominal measurement range, sensitivity, linearity, hysteresis) in controlled environment (no influence factor, no extra operational constraint). Next they must provide a detailed analysis of the influence of prominent parameters like temperature, humidity, radiation, stress, strain… and checking of the insignificancy of second order parameters like vibration for instance. They must provide the overall uncertainty based on testing reports.
- ✓ 2) Ageing tests under single then coupled influence parameters (γ Radiation, Temperature, Humidity, Salinity, O_2, H_2, H_2S, high pH, strain, deformation…). Those tests aims at accelerating artificially the normal degradation of a monitoring component (MC) with time of use. It is meant to be representative for DGR service conditions, but with higher intensity of stresses, in order to reduce the duration of experiments.
- ✓ 3) Communication tests for a multitude of monitoring components in cybersafe conditions as close as possible of that of the future DGR.

The third step concerns testing on-site meaning testing of the whole system under realistic conditions. It is done targeted to assess the whole system under realistic conditions. It can also be part of the safety demonstrations. Tests have to be performed under real conditions of use, and to qualify the complete measurement chain (sensor, connecting cable and/or wireless system/controller) including all the improvements identified earlier. To reach this goal several additional steps are required:

- ✓ Choice of real reference structures to be instrumented with the sensing solution: the structure should be enough representative of the final structure or similar to it. Is should not have any specifics which could disturb the qualification procedure (example: seasonal opening of cracks, alkali aggregate reaction in the concrete). As far as known, the best reference structures can be found in current long-term experiments at URLs and in dismantled long-term experiments. Direct experiments at the future Repository could also be considered (when possible)
- ✓ List of setup and commissioning requirements on site.
- ✓ Choice of an already qualified sensor system which allows to demonstrate that the new measurement chain meet its requirements on the field (intercomparison metrology).
- ✓ Comparison of responses coherence based on main metrological features (intercomparison exercises).
- ✓ Follow-up of ageing clues of the sensing chain.
- ✓ Validation of the communication devices.

- ✓ Periodic synthesis about metrological discrepancies, unidentified influence factors, operational constraints and clues about ageing (back to step 2 or 1 depending on the complexity).

At last, previous to on-site tests, **an optional step based on mock-up tests** may be considered if there is a need such as in the Vercors mock-up realized for a more realistic use of components.

By following the described methodology for all components, a much improved result in the selection process would be expected. The best way to articulate this methodology could be filling up a template similar to that utilized in the space industry (Figure 3-2) and presented next.

6.2. ADOC - Approval DOCument for a monitoring component qualification

Project:	**Doc n°:**
Prepared by:	**Date:**
Approval requested by:	
Family:	**Component:**
Technology Detail specification:	

Approval status:

Evaluation programme required:	☐ Yes	☒ Not

Selection of components

TRL:	Fit the D31requirements :	☐ Ok	☐ Not Ok
Influence parameters with measurement range and sensitivity:			
Sensitivity to influence parameters		☐ Ok	☐ Not Ok
Verification functional and ergonomic characteristics		☐ Ok	☐ Not Ok
Verification of metrological characteristics		☐ Ok	☐ Not Ok
Verification of compliance with current standards		☐ Ok	☐ Not Ok
Requirement for additional tests (in case not ok)		☐ Yes	☐ No
If yes, test required Lab – Robustness		☐ Yes	☐ No
Lab – Robustness tests		☐ Yes	☐ No
Lab – Ageing tests		☐ Yes	☐ No
Mock-up tests		☐ Yes	☐ No
In situ – Long-term		☐ Yes	☐ No
In situ – demonstration		☐ Yes	☐ No

Laboratory test (testing of components/combined components under adverse conditions)

1. Robustness tests:	☐ Yes	☐ No
Laboratory name:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	
2. Ageing tests	☐ Yes	☐ No
Laboratory name:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	
3. Communication tests	☐ Yes	☐ No
Laboratory name:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	

On-site test (testing of the whole components under real conditions) or off-site at large mock-up (optional)

1. Tests at URLS / offsite at large mock-up	☐ Yes	☐ No
URL/Mockup:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	
2. Test at DGR witness structure/cells	☐ Yes	☐ No
DGR:	Certification/accreditation number:	
Detailed Specifications: (type of test, steps, iterations…):		
Reporting: Number	Date	
Results: ☐ Ok	☐ Not Ok	

7. References

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[2] Andra, “1419-Q1 v1 Modern2020 WP2 Questionnaire-V2, available on ProjectPlace”.

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8. Appendices

8.1. Appendix 1: Part Approval Document for qualifying components in the Space field

PROJECT:................ Doc n°:.................... Prepared by: ....
Issue:...................... Date:....................

Approval requested by:...............................
Family:.................... Fcode [ ] Group:................. Gcode [ ]
Component Number:...
Commercial Equivalent Designation:.....................
Manufacturer/ Country:.................................
Technology/Characteristics (value or range of values with tolerance, voltage, package etc): ....
Pure tin free (Y/N) [ ]
Generic specification:.....................
Detail specification:........................ Issue:..... Rev.:..... variant:.......
Specification amendment: .... Issue:..... Rev.:..... variant:.......
Quality level:.......................... Procurement by:..............................

APPROVAL STATUS

EPPL Part 1/2 listed (1/2/N) [ ]
ESCC QPL or EQML listed. (Y/N) [ ]
MIL QPL or QML listed (Y/N) [ ] If yes: QPL/QML Reference:...............................
Other approvals/former usage ....
Evaluation programme required (Y/N) [ ]
If yes reference of the Evaluation Programme:..............................

PROCUREMENT INSPECTIONS and TESTS

Precap (Y/N) [ ]
Lot acceptance:
ESCC LAT/LVT level or subgroup [ ]
MIL QCI/TCI group [ ]
Buy-off (Y/N) [ ]
DPA (Y/N) [ ] if yes: sample size ....

Complementary tests ....

RADIATION HARDNESS DATA

Radiation Hardness Assurance Plan applicable (Y/N)[ ]
Doc. Ref.: ....

Total Dose Effects:
Evaluation Test Data (report) reference: ....

Single Event Effects: SEL/SEU/SET/SEFI/SEB/SEGR/others: *(cross out when non applicable)*
Evaluation Test Data (report) reference: ....

RVT required (Y/N)[ ]

REMARKS

Approval customer .... Date ....

Approval first-level supplier .... Date ....

8.2. Appendix 2: Experiment test forms

Receive: 11/01/2018

Experiment Test Form – Monitoring components check-up [FEBEX “in-situ”/GTS URL]

To get the feedback on the components of the monitoring systems that worked under similar conditions

Type:

☒ Long-term ☐ Demonstrator Dismantled: Yes ☒ No ☐ On-going: Yes ☐ No ☒

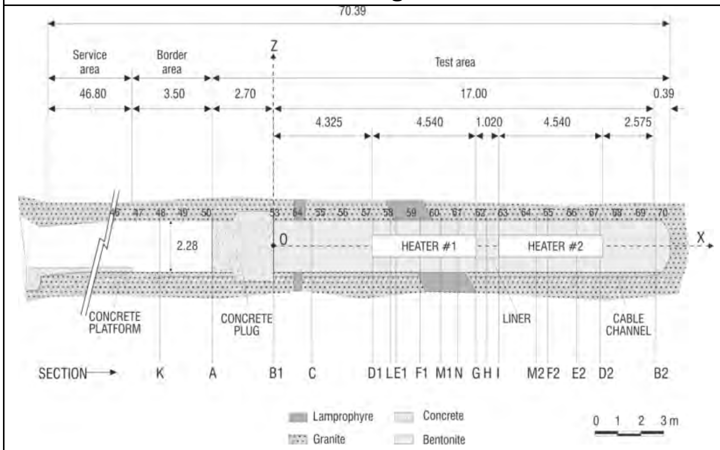
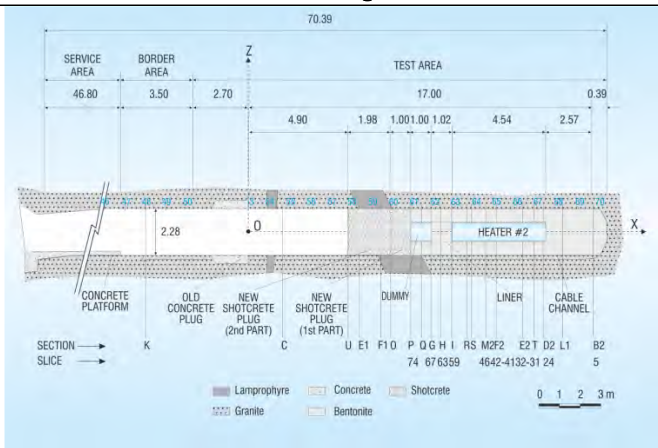
Goals:

To study the behavior of near-field components in a repository for high-level radioactive waste in granite formations:

- Demonstration of the feasibility of handling and constructing an engineered barriers system
- Study of the thermo-hydro-mechanical (THM) processes in the near field
- Study of the thermo-hydro-geochemical(THG) processes in the near field

Means:

Two electrical heaters were placed in a horizontal drift excavated in the granodiorite of the Grimsel Test Site in Switzerland, and surrounded by a barrier made of highly compacted bentonite blocks (FEBEX bentonite or Serrata type). A total of 632 monitoring instruments or sensors were installed to track the most essential THM parameters: total pressure cells, pore pressure sensors, thermocouples, displacement sensors, moisture sensors of different types (capacitive, psychrometric and TDR) and others (FEBEX I, see figure below at the left). After 5 years of operation, a partial dismantling of the in-situ test was carried out in 2002. The operation comprised the demolition of the recess-concrete plug, the removal of the buffer up to the first heater (except the last meter) including 164 sensors, the heater#1, the installation of 47 new sensors and the sealing with a new shotcrete plug (FEBEX II, see figure below at the right). All time a constant temperature of 100 °C was maintained at the heater-bentonite interface, while the bentonite buffer was slowly hydrating with the natural ground water inflow from the rock. After more than 18 years of heating under repository-like conditions, the final dismantling was conducted. The main purpose of the final dismantling was to investigate the state of the components such as heater, bentonite and rock, as well as to inspect conditions of the sensors to evaluate the reliability of the data generated to compare with modelling results.

FEBEX I configuration	FEBEX II configuration
	

Receive: 11/01/2018

Main results: Behaviour of the monitoring components since installation

<table>
<tr><td>Sensor type</td><td>Total number (Wired/Wireless)</td><td rowspan="2">
<table>
<tr><th>Type</th><th>Total No.</th><th>Out of order</th><th>Saturated</th><th>Flooded</th><th>Mechanical</th><th>Cable</th></tr>
<tr><td>S Plug</td><td>4</td><td>0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>P Kulite</td><td>2</td><td>2</td><td></td><td>2</td><td></td><td></td></tr>
<tr><td>WC Vaisala</td><td>3</td><td>3</td><td></td><td></td><td></td><td>3</td></tr>
<tr><td>3S</td><td>3</td><td>3</td><td></td><td>3</td><td></td><td></td></tr>
<tr><td>WT</td><td>10</td><td>1</td><td></td><td></td><td></td><td>1</td></tr>
<tr><td>WC Rotronic</td><td>31</td><td>31</td><td>20</td><td>11</td><td></td><td></td></tr>
<tr><td>WP</td><td>24</td><td>19</td><td>8</td><td></td><td></td><td>11</td></tr>
<tr><td>P Geokon</td><td>6</td><td>3</td><td></td><td></td><td>3</td><td></td></tr>
<tr><td>SH Geokon</td><td>7</td><td>6</td><td></td><td></td><td>6</td><td></td></tr>
<tr><td>SB Geokon</td><td>4</td><td>3</td><td></td><td></td><td>3</td><td></td></tr>
<tr><td>Q Geokon</td><td>28</td><td>23</td><td></td><td></td><td></td><td>23</td></tr>
<tr><td>T</td><td>54</td><td>14</td><td></td><td></td><td>14</td><td></td></tr>
<tr><td>Total</td><td>176</td><td>108</td><td>28</td><td>16</td><td>26</td><td>38</td></tr>
</table>
</td></tr>
<tr><td>☒ Total stress or swelling pressure (P)
☒ Pore pressure (Q)
☒ Moisture (WC, WT or WP)
☒ Displacement (S, SH or SB)
☒ Temperature (T)
☒ Crackmeter (3S)</td><td>See table, all of them were wired ones.</td></tr>
</table>

Main results: Failure origin and suggested improvements

Sensors	Failure origin (If any)	Possible improvements
T type thermocouples	The performance was excellent except for those damaged by corrosion, up to 72% survived. The accuracy of the still operative ones had not varied from the installation time (below ±1 ºC) showing errors below 5.3%	Use of Titanium instead SS316L or similar steels alloys.
Capacitive type moisture sensors	They stayed functional for a duration which was way longer than what was initially expected operative lifetime (6 months). 12 out of 31 units lasted for more than five years and one was operative until 2005 (almost nine years). Their readings were accurate and, given their wide range, the data obtained from them are very useful for tracking the bentonite buffer hydration process that started from low initial water content and it was sufficiently slow.	No need of extending their operation after reaching the saturation of the measuring chamber.
Psychrometric type moisture sensors	They prove to be very fragile for the bentonite buffer environment with the arrangement used (commercial), only 5 out of 24 remained operative, but resulted damaged during dismantling. They also seemed to be highly sensitive to contamination by salt (laboratory results for surviving ones) but data recorded from those installed in the outer buffer ring seemed to be sufficiently accurate and they matched with the capacitive ones.	Use of reinforced body and better cable. Use of a different measuring method, dew point instead psychrometric. Do not use low TRL sensors.
TDRs	They performed well under the harsh environment (combination of temperature, stress, high moisture and salt precipitation), 7 out of 10 remained operative and provided consistent data after a re-scaling.	Avoid blocks junctions, use of better plastics, improve cable-sensor connections, avoid cable stress due to bentonite swelling. Do not use low TRL sensors.
Total pressure cells (Vibrating Wire)	Their behavior was good and the only difficulty resulted from the weakness of the embedded thermistor that failed in some cases, half of them failed during operation. Malfunction was also caused by the cable(s) that was most likely damaged during	Use of better thermistors and plastics for the cable. Improve cable-sensor connections and avoid cable stress due to bentonite swelling.

	operation.	
Pore pressure sensors (Vibrating Wire)	Overall, these sensors provided, very low pressure readings, showing positive values only at the most humid parts located at the outer part of the buffer. They were the best surviving ones, although 11 out of 28 showed problems during operation, usually due to damages in the cable and thus 22 units were well functioning in the laboratory.	Use of better thermistors and plastics for the cable. Improve cable-sensor connections and avoid cable stress due to bentonite swelling.
Displacement sensors (Vibrating Wire)	Only 2 out of 11 remained operative and all the recovered sensors showed damages due to corrosion in the anchoring pieces only. The tube of the sensors was bent in several cases that hindered the precise measurement of the displacement. The confidence on the readings obtained from these sensors was poor.	Use of better thermistors and plastics for the cable. Improve cable-sensor connections and avoid cable stress due to bentonite swelling. Avoid blocks junctions.
Crackmeter (prototype)	It failed quite soon due to a complete flooding and the damage of the associated electronics.	Do not use low TRL sensors.

Main feedback (even partial):

The performance of the installed sensors turned out satisfactory and significantly better than initially expected. Most of them kept providing reliable and valuable information about the THM parameters for more than 18 years.
Furthermore, a significant amount of information was obtained regarding the real status of the sensors after more than 18 years of “in-situ” operation, in conditions similar to those of a HLW repository except for radiation. The inspection of the sensor status yielded some recommendations for improvements for future experiments and monitoring programs.
The use of high TRL sensors using passive measuring methods (as the vibrating wire technique) demonstrated to be the best choice. The failure rate for the low TRL sensors could be minimized for future applications by improving the mechanical protection, using corrosion resistant metals and avoiding weak plastic parts.
The cables, if not avoided (i.e. by using wireless devices), should be armorer, built with long lasting materials and routed to provide flexibility when pulled due to bentonite swelling/movements appear.
The sensor bodies shouldn’t be too long and the joints between the bentonite blocks/layers should be avoided as much as possible to minimise mechanical deformations largely resulting from shearing, which could lead to fatal damages on the sensors’ functionality.
The checking and re-scaling of the survived sensors indicated that the accuracy of the data generated by these sensors remained rather unchanged, they showed negligible or very low drift for most of them (not for all parameters) , and that the obtained data were trustworthy.

Additional comments

Only the sensors installed in the bentonite buffer were properly studied.

Requester’s signature:

Date: (11/01/2018)

Receive: 11/01/2018

Main references:

Huertas F. (ENRESA) 2000: FEBEX full-scale engineered barriers experiment for a deep geological repository for high level radioactive waste in crystalline host rock FINAL REPORT. ENRESA, Technical Report 1/2000.
Huertas F. (ENRESA) 2006: FEBEX full-scale engineered barriers experiment for a deep geological repository for high level radioactive waste in crystalline host rock. Updated Final Report 1994-2004. ENRESA, Technical Report 05-0/2006.
García-Siñeriz, J-L. et al. 2006 FEBEX II Project. Post-mortem Analysis: Instruments. . ENRESA, Technical Report 05-4/2006.
Rey, M.et all. 2016. FEBEX-DP: Post-mortem analysis: Sensors. Nagra Arbeitsbereicht NAB16-20. Wettingen, 122 pp

Glossary:

FEBEX: Full-scale Engineered Barrier Experiment in Crystalline Host Rock; GTS: Grimsel Test Site; HLW: High Level waste; SS: Stainless Steel; TDR: Time Domain Reflectometry; TRL: Technological Readiness Level; URL: Underground Research Laboratory;

Receive: 10/04/2018

Experiment Test Form – Monitoring components check-up [“GCR”/ CMHM URL]

To get the feedback on the components of the monitoring systems that worked under similar conditions

Type:

☐ Long-term ☒ Demonstrator Dismantled: Yes ☐ No ☐ On-going: Yes ☒ No ☐

Goals:

In the framework of the ORS* experiment, a specific monitoring section was implemented inside a circular cross-section of about 3.6 m length with 4.30 m in diameter, which aims to be representative of the monitoring system for IL-LLW cells. The monitoring system has been implemented with the following goals:

- Test implementation procedures for sensors, particularly for innovative technologies
- In-situ test of different complementary sensor technologies for the THM characterization
- Obtain representative feedback on durability and robustness of sensors technologies
- Test field calibration of temperature device in order to obtain traceable measurements

Means:

In order to experiment and qualify components of this strategy, a demonstrator of a potential monitoring system, implemented in a segment of 3.6m of an excavated gallery, has been performed in 2011 in the Andra's Underground Research Laboratory (URL) sited at Bure in the Meuse/ Hate Marne district (France). This segment consists of a concrete liner that supports the rock convergences at -490 m under the surface. A major goal of this demonstrator is to verify the mechanical phenomenology (e.g. foreseen rock strain or displacement surrounding the support) but also the pertinence of the association of sensors used for the thermo-hydro-mechanical monitoring.

In the Andra’s URL at -490 m under the surface inside the clay rock, according to the major horizontal stress field, the GCR* gallery, about 65 m length, was excavated between 2010 to 2011 using a tunneling machine with a road header. This gallery has a large excavated diameter about 5.40 m covered by shotcrete liner, 20 cm thick, immediately after excavation. It aims to retain the elements in the rock's support systems in the medium and long term on THM behaviors and more particularly on the EDZ extension. Six months after, a concrete ring, poured in situ, was built with three types of liner, 30 cm of thickness each, and performed 3 types of support made by stiff concrete type C60 (60 MPa at 28 days) followed by a C40, with compressible shims both (cf. Figure 1), while the last section was made by C60 without compressible shims. Three supports in order to see the loading impact on each supporting type.

A specific section of the GCR gallery was dedicated as a monitoring demonstrator. This section contains 123 punctual sensors and 11 distributed optical fibers sensors (OFS), providing THM measurements every 30 minutes (5 or 10 minutes in the first months). The sensors were installed in order to provide, for some of the monitoring parameters, punctual and distributed technologies for redundancy. The punctual sensors installed were (Table1):

Distributed strain and temperature measurements provided by OFS cable were installed. Two different types of OFS for strains and temperatures were installed and one only for temperatures, in order to assess installation protocol, robustness and metrological performances. For that, temperatures were measured by Raman scattering in multimode OFS and compared to platinum probes (Pt100, Pt1000). Similarly, strains were obtained by distributed Brillouin scattering within monomode OFS, and compared to VWE sensors.

Receive: 10/04/2018

Table 1: Measurement and sensors installed

Type of measurement	Sensor type	Model	Monitoring objective
Strain	Vibrating Wire Extensometer (VWE):	SG1 (géo-instrumentation)	measure strain in the concrete liner
Water content	Time Domain Reflectometry (TDR):	HydraPter (Cementys)	measure volumetric water into the concrete liner
pressure of groundwater	Pore Water Pressure (PWP):	EP1 (Géo-instrumentation)	measure pore water pressure into the rock near field
Total Pressure	Total pressure (TP)	NAT 7.5 MPa (Geokon)	Measure total pressure at the interface rock - shotcrete
Convergences	Extensometer Multi-points Single-rod (EMS)	Inductive (Geokon)	Measure the radial displacements of the rock into the borehole
Temperatures	Platinum probes and thermistors	TC, Solexperts, géo-instrumentation	Remove thermal effects on strain or pore water pressure measurements

Gallery construction steps

Figure 1: GCR gallery concept (1), beams & bolts (2) and the entire gallery after excavation and projection of shotcrete (3) & with concrete liner and slabe(4)

Design of the monitoring section

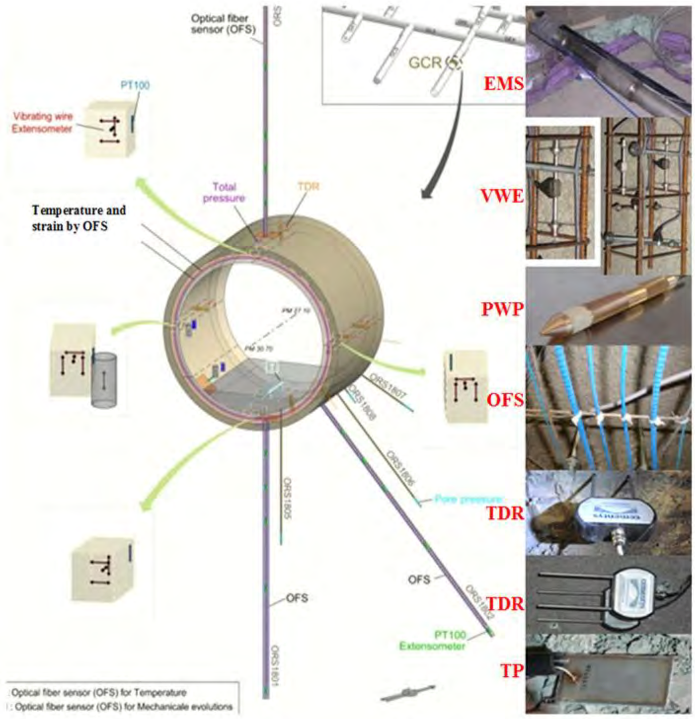


Figure 2: Sensors' location in the monitoring section test (demonstrator)

Receive: 10/04/2018

Main results

Table 2: Behaviour of the monitoring components since installation

Sensor type	Total number (Wired/ Wireless)
See table 1	See table, all of them were wired ones.

Type	Total Installed	Total Failed	Argilite media Installed	Argilite media Failed	Shotcrete Installed	Shotcrete Failed	Concrete liner Installed	Concrete liner Failed	Concrete apron Installed	Concrete apron Failed	Concrete samples Installed	Concrete samples Failed	Concrete samples in gallery Installed	Concrete samples in gallery Failed
FO	7	2	3				1		1		2	2		
PT100	24	0	4		3		5		12					
PT1000	18	1	18	1										
VWE thermistor	22	1					16				2		4	1
TDR	14	0	6				8							
PWP	5	0	4				1							
EMS	15	0	15											
TP	3	1			3	1								
VWE	22	1					16				2		4	1
FO brillouin	4	3					2	1			2	2		
Total sensors	134	9			% survival rate				93,3					

Table 3: Failure origin and suggested improvements

Sensors	Difficulties/ Failures origin (If any)	Possible improvements
Time Domain Reflectometry (TDR)	The sensor is quite simple (mainly two or three metallic rod). The sensor is robust. Nevertheless, in the argillite media, it was difficult to obtain total contact between the rods and the surrounding rock. A filling material was necessary to fill up the gaps but the representativeness is under discussion It was easier with concrete The calibration is a problem	Calibration procedure has to be improved A better match between simulation and measurement has to be considered
Vibrating Wire Extensometer (VWE)SG1:	Up and running normal.	Radiation tolerant sensor version has been developed
Total Pressure (TP)	1 sensor failed directly during the installation. The other working well but no load has been observed.	Sensors with punch-tube have been tested since that and have a better contact.
Extensometer Multi-points Single-rod (EMS)	The sensors run quite normally but a lot of parasitic noise and "shift" on measurements have been observed which included a specific data treatment to remove all spurious values	Investigation didn't allow to understand the origin of the parasitic noise and offset
Distributed optical fiber "general"	Several breaks, between concrete support and the cable trays in the gallery or at the entrance into concrete, were observed during the installation phases. Some damages were repaired, when accessible, but difficulties appear after work to localize perfectly the measurement points along the optical line.	Integration of protections on specific locations around the OFS cables allowed next tests to succeed without any break.
Raman OFS technology	<u>Raman optical device:</u> The instrument has been working continuously for 5 years and must have been replaced in 2017 [because of failure of the instrument]. Similarly, Andra partners faced durability limitation.	/
Pt100	Up and running normal	

Receive: 10/04/2018

Main feedback (even partial):

The survival rate of sensors of this monitoring system test six years after installation is about 95%. This has shown the robustness of selected technologies, even for most innovative and recent ones.

This real-scale experiment shows that optical fiber distributed sensing are well suited for underground tunnel monitoring. It also appears that the optical fiber cables chosen were sufficiently robust to tolerate construction conditions. When dealing with distributed data, a major difficulty is accurate event localization. This was solved by creating artificial events, as thermal excitation, during construction steps and after reparations when breaks occur to provide an accurate map.

Sensors tested provided data which allowed improving models and confirming the potential suitability between measurement's need and qualified sensors. As an example, the inductive extensometer in borehole allowed to characterize the evolution of the EDZ and was able to provide the same level of information as the other systems, well known and approved, like Invar wire.

Data will be acquired for several years in order to obtain information about aging, accuracy, possible drift over time and robustness of sensors installed. In addition, measurements will be compared with different nondestructive methods in order to obtain the required level of reliable performances.

Additional comments

Requester's signature:

Date: (18/04/2018)

Main references:

[1.] Radwan Farhoud, Guillaume Hermand, Jean-Bernard Kazmierczak, Laure Malherbe, Cyrille Balland. A Highly Instrumented Underground Research Gallery as a Monitoring Concept for Radioactive Waste Cells - Data Measurement Qualification

[2.] Le Cam, Vincent and Mevel, Laurent and Schoefs, Franck. EWSHM - 7th European Workshop on Structural Health Monitoring, Jul 2014, Nantes, France. 2014

[3.] Radwan FARHOUD, Johan Bertrand, Stephane Buschaert, Sylvie Delepine-Lesoille, Guillaume Hermand, TINCE (2013): Full scale in situ monitoring section test in the Andra's Underground Research Laboratory

[4.] FARHOUD R., Bertrand J., Buschaert S., Delepine-Lesoille S., Hermand G., Dubois J.-Ph., De Combarieu M. (2013): Design and development of a large-scale in situ monitoring test in the French URL at the Centre Meuse / Haute-Marne. - MoDeRn International Conference and Workshop Monitoring in Geological Disposal of Radioactive Waste

Glossary:

ORS : Observation of concrete liners (in French : Observation du revêtement et du Soutènement)
GCR : Stiff liner gallery (in French : gallerie de conception rigide)
C60 / C40 : compression resistance values (40 or 60 MPa) of concrete

Receive: 26/01/2018

Experiment Test Form – Monitoring components check-up [MPT "in-situ"/Äspö URL]

To get the feedback on the components of the monitoring systems that worked under similar conditions

Type:

☒ Long-term	☐ Demonstrator	Dismantled: Yes ☐ No ☒	On-going: Yes ☒ No ☐

Goals:

The main objectives of the MPT are to test the system components in full scale and in combination with each other to obtain an initial verification of design implementation and component function. This includes the ability to manufacture full scale components, carry out installation (according to DAWE*) and monitor the initial system state of the MPT and its subsequent evolution.

The test also provides important experiences from working in full scale at in situ conditions, thus enabling the recognition of potential implementation issues of the DAWE design.

**KBS-3H reference design Drainage Artificial Watering and air Evacuation*

Instrumentation objectives**:

The objective of the test instrumentation is to study the buffer and filling component behaviour during the early part of the buffer evolution; movements in the system, water content, pore and total pressure and buffer swelling pressure at the rock interface will be measured. The development of swelling pressure is investigated to evaluate e.g. its effect on thermally induced spalling.

****It should be noted, that in the original planning there were only 400 days of operation planned before dismantling, however, during detailed planning it was decided to extend the monitoring phase.*

Means:

The Multi Purpose test is part of SKB and Posivas development of the KBS-3H design (Posiva SKB report 06. KBS-3H System Design Phase 2011-2017. Final report). The MPT was part of the EC LucoeX project and partly funded by the European Commission.

In 2004–2005 two deposition drifts (Ø 1.85 m) were excavated at the −220 m level of the Äspö Hard Rock Laboratory (Äspö HRL), Sweden; one 15 m long and one 95 m long (Bäckblom and Lindgren 2005), Figure 1. The 95 m drift has been used to test and further develop a horizontal deposition machine for disposing full scale concrete dummy distance blocks and fully deployed (dummy) Supercontainers, while the 15 m drift has been used to test the compartment plug (SKB 2012).

Receive: 26/01/2018

Figure 1. *The 95 m drift at Äspö HRL, Ø1.85 m*

The Multi Purpose Test (MPT) is the next step of the KBS-3H development and integrates the key disposal components, including the Supercontainer (copper canister surrounded by MX80 bentonite blocks with an outer steel shell), distance blocks (MX80 bentonite), compartment plug (steel), transition block (MX80 bentonite) and pellets filling (MX80 bentonite), (Kronberg 2016). It utilises the innermost 19 m of the 95 m drift at the Äspö HRL and for the first time introduces buffer manufacturing (Johannesson 2014), assembly and deposition of KBS-3H bentonite components and closure by way of a compartment plug, followed by monitoring of the early buffer evolution (Pintado X et al 2016 and Schatz T et al 2017). The MPT project also includes upgrading and rebuilding of the control system the deposition machine (Ojala and Von Numers 2015).

The MPT started 2011 and the installation was completed end 2013 and the monitoring is now ongoing. The original time schedule was to dismantle and evaluated the MPT end 2014 but the dismantling and analysis of results is now postponed and the new date is not yet decided.

The test is basically a shortened non-heated installation of the KBS-3H reference design, Drainage Artificial Watering and air Evacuation (DAWE). It includes the main KBS-3H components as shown in Figure 2 which also includes the measuring sections. Table 1 shows the distribution of sensors by sections and Table 2 shows the specific sensor models. The test is installed according to DAWE after which the test conditions are monitored.

A total of 227 sensors were installed and 33 of these were wireless.

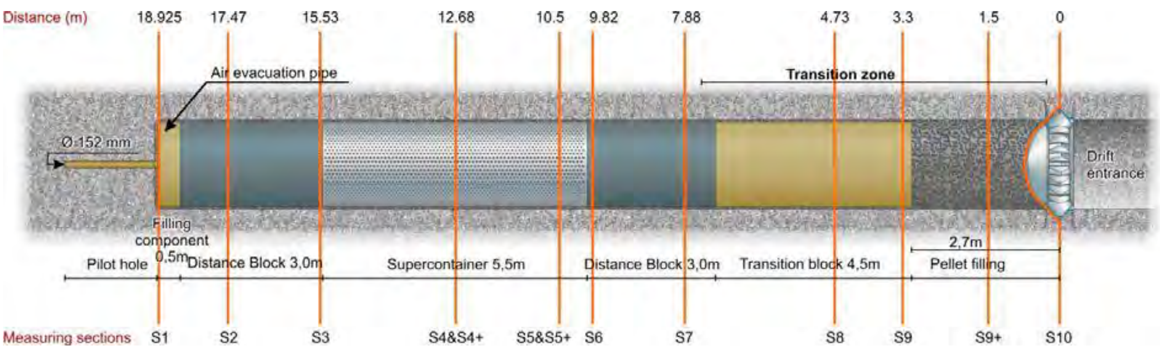


Figure 2. *Schematic illustration of the MPT layout.*

There is no parallel tunnel close to the MPT drift, so all cabling had to be taken out through the plug. The KBS-3H geometries also limit the solutions for sensor installations as there is only 43.5 mm between the components and the drift wall, Figure 3 shows the limited space remaining when the 44 ton Supercontainer has been installed. Several novel cabling solutions had to be devised in order to fit the sensors. Basically all cables are protected with stainless steel tubing all the way from the sensor and out through the plug.

Receive: 26/01/2018

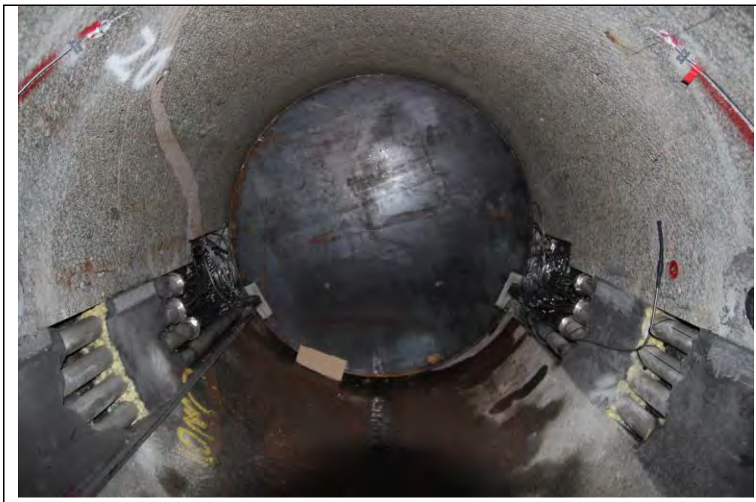


Figure 3. *Photo from the installation of the Supercontainer.*

Table 2. MPT sensor distribution, black are wired, blue are tubing's and the red are wireless. The abbreviations are given in the table below and the sensor models are presented in Table 2.

	Sections												
Sensors	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S9+**	**S10**	**Out**	**Tot**
TP rock	5	4		2			4	4	2	6			27
TP plug											2+1		3
TP buffer				4	4	4			1				13
PP rock short	1	4					4						9
PP rock borehole									18				18
PP buffer		1+3		4	2+3		1+3				3+3		23
WC		3+3		4	2+3		3+3	4+3	3+3				34
WP		6		4	4		6	6	6				32
WF	1	2		2	2		2	2	2				13
DS				4	4								8
DB									2				2
DC												3	3
IS				2									2
IB		1					1		1+1				4
GP	1					1					1		3
SG					8							24	32
FM												1	1
Total	8	27	0	26	32	5	27	19	39	6	10	28	227
Tubings	2	4	0	0	0	1	4	0	0	0	1	0	12
Wireless	0	6	0	0	6	0	6	5	6	0	4		33
Wired	8	21	0	26	26	5	21	14	33	6	6	28	194

Abbreviations

Code	Sensor
TP	Total pressure
PP	Pore pressure
WC	Water content capacitive
WP	Water content psychometric
WF	Water content FDR
DS	Displacement Supercontainer
DB	Displacement bentonite
DC	Displacement collar
IS	Inclination Supercontainer
IB	Inclination bentonite
SG	Strain Gage
GP	Gas Pressure
FM	Flow Meter

Table 2. Sensor models

Receive: 26/01/2018

Model of total pressure cells for rock (TP rock)	Geokon 4820 “Jackout Cell”
Model of total pressure cells for bentonite (TP buffer)	Special version of 3500-1x-10MPa, GEOKON 3500 Earth Pressure Cell made by ÅF – Rock Engineering & Measurement Technology
Model of pore pressure sensors for boreholes (PP rock)	KELLER series 23
Model of pore pressure sensors suggested for bentonite (PP buffer)	XPM10-A3 Measurement Specialities
Model of relative humidity sensors (WC)	Aitemin SHT75 V3
Model of psychrometers (WP)	WESCOR type PST-55 retrofitted by AITEMIN
Model of FDR sensor (WF)	Thetaprobe (Delta-T) ML2x
Model of LVDT sensor (DS/DB/DC)	LVDT SCHAEVITZ type DCW-1000A (spring return version)
Model of inclinometer (IS/IB)	Measurement Specialties DPL series
Model of suggested strain gauge system (SG)	HBM 1-LY41-3/350 for plug dome and HBM 1-XY101-3/350 connected to Quantum MX1615
Model of gas pressure transducer (GP)	KELLER series 23
Model of flowmeter (FM)	YOUNG 52203 (Tipping bucket only)

The current status, early 2016, of the sensors is listed in the Table 3. There are 90+ sensors functioning normally and it is quite likely that these sensors could remain so over several additional years.

Table 3. Status of the MPT sensors

		Status					
Sensors	Tot	Up (normal)	Up (noisy)	Over-ranged	<LOD	Down (wired)	Down (wireless)
TP rock	27	27					
TP plug	3					2	1
TP buffer	13					13	
PP rock short	9	5				4	
PP rock borehole	18	18					
PP buffer	23	6			1	4	12
WC	34	2		13		4	15
WP	32	13	8	2	7	2	
WF	13					11	2
DS	8	6				2	
DB	2						2
DC	3				3		
IS	2	1				1	
IB	4	3					1
GP	3			3			
SG	32	9				23	
FM	1				1		
Total	**227**	**90**	**8**	**18**	**12**	**66**	**33**

GP sensors were replaced by PP pressure. The three sensors are running. FDR sensors were working till day 500 approximately.

SG in supercontainer are faulty. Some now SG have been installed in plug.

LOD: Limit Of Detection.

Receive: 26/01/2018

Main results: Failure origin and suggested improvements

Sensors	Failure origin (If any)	Possible improvements
Geokon 4820 "Jackout cell"	Up and running normal.	
Special version of 3500-1x-10MPa, GEOKON 3500 Earth Pressure Cell made by ÅF – Rock Engineering & Measurement Technology	The cable shielding was removed due to practical problems with the lead-throughs during installation of these sensors, and the sensors may not be properly grounded as a result. The two sensors on the plug also showed significant noise development until finally, the signals were lost.	There is good experience from these sensors and if installed properly they generally perform well. However there is some issue as the 2 sensors used on the plug were noisy and eventually failed even with normal cabling. This should be examined closely when dismantled. The type of signal (few mV) probably also played a role. It may be best to avoid using amplified Weasthone type sensors when dealing with long cables in general.
KELLER series 23 (water)	Mostly up and running normal. Some of the cables had to be extended and there could be connection issues in these.	There is good experience from these sensors and if installed properly they generally perform well. A few are down, and when dismantling the origin of failure should be checked.
XPM10-A3 Measurement Specialities	Approximately half up and running. Failure origin for the other half is currently unknown. *The pore pressure sensors in blocks need a lot of time (years) for starting measuring. The sensors needs to be saturated and some liquid water should be inside. The experience in other "in situ" tests says that the time for measuring could delay one or two years, maybe more. One strange thing was to measure relatively early, which could be due to cracks or some preference path of water.*	When dismantling the origin of failure should be checked.
Aitemin SHT75 V3	Mostly normal function but now over-ranged.	Locate them away from water sources
WESCOR type PST-55 retrofitted by AITEMIN	Mostly normal function.	
Thetaprobe (Delta-T) ML2x	Initially working (~500 days) but now all down, probably due to electric system failure.	The origin of failure should be checked.
LVDT SCHAEVITZ type DCW-1000A (spring return version)	The installation of the KBS-3H components is quite intricate and the sensors could have become over-ranged after the installation. This sensor type seems to have problems in the Äspö environment.	The use of larger displacement range sensors could mitigate the problem in future tests; however, they may not be robust enough for the Äspö environment, which should be assessed at dismantling.
Measurement Specialties DPL series	Mostly operational, but the start position is not fully known in a KBS-3H setup which makes data assessment difficult.	The uncertainties in the start position and irregular swelling make the data very difficult to interpret in relation to component movement.
HBM 1-LY41-3/350 for	Inside the test on the Supercontainer: attempted	The glued on version has a limited

plug dome and HBM 1-XY101-3/350 connected to Quantum MX1615	just to assess if possible, however, not working inside the moist system, all down. On the steel plug: normal function to start with, however, dropping of one by one due to the Äspö environment/rust developing on the plug surface.	time of operation due to rust development on the KBS-3H plug.
KELLER series 23 (gas)	Normal function but now over-ranged.	
YOUNG 52203 (Tipping bucket only)	Operational.	Not in use due to a fully water tight plug.
Wireless system	The wireless system was working as intended only at the very beginning of the test, before water filling of the voids according to DAWE. Although the transmitters were encapsulated and their batteries calculated to run for 4 years at a measuring interval of 12 hours, most signals were lost during the early stages of the test. The potential advantages offered by this kind of system justify the attempt to use it. The main conclusion is that added redundancy is needed, e.g., the inclusion of additional receivers or antennas connected to redundant *The DAWE water filling disturbed the signal and for this reason, it was not possible to receive at the beginning but after that, it seems the water damaged the receivers, so the redundancy can help a lot. Another option is to have two or more antennas and the receiver out of the gallery, so it is possible to protect the receiver as well.* *In any case, a memory card was inserted in the transmitter, so it will be possible to recover the measurements when the test is going to be dismantled. This dismantling should be done carefully for avoiding damage in the transmitters.*	The origin of failure should be assessed at dismantling in order to improve the system. For future experiments, transmitter operation could be improved if signals are collected over discrete periods of time and transmitted only once per week or per month, thus decreasing the battery consumption and extending operational lifetimes. As the measuring frequency of the transmitters can be adjusted remotely, the best approach could be to set a relatively high frequency (every 10 minutes for example) during the early stages of the test and then change later to a lower frequency in order to preserve the duration of the batteries. If the transmitters do not receive any order from the receivers during a certain period of time (one day for example), the measuring period could be increased to 12–24 hours automatically. Improvements are on-going in Modern2020

Main feedback (even partial):

The MPT installation was the first full scale KBS-3H installation and given how many new and novel solutions that had to be developed for sensor installation and cabling the outcome is deemed reasonable and the sensors are provide information about the buffer development.

A thorough assessment should be done on the sensors when the test is dismantled in order to better determine origins of failure.

The KBS-3H project gained a lot of experiences from the MPT and methodologies are now available for both component assembly and installation including sensors.

Additional comments

Magnus Kronberg, Mats Lundqvist

Requester's signature:

Date: **(26/01/2018)**

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Glossary:

MPT: Multi Purpose Test; DAWE: Drainage, Artificial Watering and air Evacuation

Receive: 11/01/2018

Experiment Test Form – Monitoring components check-up [POPLU / ONKALO URF]

To get the feedback on the components of the monitoring systems that worked under similar conditions

Type:

☐ Long-term ☒ Demonstrator Dismantled: Yes ☐ No ☒ On-going: Yes ☐ No ☒

Goals:

The full-scale underground experiment POPLU was one of the demonstrations in a project of Euratom's Seventh Framework Programme called DOPAS ("Full-Scale Demonstration Of Plugs And Seals"), which was running from 2012-2016. The DOPAS project compiled the design basis of plugs and seals, developed new technologies for plug and seal materials and for the assembly and construction of plug and seal systems, carried out full or partial design of the systems, and performed partly or wholly five full-scale plug and seal tests (http://www.posiva.fi/dopas).
Instrumentation and monitoring of performance of engineered barrier systems (EBS) are often an integral part of demonstration of safety of a repository. Monitoring of experiments, from lab-scale to full-scale in-situ demonstrations, help establish protocols for understanding material evolution and risks. The inputs from monitoring are used for conformance assessment compared to requirements and provide feedback to the design basis. Information gained from monitoring of demonstrations such as DOPAS is also used to develop strategies for subsequent monitoring during the operational phase of a repository.

Means:

Within POPLU a deposition tunnel end plug for deep geological repositories was constructed at Posiva's underground rock characterization facility ONKALO in the crystalline bedrock of Olkiluoto. It separates the demonstration tunnel from the vehicle connection and is instrumented with sensors continuously measuring displacements, strain, humidity, mechanical, pore water pressure and temperature under very demanding conditions. Furthermore, sensors allow for monitoring the pressure being applied by pumping water into a filter layer behind the plug and the observation and control of the main parameters needed during the pressurization of the structure. An artificial pressurization routine was conducted within the short timescale of the demonstration in order to simulate the 100 year expected lifetime of the concrete structure. The in-pumped water and any out-flowing leakage was determined by a monitoring system to analyse the performance of sealing mechanisms of the structure.
The relative humidity in the tunnels can be close to 100 % and the temperature is nearly constant at +10 to 12 °C. The maximum pH-value inside the concrete and back structure can be around 11 due to the use of low-pH cementitious materials. The material of sensors and cables should highly resist corrosion and therefore be made of stainless materials, e.g. copper, stainless steel or titanium.
The water pressure within the POPLU and DOMPLU demonstrations was defined to be up to 10 MPa. Since in the operational use of a deposition tunnel the maximum pressure will raise slowly, the pressure uptake in this demonstration experiment was accelerated by means of high pressure pumps. The sensors and cables needed to be covered by protection pipes where possible. The high pressure with a maximum of 10 MPa will be gradually decreased from the back to the front face of the plug and reaching 0 MPa at the front part of the plug. On the other hand, deficiencies in the sealing system and possible cracks in the rock mass and concrete can raise the water pressure almost to its maximum and therefore the cables of pressure sensors in the gap between the plug and rock have to be sheltered.
During the concrete casting phase, the sensors needed to be protected from concrete vibration work, by installing them as far as possible from vibration alleys and sheltering them with protection tubes. During the hardening and cement hydration process of the concrete, the temperature can raise up to 60 °C, which is usually not a limitation for normal types of sensors.
The high water pressure can damage the sensors, but it can also penetrate to the cables and connections. The cables are selected to resist high pressure, but also to pass through the lead through flanges to prevent any leakage through the wire or on the surface of the wire. Since the concrete shrinks after the casting phase, the wires are sealed against possible water leakage using different methods (e.g. small bentonite belts around cables, flanges,

sealing of sheltering pipes).
The duration time of the DOPAS plug tests was assumed to be about 5 years and most of the sensors, cables and connections cannot be replaced or maintained during operation. Therefore they needed to be durable enough to be in constant function without service or maintenance for the entire operation time. Almost all sensors will be installed permanently inside the structure (inside the concrete plug, inside rock or inside bentonite clay) and therefore they needed to work reliably without any calibration during the entire test duration. A post calibration may be possible on a few sensors later on, during the decommissioning phase after the test has been stopped. Additionally, special concrete specimens with embedded sensors will be produced parallel to the casting of the plug and stored inside ONKALO to enable calibration of sensors after the test.
For the POPLU case, all materials used in the instrumentation and monitoring program needed to be pre-approved by Posiva regarding foreign materials used in ONKALO, so as to ensure the environmental safety of the site.

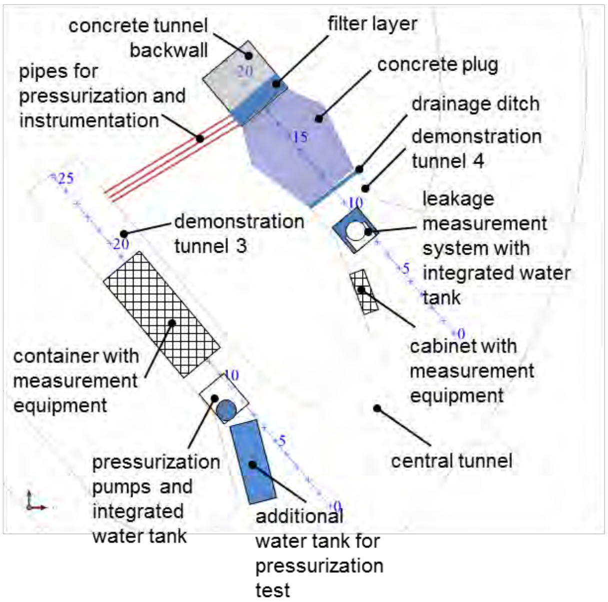

Figure 1. Top view of POPLU monitoring system arranged in demonstration tunnels 3 and 4, including pressurization system, leakage measurement system and data collection measuring equipment.

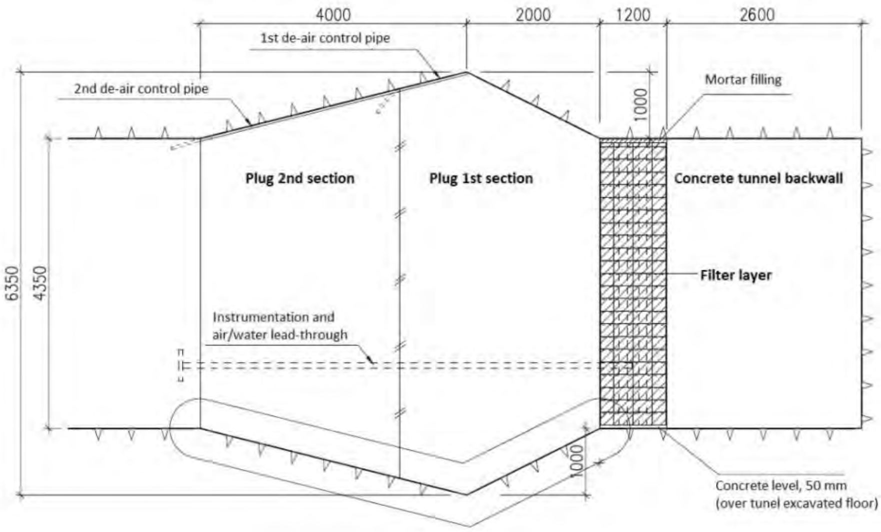

Figure 2: Schematic illustration of the Posiva's wedge-shaped plug being tested in POPLU

Table 1: Overview of monitoring data utilisation for plug performance assessment.

Data from plug monitoring systems	concrete casting	concrete hydration	initial pressurization	rapid pressurization (wedge test)
temperature		X		
relative humidity		X	X	X
pore pressure			X	X
total pressure	X	X	X	X
strain			X	X
displacement	X		X	X
leakage amount			X	X

Sensor type	Total number (all wired)
☒ temperature	8 pc. (standalone)+ 50 pc. (integrated)
☒ relative humidity	7 pc.
☒ pore pressure	11 pc.
☒ total pressure	11 pc.
☒ strain	32 pc.
☒ displacement	12 pc.
☒ leakage amount	1 pc.

Main results: Failor origin and suggested improvements

The instrumentation, pressurisation system and leakage detection system components of the monitoring system have performed well. The data collection, transfer and back-up system have also performed well. The system has given reliable information during the construction and casting activities, which have helped in decision making.

For long-term performance of the POPLU experiment, the primary concern with the sensor arrangement within plug section two is the risk of a pathway for water leakage that has been realised. Approximately seven sensors have shown water running along their cabling and/or sheltering tubes at the front face of the plug. The amount of water leakage along the monitoring system is less than the estimated plug interface (rock) leakage in the slot area. The experience leads to lessons about the best selection for materials and sheltering, including fasteners and other components. The instrumentation system was designed with redundancies and variable configurations, so as to learn which solutions for the harsh environment of repository monitoring are the best.

A parameter-by-parameter evaluation of the monitoring system, is provided in Table 2, which is a summary provided in the DOPAS Integrated Summary report Deliverable D4.4 and DOPAS Experimental Summary report Deliverable D4.5.

Receive: 11/01/2018

Table 2: Evaluation of the POPLU experiment monitoring system.

Sensor	Parameter(s)	Evaluation
K30-2-506 K-type INOR TCA-M10-MT1	Temperature in the concrete plug and concrete back wall	Temperature measurement was mainly used to follow temperatures during and after casting where the sensors performed consistently. Inor type sensors showed incompatibility with data loggers. A new logging solution had to be installed. Cause for incompatibility is still unknown. Temperature measurement suffered from distortions before final installation, when all shielding was connected properly. There is still noise superimposed on the measurements. Its cause is not yet identified.
Fuktcom, FE102 Aitemin, SHT75 V3	Relative humidity in the concrete plug and concrete back wall	Two of three Aitemin sensors failed before or during pressurisation. Three of four Fuktcom sensors show constantly 100% RH, partly interrupted by failure signals. Either the sealing of some of the sensors has failed or the sensor itself failed in contact with pressurised concrete pore water (RH close to 100%). Some of the measurement readings include distortion.
Kyowa, KFG-5-120-C1-11L1M2R	Strain in the concrete plug, measured with strain gauges attached to rebars of 100 cm length.	With increasing time of pressurisation, more and more strain gages showed conspicuous readings or failed. For some of the sensors, the sealing of the sensor connections to the sheltering has failed and readings include distortion. Although tested for pressures up to 100 bars and for 48 hours in a pressure vessel prior to installation, the sealing concept can be considered as not sufficient for the harsh environment inside the pressurised concrete.
RDP Electronis LTD, SSD500/1425 Kyowa, BCD-5B	Displacement of the plug is measured relative to the surrounding rock. LVDT-sensors (SSD500/1425) measure displacement from the back part of the plug and Kyowa “Omega” sensors from the surface of the plug.	Generally, all sensors are performing well. Little distortion is superimposed to the measurements, caused by strong electromagnetic fields of unknown source.
Geokon, 4800-1X-10	Total pressure in the filter layer and in the interface between concrete plug and rock surface	Sensors are generally performing well, showing pressure changes in the filter layer and plug/rock interface accurately. For the sensors in the interface, the pressure values cannot be considered as absolute pressure values due to the stiff embedment of the sensors, which are meant to be used in soil, or other non-rigid media.
Geokon, 4500SHX-3-10	Pore pressure in the filter layer and in the interface between concrete plug and rock surface	Sensors are generally performing well, showing pressure changes in the filter layer and plug/rock interface accurately. The sensors demand a pre-filling with water prior installation. Owing to the long period between installation and concrete casting, some of the water might have evaporated and been replaced by air. The sensors showed only accurate reading, after pressurised water contacted the sensor and replaced or dissolved the air inside the sensor. After that, sensor readings are considered to be reliable.

Drück PTX 1830 + DataTaker	Water pressure in near-field rock, Hydraulic head (mH2O) in nearby boreholes (ONK-PH21, -PH22, -PH23 and ONK-PVA11)	Sensors are performing well. Some distractions in ONK-PH21 between L5 (22,25m) – L9 (2,5m) since 12.4.2016. Might be due to packer pressure increasing. Monitoring the situation weekly. In other boreholes, no indication from POPLU pressurisation.
Interfels Multi-Point Borehole Extensometer (MPBX)	Displacement measurements of the rock and temperature inside the borehole	All the sensors are working well. Measurements of the rock displacement during the pressurisation. Measurements of temperature used to correct the errors of the displacement measurements due to thermal expansion of the extensometers.

Based on the experience of the POPLU experiment to date, the following lessons are noted:

- The choice of sensors and the data acquisition must be considered for the harsh repository working environment. In addition to climatic and pressure conditions, there can also be disturbances caused by simultaneous on-going construction and machines (such as blasting from nearby rock excavation) and signal disturbances/noise caused by electromagnetic fields. These items need to be factored in when designing the monitoring systems and evaluating performance data.
- The quality control methods for sensors in laboratory conditions prior to on-site installation needs to be developed for the complexity of the harsh repository environments, especially since post-monitoring sensor retrieval and calibration is often not possible. For example, the strain gauge connects were quality-control tested at 100 bars for 1 hour in laboratory conditions prior to installation to evaluate watertightness and durability. After field installation for POPLU, some of these sensors had questionable readings and the associated data may be disregarded or considered inaccurate in POPLU performance interpretation.
- The complex structure and building process influences the instrumentation support aspects, such as the need for long wires and wire extension possibilities on-site; need for temporary re-location and adjustment of sensor location; re-connection of wiring and data collection boxes so as to avoid damages during construction (i.e., use of temporary sheltering cabinets).
- Access to the plug construction area should be protected from unnecessary visitors and/or contractors as much as possible so as not to disturb the monitoring system during the installation phases. For instance, some of the POPLU sensors (including sheltering tubes and connectors) show leakage which may be attributed to unintentional movement of components of the monitoring system after experts had finished installation but before concrete casting.
- The use and functionality of relative humidity sensors in plug environments needs to be evaluated, together with their sheltering system. POPLU has experienced failure with all (3) Aitemin and 1 of 4 Fuktom sensors, which is potentially attributed to moisture levels close to the saturation level (100%).
- Both polyvinylidene fluoride (PVDF) and steel tubes have been used for shielding of wires connecting the sensors to the data logging system. The selection of tube type depended on the geometry of the plug and where the wires were being fed. The tube material mechanical properties (like brittleness) may be variable, and thus the connection method between tubes could be influencing the risk of defects and thus leakage.
- There is a lack of compatibility between some sensors and data takers, such as conflict between the Inor thermocouples and data loggers used in POPLU. Such compatibilities should be evaluated before installation or possibly addressed even before equipment procurement.
- There needs to be accurate planning about how to store, transfer and back up the data frequently. The ease of data access is needed for rapid response addressing risk mitigation (i.e., in response to sensor readings and leakage, if the pumps then need to be lowered).

Receive: 11/01/2018

Main feedback (even partial):

Monitoring systems were designed to assess plug performance based on properties of temperature, relative humidity, total pressure, pore pressure, strain and displacement of the concrete, clay and rock. The monitoring system was composed of sensors, wires and shielding, data collection systems, pressurization systems and near field monitoring including leakage assessment. In general, the monitoring systems of POPLU have performed well, and have been used to evaluate the performance of the experiment with respect to design specifications. The systems were designed and installed based on past experiences, including improvements to aspects especially related to watertightness for the extreme environment associated with pressurization. Monitoring results have fed back to the design basis and form an integral part of repository safety demonstration. The POPLU monitoring system design and experience can also be utilized in various other applications when evaluating material performance in challenging environments.

Requester's signature:

Date: (11/01/2018)

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Experiment Test Form – Monitoring components check-up [Prototype Repository "in-situ"/Äspö URL]

To get the feedback on the components of the monitoring systems that worked under similar conditions

Type:

☒ Long-term	☐ Demonstrator	Dismantled: Yes ☒ No ☐	On-going: Yes ☐ No ☒

Goals:

The main objectives for the Prototype Repository are to:

- Test and demonstrate the integrated function of the final repository components under realistic conditions in full-scale and to compare results with model predictions and assumptions.
- Develop, test and demonstrate appropriate engineering standards and quality assurance methods.
- Simulate appropriate parts of the repository design and construction processes.

Means:

The test is located in the innermost section of a TBM-tunnel at the -450 m level at Äspö Hard Rock Laboratory. The layout involves altogether six deposition holes, four in an inner section and two in an outer, see Figure 1. Canisters with dimension and weight according to the current plans for the final repository and with heaters to simulate the thermal energy output from the spent nuclear fuel have been positioned in the holes and surrounded by bentonite buffer. The deposition holes are placed with a centre distance of 6 m. This distance was evaluated considering the thermal diffusivity of the rock mass and the maximum acceptable temperature of the buffer. The deposition tunnel is backfilled with a mixture of bentonite and crushed rock (30/70). A massive concrete plug, designed to withstand full water and swelling pressures, separates the test area from the open tunnel system and a second plug separates the two sections. This layout provides two more or less independent test sections.

Sensors were installed both in the rock, the backfill and the buffer. The housings of the sensors were made of titanium. The wires from the sensors were led in titanium tubes in the buffer and in polyamide tubes in the backfill and in the rock to a nearby tunnel where the data accusation system was situated, see Figure 1.
The outer test section was retrieved during 2011 after approximately eight years of water uptake of the buffer and backfill. This document is only dealing with sensors installed in the buffer and the backfill of the outer test section.

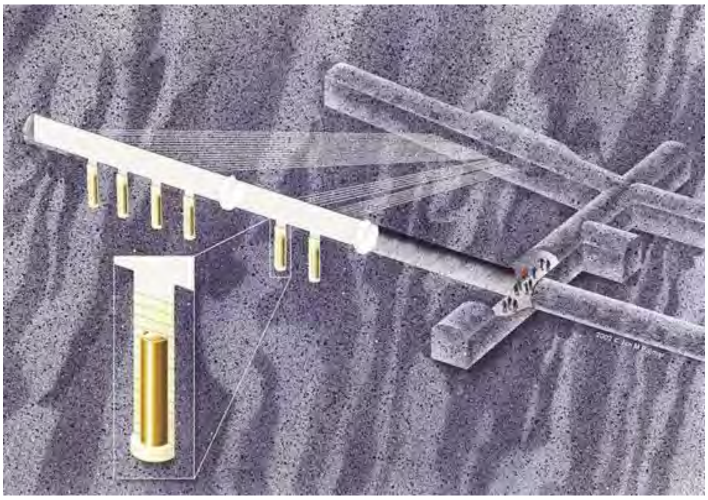

Figure 1. The layout of the Prototype Repository

Main results: Behaviour of the monitoring components since installation

Sensor type	Total number (Wired/Wireless)	
☒ Total stress or swelling pressure (P) ☒ Pore pressure (Q) ☒ Moisture (WC, WT or WP) ☐ Displacement (S, SH or SB) ☒ Temperature (T) ☐ Crackmeter (3S)	See Table 1, all of them were wired.	See Table 1 below

Table 1 Installed sensors in the backfill and the buffer in the outer section of the Prototype Repository. The table is showing the type of installed sensor, the total amount of installed sensors, the number of still working sensors at the retrieval of the test, the number of retrieved sensors and the number of tested sensors.

Sensor type	Installed	Worked at the end of the test	Retrieved	Tested afterwards
Geokon 4800 Total Pressure Buffer	31	24	19	10
Geokon 4500 Pore Pressure	12	8	8	8
Kulite Total Pressure Buffer	23	6	7	2
Kulite Pore Pressure Buffer	14	2	0	0
Pentronic, Temperature Buffer	64	50	0	0
Rotronic Rh Buffer	33			0
Vaisala Rh Buffer	34		7	0
Wescor Rh Buffer	35	9	0	0
Geokon 4850 Total Pressure Backfill	8	8	7	6
Geokon 4500 Pore Pressure Backfill	14	11	9	9
Kulite Total Pressure Backfill	8	3	0	0
Kulite Pore Pressure Backfill	4	1	0	0
Pentronic, Temperature Backfill	16	15	0	0
Wescor Rh Backfill	32	0	0	0

Main results: Failure origin and suggested improvements

Sensors	Failure origin (If any)	Possible improvements
T type thermocouples	The performance was ok. 81 % of the installed sensors were still working after 8 years of saturation. None of the installed sensors were tested afterwards. The reason for failure was probably due to large deformations of the thermocouples.	The analyses of the failed sensors are not indicating failure due to corrosion. Use of Titanium instead of Cupro-nickel might improve the strength of the senor.
Capacitive type moisture sensors	Two types of capacitive sensors were used in the test, Rotronic and Vaisala. The reason for failure was either that the sensor or the boxes (for Vaisala) with electronics were drenched during the test. None of the installed sensors could be checked afterwards.	Improve of the boxes for the electronics or avoid sensors which need electronics outside the housing of the sensor. See also “Main feedback” below.
Psychrometric type moisture sensors	The sensors (Wescor) worked well until liquid water entered the sensors. None of the sensors were tested afterwards.	
Total pressure sensor (Vibrating Wire)	This type of sensor (Geokon) worked well. The reason for failure was probably due to mechanical forces on the body of the sensors or on the tube through which the cable was led. The tube was	See “Main feedback” below

	made of titanium in the buffer and of polyamide in the backfill. The sensors were tested after the retrieval with good results.	
Pore pressure sensors (Vibrating Wire)	This type of sensor (Geokon) worked well. The reason for failure was probably due to mechanical forces on the body of the sensors or on the tube through which the cable was led. The tube was made of titanium in the buffer and of polyamide in the backfill.	See “Main feedback” below.
Total pressure sensor (Piezo resistive)	Many of this type of sensor Kulite failed during operation due to mechanical forces on the housing. The tube was welded on the housing and this was a weak part of the sensor which was observed at the retrieval of the test..	Improve the welding or use couplings of type Swagelok to connect the tubing to the housing of the sensor. See also “Main feedback” below
Pore pressure sensor (Piezo resistive)	Many of this type of sensor Kulite failed during operation due to mechanical forces on the housing. The tube was welded on the housing and this was a weak part of the sensor which was observed at the retrieval of the test.	Improve the welding or use couplings of type Swagelok to connect the tubing to the housing of the sensor. See also “Main feedback” below

Main feedback (even partial):

Many of the installed sensors failed probably due to large forces on the housing of the sensors or on the tubing for the wires. It is favorable if the sensors could be tested mechanically before installation. One way to avoid sensor failures might be to separate the mechanical protection of the cable from the protection from high water pressure.

Many of installed sensors for measuring pore pressure and total pressure of type Geokon were tested afterwards with good results. They showed a maximum deviation from the applied pressure of ±2%. The judgment is thereby that all the Geokon sensors installed in the test have given reliable readings until failure or termination of the experiment.

Additional comments

Installed sensors for measuring the strains and stresses in the rock around the two deposition holes did not work at all.

Lars-Erik Johannesson

Requester’s signature:

Date: **(31/01/2018)**

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Development and Demonstration of monitoring strategies and technologies for geological disposal

Main references:

Börgesson L. and Sandén T., 2002. Prototype Repository. Instrumentation of buffer and Backfill in Section II. SKB International Progress Report IPR-03-21.

Goudarzi R, 2014. Prototype Repository - Sensor data report (Period 01-09-17 - 13-01-01). Report No 25, SKB P-13-39, Svensk Kärnbränslehantering AB.

Nilsson U, 2013. Prototype Repository – Validation of retrieved sensors from the Prototype experiment at Äspö Hard Rock laboratory. SKB P-13-31, Svensk Kärnbränslehantering AB.

Svemar C., Johannesson L., Grahm P., Kristensson O., Lönnqvist M., Nilsson U., 2016. Prototype Repository. Opening and retrieval of outer section of Prototype Repository at Äspö Hard Rock Laboratory. Summary report. SKB TR-13-22.

Glossary:

Prototype repository, Retrieval, Outer section, Plug, Backfill, Buffer, Electrical heater, Instrumentation, Copper corrosion

Receive: ___/___/______

Experiment Test Form – Monitoring components chek-up [SEALEX-IRSN/Tournemire URL]

To get the feedback on the components of the monitoring systems that worked under similar conditions

Type:

☒ Long-term ☐ Demonstrator Dismantled: Yes ☐ No ☒ On-going: Yes ☒ No ☐

Goals:

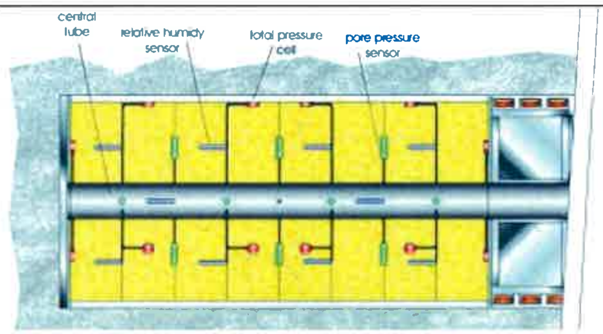
To study the long-term performance of clay-based sealing systems in a DGR*by:

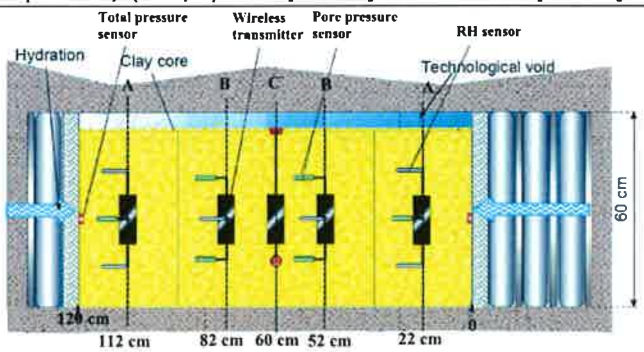
- quantifying the impact of intra-core geometry (voids) on the hydraulic properties of sealing systems,
- testing the long-term hydraulic performance of seals in normal conditions for different clay core compositions (pure bentonite or bentonite/sand mixtures) and conditionings (pre-compacted blocks or in-situ compacted),
- investigating the concept of robustness by considering altered scenarios, such as an incidental decrease of the swelling pressure (eg originating from the failure of the confining plugs).

Means:

Six in-situ tests emplaced in horizontal boreholes (dip072°), of 60 cm diameter and 5.4m length, excavated into a shale formation (Toarcian-Domerian) at the Tournemire URL. Each experiment consists in a bentonite-based core (compacted to a dry density of 1.97 Mg/m^3) mechanically confined at both ends, which represents a generic seal mock-up, except for the artificial saturation system. Experiments were performed under two main configurations: 1) a reference test (RT-1) with wired sensors and 5 perfomance tests with wireless sensors.

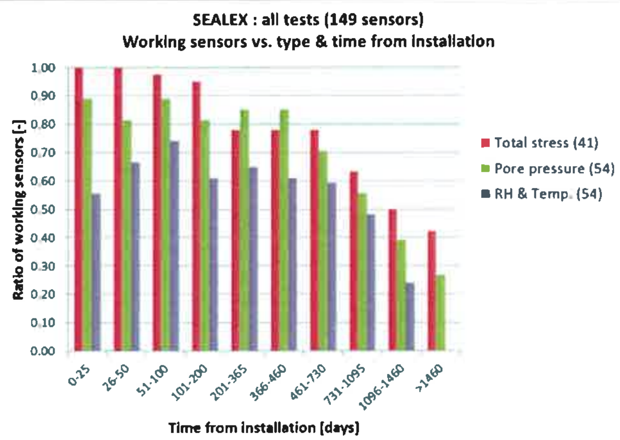
1 Reference test [RT-1] (wired sensors connected through a central tube) in pre-compacted monolithic disks of a bentonite/sand mixture (70/30 in dry mass)	5 Performance tests (wireless sensors) a) monolithic disks/pre-compacted (70/30) with [PT-A1] and without [PT-N1] Confinement Loss (CL), b) disks + joints /pre-compacted (70/30) [PT-N2], c) pellets+powder /in situ compacted / (100/0) with [PT-N4] and without [PT-N3] CL.





Main results: Behaviour of the monitoring components since installation

Sensor type	Total number (Wired/Wireless)
☒ Total stress or swelling pressure (P_{tot})	41 (16/25)
☒ Pore pressure (P_w)	54 (14/40)
☒ Relative humidity/ Temperature (RH/T)	54 (14/40)



Receive: ___/___/______

Main results: Failure origin and suggested improvements

Sensors	Failure origin (If any)	Possible improvements (pending confirmation at dismantling)
RH/T (W & WL)	Water saturation ≈ 1	Self-protection or pairing after liquid water inflow
P_{tot} & P_w (W & WL)	Sensor break after 2 years operation? Cable failure by shear? Cable failure by traction? Emitter box failure?	Ageing? Loose the connexion Use reinforced-sheath with slack cable or suppress cables between sensors and emitter (RFID like) Reinforcement or shape optimization

Main feedback (even partial):

At SEALEX* the monitoring components likely suffered three kinds of losses linked to:

1. Breaks during installation works and/or under resaturation process of the bentonite-based seal.
2. Sensitivity of capacitive humidity sensors at ~100% RH* conditions (~ free water).
3. Life-time of the component itself.

The first causes of loss could be easily improved by: i) reinforcing cables and boxes or ii) excluding any cables and working wirelessly.
The second cause is in favour of a different technique (eg TDR*, FDR*, Tensiometer, GMS*, OF* humidity sensors) for measuring humidity, if there is no way to improve it.
The third cause can only be discussed after the experiment dismantling. However, at this stage one can already claim that a two-years operation seems very insufficient for monitoring a DGR*. For this reason a full qualification of components must be achieved especially through making of ageing tests.

Additional comments

Signature:

Date: 19/12/2017

Main references:

[PT-N1, PT-N2; PT-A1] http://dx.doi.org/10.1016/j.ijrmms.2016.07.011;
[PT-N1] http://dx.doi.org/10.1016/j.enggeo.2013.05.009; http://dx.doi.org/10.1016/j.enggeo.2016.02.013

Glossary:

SEALEX: SEALing EXperiment; DGR: Deep Geological Repository; RH: Relative Humidity; TDR: Time Domain Reflectometry; TDT: Time Domain Transmission; FDR: Frequency Domain Reflectometry; GMS: Granular Matrix Sensors; OF: Optic Fibers; RFID: Radio Frequency Identification

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8.3. Appendix 3: Ageing test forms

Receive: ___/___/______

Ageing Test Form for monitoring components – [AMBERG Infraestructuras S.A.]

Experiment goals/attempts in terms of hardening/ageing/qualification:

To try accelerating the effects of the EBS system in the sensors and cables in order to get fast enough results about the readiness level (in terms of work environment withstanding) of them to operate during decades (ideally 100 years)

Stress type:

☐ Radiation ☐ Humidity ☐ Temperature ☐ H_2

☒ Other, namely: Combination of stresses and cycles: temperature + humidity + pressure + salinity

Component to be tested:

developed for Modern2020 ☐ Yes ● No

☐ Optic Fiber ☒ Cable ☒ Transducer… ☐ Other, namely…

Name: Vibrating wire transducers from geokon: pore pressure, total pressure & displacement
Temocouples type T

Experiment details:

The effects of the hardening/ageing/qualification protocol could be compared with sensors retrieved that worked under such conditions during long periods, as those retrieved from FEBEX in-situ (18 years of operation), to determine how effective the procedure is.

Irradiation tests: ☐ Yes ☐ No ☒ Optional

Country case:

☐ French case: *extrado of emplacement metallic liners for HL cells with expected TID of about 10MGy for 100years*

☐ Belgian case: *extrado of concreted supercontainers of HLwastes with a TID of about 30 Gy for 100years*

☒ Other case: *to be detrermined*

Irradiator:

γ-irradiations : ☒ RITA(CEN) ☐ IRMA(IRSN) ☐ Other: | Neutron irradiations ☐ BRI(CEN)

Access to retricted area : ☒ Yes Contact person: | ☐ No

Experimental conditions:

TID (kGy): 1,000 Dose rate (kGy/h): 3 Test duration (d): 15

On-line measurement: ☐ Yes ☐ No If yes, interrogator type:

Time schedule for tests:

Other stresses: ☐ Yes ☒ No

☐ Temperature ☐ Humidity ☐ H_2 ☐ Other

Material:

Conditions (Range/duration): I guess the radiation tests should be done de-coupled from the other stresses to simplify the procedure

Receive: ___/___/______

Figures (if any)	

Main results (even partial):

The main result should be a reasonable short procedure to ascertain if a sensor with its cable could be used for EBS monitoring during decades avoiding the need of long term tests for the purpose.

Main conclusions (even partial) related to the component qualification:

Gain confidence of the hardening/qualification of the components of the future monitoring system.

Additional comments

After getting the right procedure, it could be applied to the components developed in Modern2020.

Requester's signature:

Date: 18/12/2017

Glossary

TID: Total Ionizing Dose expressed in Gray unit (Gy)
Gy: The gray is a derivative unit of ionizing radiation dose in the international system unit. It is defined as the absorption of one joule of radiation energy per kilogram of matter.
Qualification:….
Hardening:…
Ageing:….

Receive: ___/___/______

Ageing Test Form for monitoring components – [*Andra / ageing tests in IRMA*]

Experiment goals/attempts in terms of hardening/ageing/qualification:

1. Evaluate possible coupled influence of temperature and gamma rays on Brillouin and Rayleigh scattering properties in silica optical fibers, envisioned for strain and temperature sensing in underground repositories. This was performed on a special silica optical fiber, based on F-dopants in order to reach a "radiation hard" behavior, in other words a compatibility with radiative environment. A reference Ge-doped silica optical fiber was collocated to enhance performances of the optical fiber designed within the MODERN2020 project.
2. Evaluate whether the strain transfer function of optical fiber strain sensing cables (=the function that links the concrete host material to the optical fiber core through the coatings and sheaths of the cable) might change after gamma exposure.

Stress type:

☒ Radiation	☐ Humidity	☒ Temperature	☐ H_2
☐ Other, namely:			

Component to be tested:

developed for Modern2020	☒ Yes	☐ No	
☒ Optic Fiber	☒ Cable	☐ Transducer...	☐ Other, namely...

Name:

1. One optical fiber with F dopant in the optical cladding (for high-tolerance to radiation) and carbon-acrylate primary coating (for hydrogen sealing), supplied by iXBlue thanks to MODERN2020 funds. At four temperatures.
2. A reference optical fiber (5,2% Ge in the silica core, pure silica cladding) was collocated to quantify influence of dopants. Evaluated at 4 temperatures also.
3. Two strain sensing (called FIMT and V9) cables realized by BRUGG company thanks to MODERN2020 funds, using the special optical fiber

Experiment details:

Several samples of the naked optical fibers (1 and 2) were realized, coiling 30m of fiber without stress. 4 samples were placed under radiation at 4 different temperatures (room temperature, 80°C, 100°C and 120°C) imposed by heating silicones. Brillouin and Rayleigh scatterings were measured during gamma ray exposure. A 5th sample (of 1) was prepared and placed for on-line optical spectrum measurement.
200m of strain sensing cables (3) were exposed to gamma rays. Later, the irradiated samples will be placed on mechanical loading machines to evaluate possible evolution of the strain transfer function of the cable. A short length of sensing cable was measured on-line to evaluate signal-to-noise ratio evolution.

Irradiation tests: ☒ Yes ☐ No

Country case:
☒ French case: *extrado of emplacement metallic liners for HL cells with expected TID of about 10MGy for 100years*
☐ Belgian case: *extrado of concreted supercontainers of HLwastes with a TID of about 30 Gy for 100years*
☐ Other case:

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Irradiator:			
γ-irradiations : ☐ RITA(CEN)	☒ IRMA(IRSN)	☐ Other:	Neutron irradiations ☐ BRI(CEN)
Access to restricted area : ☒ Yes	Contact person:		☐ No
Experimental conditions:			
TID (kGy): 1,000	Dose rate (kGy/h): 3		Test duration (d): 15
On-line measurement: ☒ Yes	☐ No	If yes, interrogator type: (i) Neubrescope for Brillouin and Rayleigh scatterings and (ii) optical spectrum measurement	
Time schedule for tests: 2017 Nov.			

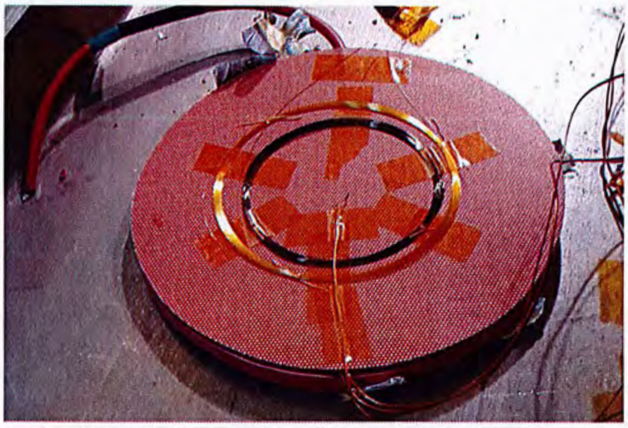
Other stresses: ☒ Yes ☐ No

☒ Temperature ☐ Humidity ☐ H_2 ☒ Other

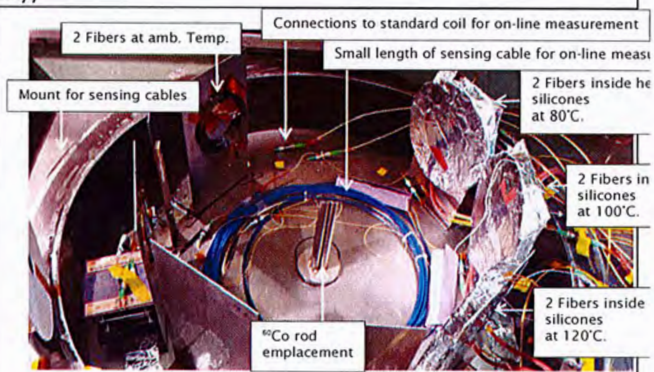
Material: Component 1 and 2 are wrapped into three heating silicones from Winkler, which enable to reach 180 ° C in temperature. They consist of a moisture-resistant braided heating resistor between two reinforced silicone layers. The assembly is vulcanized so as to achieve an homogeneous structure. The 3 selected temperature were 80°C, 100°C and 120°C, because the expected temperature range at the extrado of emplacement metallic liners for HL cells is [70;100] °C. Samples at ambient temperature were not inserted inside silicones.

Conditions (Range/duration): same as for all irradiated material

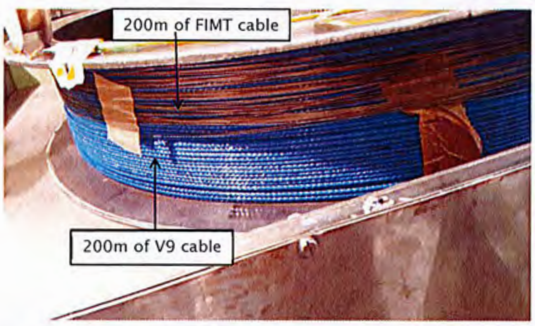
Figures (if any)



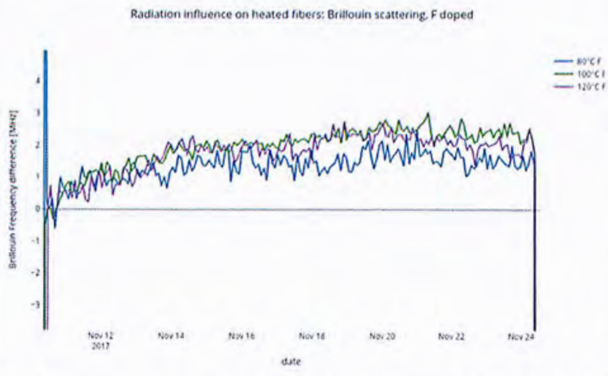
Inside view of one heating silicon with 2 enrolled optical fibers (1 and 2) and one thermocouple



Picture of all the samples before the radioactive rod emplacement



Optical fiber strain sensing cables (3) on their mount



Brillouin frequency shifts of the F-doped fiber (1), for 3 heating temperatures, as a function of time (or irradiation dose)

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Receive: ___/___/______

Main results (even partial):

In accordance with Literature, we observed
-optical losses increase with gamma exposure: Radiation Inducted Attenuation (RIA) is larger for Ge-doped fiber (2) than F-doped fibers (1)
-a small positive Brillouin Frequency shifts under radiation: less than 4MHz (which corresponds to 80µm) at 1MGy. It is higher for Ge-doped fiber (4MHz) than F-doped fiber (2MHz).
-a small negative Rayleigh Frequency shifts under radiation: less than 3GHz (respectively 8GHz) for the F-doped (respectively Ge-doped) fiber at 1MGy. 1GHz corresponds to 7µm/m.

Temperature influence on Brillouin and Rayleigh shifts under radiation is very small, whatever the optical fiber type. We observe that increased temperature reduces RIA, hence improves the Signal-to-Noise Ratio which finally improves maximal distance range of the optical fiber sensing system. This remains to be carefully quantified.

Main conclusions (even partial) related to the component qualification:

Special optical fibers, F-doped in the cladding with pure silica core must be selected (rather than standard fibers ge-doped in the core).
Up to 1MGy total dose, strain measurements based on Brillouin or Rayleigh scatterings insuch F-doped silica optical fibers will be possible, however with increased uncertainty (2MHz –which corresponds to 40µm/m- instead of 0.5MHz) and reduced total distance range (value to be quantified later).
Radiation ageing tests performed at room temperature over-estimate impact because temperature reduces RIA.

Additional comments

We observe coupled temperature and gamma influences: results obtained under radiation only were pessimistic. From the obtained data we will be able to quantify reduced distance ranges under radiations for strain sensing systems based on Brillouin and Rayleigh scatterings.
In the future we must evaluate if carbon-coating remains efficient towards hydrogen migration into silica after gamma exposure. We will also quantify radiation impact on the external coating of the optical fiber: is the strain sensing cable degraded?

Requester's signature:

Date: 30/01/2018 (dd/mm/yyyy)

Glossary

TID: Total Ionizing Dose expressed in Gray unit (Gy)
Gy: The gray is a derivative unit of ionizing radiation dose in the international system unit. It is defined as the absorption of one joule of radiation energy per kilogram of matter.
Ageing: Process to accelerate artificially the normal degradation of a monitoring component with time of use. The process may be artificially accelerated with Temperature, Radiation, Chemistry, Humidity, Strain… It is meant to be representative for DGR service conditions, but with higher intensity of stresses, in order to reduce the duration of experiments.

Receive: ___/___/______

Ageing Test Form for monitoring components – *University of MONS*/Telecoms Group

Experiment goals/attempts in terms of hardening/ageing/qualification:

1. Qualify stability of hydrogen layer for transport and irradiation
2. Evaluate polymer fibres as carriers for other layers and as sensors in their own right.

Stress type:

☒ Radiation ☐ Humidity ☐ Temperature ☐ H_2

☐ Other, namely:

Component to be tested:

developed for Modern2020 ■ Yes ☐ No

☒ Optic Fiber ☐ Cable ☐ Transducer… ☐ Other, namely…

Name:
1. PMMA mPOF
2. functionalized silica fibres for Hydrogen sensing

Experiment details:

Fibres were prepared at UMONS and transported by car to Mol for testing at RITA. Fibres were mounted in the canister in the on site laboratory with spectra taken pre and post mounting to ensure functionality prior to irradiation. The canister was then taken by SCK personnel into the secured restricted zone where it was placed into their setup. First the temperature of the canister was stabilised and when stable, irradiation began from their isolated source. Sensors were observed online with regard to their spectral profile, but hydrogen sensing functionality was not possible at the same time.

Irradiation tests: ☒ Yes ☐ No

Country case:

☒ French case: *extrado of emplacement metallic liners for HL cells with expected TID of about 10MGy for 100years*

☒ Belgian case: *extrado of concreted supercontainers of HLwastes with a TID of about 30 Gy for 100years*

☒ Other case: *Insertion with Belgian container, leading to higher radiation levels of unknown dose. French case but for ILW pre sealing.*

Irradiator:

γ-irradiations : ☒ RITA(CEN) ☐ IRMA(IRSN) ☐ Other: | Neutron irradiations ☐ BRI(CEN)

Access to retricted area : ☐ Yes ■ No Contact person: Andrei Goussarov

Experimental conditions:

TID (kGy): 10,000 Dose rate (kGy/h): 0.41 – 0.66 Test duration (d):7

On-line measurement: ☒ Yes ☒ No If yes, interrogator type: FiberSensing 8 channel BraggMeter

Time schedule for tests: 2 test periods, the first for 10

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	kGy and a second for 100 kGy

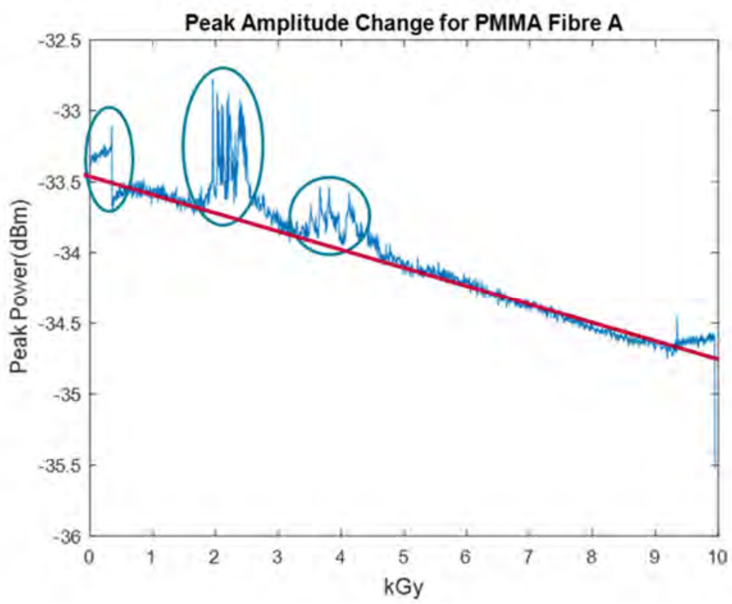
Other stresses: ☐ Yes ☒ No

☐ Temperature	☐ Humidity	☐ H_2	☐ Other

Material:
Conditions (Range/duration):

Figures (if any)

This figures describes one typical change of the FBG in PMMA fiber peak versus the total dose.



Main results (even partial):

Our hydrogen sensors showed a profile alteration within the boundaries of what could be considered normal induce changes in already published material. All tested fibres showed abnormal amplitude changes over time of a magnitude far beyond variations in equipment used. These changes are to date unexplained, but can be excluded from all fibres based on the fact that all gratings and fibre materials recorded these fluctuations at the same times and with comparable magnitudes. Our PMMA fibre shows a linear and permanent decrease in amplitude that correlates very well with the fit. It exhibits increased spectral ripple that is a consequence of coupling material degradation and a modest wavelength shift. Due to an interrogation failure, the exact causes of the wavelength shift cannot be guaranteed as uniquely due to radiation and further testing must establish or dismiss this part of the results.

Main conclusions (even partial) related to the component qualification:

While our hydrogen sensing layer is well suited for its role, the fragility of the functionalised layer is unsuitable even for basic transport. Prior to further tests, development is necessary to decrease fragility without compromising the effectiveness of the layer. The PMMA sensor shows good sensitivity to radiation along with a linear response for the irradiated region. This would be a good platform for dosimetry or indeed a humidity or strain sensor with calibration or compensation techniques. Further tests are required to prove that this behavior is generic and not specific for PMMA.

Additional comments

Date: 20/04/2018

Requester's signature:

Glossary

TID: Total Ionizing Dose expressed in Gray unit (Gy)
Gy: The gray is a derivative unit of ionizing radiation dose in the international system unit. It is defined as the absorption of one joule of radiation energy per kilogram of matter.

Receive: ___/___/______

Ageing Test Form for monitoring components [*VTT Technical Research Centre of Finland*]

Experiment goals/attempts in terms of hardening/ageing/qualification:

Ageing test goal is to simulate ageing of selected measurement system components that are considered to be used for EBS monitoring. In addition, VTT's interest is to create test plan for some of the sensors developed in MODERN2020. Ageing test are planned to be done in cycles so that it will give provisional results already during the test program. Main goal is to plan test program that would simulate Scandinavian EBS environment conditions during the 100years operational time.

Stress type:

☐ Radiation	☐ Humidity	☐ Temperature	☐ H_2
☒ Other, namely:	Ageing test will be planned to be done in cycles and consist of impact for salinity, pressure(hydrostatic and bentonite swelling pressure) and elevated temperature		

Component to be tested:

developed for Modern2020	☐ Yes	☐ No	
☐ Optic Fiber	☐ Cable	☐ Transducer…	☒ Other, namely…
Name: Test plan will consist of selected sensors and dummy sensors manufactured form different materials. Idea is to test sensor enclosure and sensor cable armoring/pipe with the dummy sensors. Dummy sensor enclosure, pipe and joints materials: Titanium Gr2, Stainless steel 316L, Monel 400, Alloy 2507			

Experiment details:

The plan is to develop procedure to simulate long-term conditions in EBS environment.
Test would consist of 20 iterative steps:

1. Selected specimens will be exposed 1 month to salinity in neutral salt spray chamber that would be equivalent of 5 years exposure. (EN ISO 9227)
2. Specimens will be exposed to 15-20MPa pressure that is consider to be hydrostatic pressure 500m below sea-level(5MPa) + swelling pressure of saturated bentonite(10-20MPa). Pressure chamber be equipped with heating elements and heated to temperature of 85C that simulates temperature close to canister.

Irradiation tests: ☐ Yes ☒ No

Country case:				
☐ French case: *extrado of emplacement metallic liners for HL cells with expected TID of about 10MGy for 100years*				
☐ Belgian case: *extrado of concreted supercontainers of HLwastes with a TID of about 30 Gy for 100years*				
☐ Other case:				
Irradiator:				
γ-irradiations : ☒ RITA(CEN)	☐ IRMA(IRSN)	☐ Other:	Neutron irradiations ☐ BRI(CEN)	
Access to retricted area : ☒ Yes	Contact person:			☐ No
Experimental conditions:				
TID (kGy): 1,000	Dose rate (kGy/h): 3		Test duration (d): 15	
On-line measurement: ☐ Yes ☐ No	If yes, interrogator type:			
Time schedule for tests:				

Receive: ___/___/______

Other stresses: ☐ Yes ☐ No

☐ Temperature	☐ Humidity	☐ H_2	☐ Other
Material:			
Conditions (Range/duration):			

Figures (if any)

Figure of neutral salt spray(NSS) chamber calibration procedure

Pressure test system with heating(Max pressure 20Mpa)

Main results (even partial):

Will give answers at least to following questions:
Is it possible to simulate well enough the repository EBS environment conditions impact to sensors?
How long selected sensors would last in simulated harsh conditions.

Main conclusions (even partial) related to the component qualification:

Identify reliability of different measurements systems components(Transduser, enclosure, cable protective pipe and pipe joints)

Receive: ___/___/______

Additional comments

Results can be used as design criteria in EBS monitoring system components development.
All electric components that will be used in EBS monitoring should be radiation hardened. List of qualified manufactures and components for space and aviation usage can be found from DLA Land and Maritime webpages.
ISO 9223 defines corrosivity classes for different atmospheres(Mines cathegory C5 ~ Corrosivity Very High).
Alloys 904L, 254 SMO, 4565,554,SMO, 2205 and 2507 are typically recommended for mine environment.

Date: ______________________ **(dd/mm/yyyy)** **Requester's signature:** ______________________

Glossary

TID: Total Ionizing Dose expressed in Gray unit (Gy)
Gy: The gray is a derivative unit of ionizing radiation dose in the international system unit. It is defined as the absorption of one joule of radiation energy per kilogram of matter.
Qualification:….
Hardening:…
Ageing:….

8.4. Appendix 4: Details on irradiation tests

	Sensor	TID, kGy (DR, kGy/h)	#	Diam., mm	Length, m	Bending diam, cm	Environment	Measurement type	DAQ	Date
Andra1	Doped silica fibers (F, Ge,Al)	1000 (~10 kGy/h)	≥10	250 µm	10-20	>8	T(80, 100,120C) + ambient T	Distributed Rayleigh and Brillouin, RIA	Neubrescope, OSA + BBS	Nov'17
Andra2	Fibercore-AFL cables	1000 (~10 kGy/h)	3-5	2	10-20	??	T measured	Distributed Rayleigh and Brillouin	Neubrescope,	Nov'17
Andra3	Brugg V9-IXblue cable	1000 (~10 kGy/h)	3-5	3.2	10-20	>20	T measured	Distributed Rayleigh and Brillouin	Neubrescope	Nov'17
Andra4	Pt probes	1000-10000 (~10 kGy/h)		6	0.15	NA	T measured	Offline	Post Mortem	Nov'17
Andra5	Fibers	1000 (1000) (~10 kGy/h)	~20	Variable	10		T measured	Offline		Nov'17
IRSN1	UMI sensors	1OOO (~10 kGy/h)	~20	10	0.01		Ambient T	Offline	Post Mortem	Nov'17
M1		<10kGy	6	Variable	15		Controlled: T, Humidity	On Line	UMONS FBG interrogator	Oct-Nov '17
M2	Functionalised Silica sensor, PMMA FBG and CYTOP FBG	Up to 200kGy	6	Variable	15	>20	Controlled: T, Humidity	On Line	UMONS FBG interrogator	Oct'17
M3		<10kGy	4+	Variable		>20	Controlled: T, Humidity, H2 [*]	On Line	UMONS FBG interrogator	2018
CEN1		1(0.7 kGy/h)	1	<60	n/A	N/A	Controlled T H	Offline	C&S	Oct'17
CEN2	mINT photonic chip	2(0.7 kGy/h)	1	<60			Controlled T H	Offline	C&S	Oct'17
CEN3		4(0.7 kGy/h)	1	<60			Controlled T H	Offline	C&S	Oct'17
CEN4		1(0.7 kGy/h)	3+3		15	>5	Controlled T H	Online T and strain	C&S	Oct'17
CEN5	Optical fibres Strain and T	2(0.7 kGy/h)	3+3		15	>5	Controlled T H	Online T and strain	C&S	Oct'17
CEN6		4(0.7 kGy/h)	3+3		15	>5	Controlled T H	Online T and starin	C&S	Oct'17