PROJECT FINAL REPORT

Grant Agreement number: 232598

Project acronym: MODERN

Project title: Monitoring Developments for safe Repository operation and staged closure

Funding Scheme: FP7 Euratom - Collaborative project – Medium-scale focused research project

Period covered from 01/05/2009 to 31/10/2013

Name, title and organisation of the scientific representative of the project's coordinator:

Nicolas SOLENTE, scientific coordinator, ANDRA

Tel: +33 1 46 11 81 49

Fax: +33 1 46 11 82 68

E-mail: nicolas.solente@andra.fr

Project website address: www.modern-fp7.eu

Contents

Note: Large parts of the text of this report are extracted or adapted from "The MoDeRn Project Synthesis - Modern deliverable D-6.1" Edited by M.J. White (Galson Sciences Limited).

1. Executive summary

Spent nuclear fuel and long-lived radioactive waste must be contained and isolated for very long periods, and current schemes for its long-term management involve disposal in deep geologic repositories. The successful implementation of a repository programme for radioactive waste relies on both the technical aspects of a sound safety strategy and scientific and engineering excellence as well as on societal aspects such as stakeholder acceptance and confidence. Monitoring is considered key in serving both ends. It underpins the technical safety strategy and quality of the engineering, and can be an important tool for public communication, contributing to public understanding of and confidence in repository behaviour.

The main goal of MoDeRn (**Mo**nitoring **De**velopments for safe **R**epository operation a**n**d staged closure), a four year Collaborative Project funded under the 7th Framework Program for Nuclear Research and Training (EURATOM) was to establish a roadmap for developing and implementing various monitoring activities for deep geological repositories. This 'reference framework' draws on experiences and lessons learned from waste-management programmes in different countries and integrates new information from various stakeholder-engagement activities. For instance, MoDeRn has reviewed broadly accepted monitoring objectives and elaborates them to better reflect the actual implementation of disposal monitoring activities.

As a core part of its activities, MoDeRn provided a clear description of monitoring objectives and strategies, taking into account a variety of physical and societal contexts, available monitoring technology, and feedback from both expert and non-expert stakeholder interactions. In relation to this, the project has defined the technical requirements of monitoring activities and has assessed the latest relevant technology. A technical workshop involving other monitoring Research and Technology Development (RTD) projects was hosted to identify RTD techniques that enhance our ability to monitor deep geological repositories. In particular, innovative monitoring approaches specific to repository design requirements are being tested within underground research laboratories. In addition, several case studies were developed to illustrate the process of mapping objectives and strategies onto the processes and parameters that need to be monitored in a given context, to illustrate the potential design of corresponding monitoring systems and possible approaches to prevent and detect measurement errors.

Interaction with stakeholders was at the heart of the MoDeRn project. Workshops and presentations at major conferences provided opportunities to report and discuss results with the research community, experts (e.g. from technical safety organisations) and non-experts (e.g. from civil society) and to collect feedback. A website (**www.modern-fp7.eu**) provides updated information about progress (e.g. via project Deliverables) and events (e.g. workshops) as well as access to relevant publications. An international conference on repository monitoring was hosted on March 19-21, 2013 at EC facilities in Luxembourg and was attended by 120 people from 18 countries.

Collectively, these activities formed the basis for a 'roadmap for repository monitoring' and are expected to have a significant societal impact. The project aimed to propose an approach to enhancing confidence in the disposal process by describing feasible monitoring activities, highlighting remaining technological obstacles, illustrating the possible uses of monitoring results and suggesting ways to involve stakeholders in the process of identifying monitoring objectives. The resulting ‘roadmap’ should enable radioactive waste management organisations in Europe and beyond to further progress towards implementing deep geological repositories that are safe and acceptable for all.

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

2. Final results and potential impact

Monitoring is considered key in serving both the technical aspects of a sound safety strategy and scientific and engineering excellence as well as the societal aspects such as stakeholder acceptance and confidence. It underpins the technical safety strategy and quality of the engineering, and can be an important tool for public communication, contributing to public understanding of and confidence in repository behaviour.

A reference framework providing guidance and advice for the development, implementation and use of a monitoring programme and discussing the potential interest and implication of stakeholders in this socio-technical activity should be beneficial to European and International Waste Management Organizations. The expected impact is to enhance their ability to move forward towards a successful, i.e. a safe and accepted implementation of the disposal process of which they are responsible.

The project results, presented as guidance and advice, condition the extent of this impact and are aimed at closely tying monitoring into the overall disposal programme. Overarching motivations – providing confidence in the disposal process and support for stepwise decision making – are related to main monitoring objectives, which in turn can be linked to processes and parameters, confronted to technical feasibility, and used to discuss the handling of hypothetical monitoring results as input to disposal process decisions. These developments should assist Waste Management Organizations to develop a realistic monitoring programme, with a clear understanding of its implementation and use during the disposal process:

- The development of monitoring objectives is directly related to safety functions and expected performances of associated barriers;
- The analysis of technical requirements confronted with the State-of-the-Art of relevant monitoring technology and on-going experience with associated RTD provides a basis to evaluate technical feasibility and limitations of the type of information monitoring can contribute;
- The engagement activities in several countries provide a basis for understanding stakeholder expectations pertaining to (i) monitoring objectives and (ii) the governance of developing, implementing and using the monitoring programme and recommendations for future engagement on this complex socio-technical activity;
- The suggestions on how to handle hypothetical monitoring results that deviate from prior predictions, especially if they should no longer support the normal or reference safety scenario, provide a basis to develop action plans taking into account such deviating results.
- The overarching motivation for monitoring is to enhance confidence of all stakeholders, by providing in-situ evidence underpinning the basis for safety, and thus prepare a future decision to close the repository. The expected impact of the MoDeRn project on repository programmes in their early development is to provide a basis understanding of the potential use and requirements associated with a monitoring programme. The expected impact on more advanced repository programmes is to provide guidance on how to conduct the focused developments needed to identify objectives, provide technologies and associate stakeholders consistent with the national context of each programme.

Table 1: List of MoDeRn Project Partners

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

List of Acronyms

2D:	Two-dimensional
3D:	Three-dimensional
AE/MS:	Acoustic emissions and microseismics
BER:	Bit error rate
CEMRC:	The Carlsbad Environmental Monitoring and Research Center
CRInSAR:	Corner reflector interferometric synthetic-aperture radar
DIC:	Digital image correlation
EBS:	Engineered barrier system
EC:	European Commission
EDZ:	Excavation disturbed zone
EIA:	Environmental impact assessment
EIS:	Electrochemical impedance spectroscopy
FEPs:	Features, events and processes
FP7:	Seventh European Community Framework Programme
HLW:	High-level waste
IAEA:	International Atomic Energy Agency
ILW:	Intermediate-level waste
LED:	Light-emitting diode
LL-ILW:	Long-lived intermediate-level waste
LLW:	Low-level waste
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure
NEA:	Nuclear Energy Agency
R&D:	Research and development
RTD:	Research and technological development
SNR:	Signal-to-noise ratio
SOTA:	State-of-the-art
S&T:	Science & Technology or scientific and technological
UK:	United Kingdom
URL:	Underground research laboratory
US:	United States
WIPP:	Waste Isolation Pilot Plant
WMO:	Waste management organisation
WSNs:	Wireless sensor networks

Glossary

This glossary provides definitions of terms that are used within this report and which are either specific to monitoring or have a specific meaning/definition within the MoDeRn Project.

Deviating Behaviour: Repository evolution that is inconsistent with the assumptions in the safety case.

Disposal Cell: The excavation in which waste is emplaced, as envisaged in the French concept for disposal of HLW.

Drift: Drift is the slow change in the response of a sensor over time owing to physical and chemical phenomena affecting the way that the sensor responds.

Engineered Barrier System (EBS): The man-made components of the repository, typically comprising the wasteform, the waste container, the buffer, the backfill, and the plugs and seals.

Extrinsic Sensor: A sensor that acts as a means of relaying signals from a remote sensor to the electronics that process the signals.

Features, Events and Processes (FEPs): Features are distinct parts or characteristics of the system. Events are changes to a system that may be characterised by a frequency of occurrence. Processes are on-going chemical and physical changes in a system.

Intrinsic Sensor: A sensor that acts as the sensing element.

LIDAR: A technology that measures distance by illuminating a target with a laser and analysing the reflected light.

Main Objectives: The specific, high-level goals of a monitoring programme. The MoDeRn Reference Framework recognises four high-level goals for monitoring: to support the basis for repository performance evaluations, to support operational safety, to support environmental protection, and to support nuclear safeguards. Supporting the basis for repository performance evaluations includes the two different aspects of supporting the basis for the long-term safety case and supporting pre-closure management of the repository.

MoDeRn Reference Framework: Information and guidance provided by the MoDeRn Project, which can be used to support the development of a comprehensive monitoring programme. The MoDeRn Reference Framework describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders in the development and implementation of a monitoring programme. The MoDeRn Reference Framework is represented by the published reports from the MoDeRn Project.

MoDeRn Monitoring Workflow: A structured approach to the development of a specific monitoring programme.

Monitoring System Failure: An instance when the outcome of implementing the monitoring system does not comply with the specified response to chemical and/or physical phenomena occurring in the repository.

Node: A device for measuring a parameter and transmitting the measured data to a receiver.

Overarching Goals: High-level statements that define the contribution of monitoring to the implementation of geological disposal. The MoDeRn Reference Framework recognises two overarching goals that all monitoring programmes will contribute towards: to support confidence building and to support decision making.

Pilot Facility: A region of the underground repository used to emplace and monitor a small but representative fraction of the waste. A pilot facility would be developed early in the operational phase of repository implementation, in order to provide information on the behaviour of the barrier system and check predictive models, and to allow early detection of any undesirable characteristics. It will also serve as a demonstration facility that provides input for decisions regarding closure of the entire facility. The waste in the pilot facility would be retrieved following operation of the facility and would be disposed of in the main repository. The pilot facility would be developed in a separate region of the repository to the main waste emplacement areas.

Parameters: Numerical indicators of properties related to FEPs.

Preliminary Parameter List: A list of possible monitoring parameters for which data could be collected to meet specific sub-objectives.

Pt100: A Pt100 sensor is a temperature sensor, in which temperature is calculated by measuring the resistance of a platinum element.

Repository Monitoring: Monitoring can have a wide interpretation. In this report, repository monitoring is used to refer to monitoring of the natural and man-made systems at a repository site.

Sub-objectives: Precise statements of the purposes of monitoring that allow the identification of processes and parameters to be monitored.

Sacrificial Cell: A sacrificial cell is an area in a repository in which real waste is emplaced and monitored for a specific period, after which the waste is retrieved and disposed of separately. Sacrificial cells are developed within the main body of repository alongside normal disposal cells for waste where there is no intention to retrieve waste.

Stakeholder: An actor with an interest in monitoring in relation to geological disposal of radioactive waste. Can include, but is not limited to, members of a WMO, regulatory organisations, advisory bodies, and members of the public and/or their representative bodies.

Trigger Values: Pre-defined results from a monitoring programme, which, if measured, would invoke further action.

3. Project context and objectives

MoDeRn builds on several decades of international (IAEA, 2001, 2006 and 2012; EC, 2004) and national initiatives. Key uses and purposes of a monitoring programme were defined (IAEA, 2001) as:

- To provide information for making management decisions in a stepwise programme of repository construction, operation and closure;
- To strengthen understanding of some aspects of system behaviour used in developing the safety case for the repository and to allow further testing of models predicting those aspects;
- To provide information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence - for as long as society requires - that the repository is having no undesirable impacts on human health and the environment;
- To accumulate an environmental database on the repository site and its surroundings that may be of use to future decision makers;
- To address the requirement to maintain nuclear safeguards, should the repository contain fissile material such as spent fuel or plutonium-rich waste.

The European Thematic Network (ETN) on Monitoring (EC, 2004) considered that monitoring aims at improving both the understanding of the role of and the options for monitoring within a phased approach to deep geological disposal of radioactive waste as well as to identify how monitoring can contribute to decision making, operational and post-closure safety and improve understanding of and confidence in repository performance.

Several national programmes, as in the US, Finland, Canada or Sweden, undertook programme-specific studies to develop national monitoring programmes associated with activities at specific sites. These programme-specific studies provide examples of monitoring objectives and the development of monitoring strategies, even specific requirements for monitoring included in national regulations, as in the US.

In 2007, both RWMC and Nirex organised an international workshop on repository monitoring in Geneva, Switzerland to "identify the general basis for the development of effective repository monitoring programmes". Among many outcomes, it recognized gaps in the development of strategic planning of international and national programmes. The value of further work on monitoring was stressed.

That same year, the EC launched the monitoring project initiative, which resulted in the MoDeRn project starting in 2009. The overall objective of the MoDeRn Project was to develop and document the collective understanding of repository monitoring approaches, technologies and stakeholder views to provide a reference point to support the development of specific national repository monitoring programmes.

The MoDeRn Project included:

- Consideration of monitoring objectives and strategies, and the development of guidance on the development of repository monitoring programmes that takes account of the applicable technical and societal context, the staged implementation of geological disposal, the capabilities of monitoring technologies, and the requirements of stakeholders (including regulators and public stakeholders), and is suitable for supporting decision making.
- Development and demonstration of innovative monitoring technologies that enhance the ability to monitor repositories, supported by a description of technical requirements and the state-of-the-art in monitoring technologies.
- Development of case studies that illustrate the process of mapping monitoring objectives and strategies to the processes and parameters that need to be monitored in a given context, the possible design of

monitoring systems, the use of monitoring to check compliance with the safety case, and possible approaches to prevent and detect failures in the monitoring system.

- Development of a better understanding of the views of public stakeholders on the role of monitoring in geological disposal, in order to provide information and guidance that could support the future development of repository-specific monitoring programmes, and, in particular, stakeholder involvement in the development and implementation of monitoring programmes.

From a technical point of view, monitoring of the engineered barrier system (EBS) is one of the biggest monitoring challenges faced by implementers. It is unique to geological disposal owing to the long timescales involved and the requirement that monitoring does not affect the passive safety of the disposal system. While the project partners recognised the importance of monitoring for operational safety, EIA and nuclear safeguards, these specific monitoring programmes are expected to call for monitoring activities and technologies similar to those already in use in tunnels and mines, at other nuclear installations, and in association with environmental protection, and it is assumed that their implementation can be planned and further developed based on prior experience. Therefore, the main focus of the technical work in the MoDeRn Project has been the monitoring of EBS performance.

In addition to the technical challenges of EBS monitoring, the other key challenge recognised at the outset of the MoDeRn Project was the development of an integrated monitoring programme (i.e. a programme that integrated a range of monitoring activities potentially derived from different perspectives). An integrated monitoring programme would reflect the range of drivers for undertaking monitoring and the multiple ways in which monitoring data could be used to support confidence and decision making during repository implementation. This includes the integration of routine operational safety, environmental or safeguards monitoring with monitoring of the EBS in support of the safety case, and, in particular, the role of monitoring in stakeholder engagement.

MoDeRn Project Activities

Eighteen partners were involved in the MoDeRn Project, representing organisations responsible for radioactive waste management (WMOs) in seven EU countries (ANDRA, DBE TECHNOLOGY, Enresa, NDA, Posiva, RAWRA and SKB), Switzerland (Nagra) the US (Sandia) and Japan (RWMC) as well as organisations with specialist expertise in monitoring (Aitemin, Euridice, NRG, and ETH Zurich) and a specialist radioactive waste management consultancy (Galson Sciences Limited). Three partner organisations offer specialist experience in researching how people interact with technology and finding ways to engage all stakeholders (e.g. civil society, experts, technical safety organisations, industry) in highly technical issues (the University of Antwerp, the University of East Anglia and the University of Gothenburg).

The programme of work included:

- Demonstration of monitoring technologies at three underground research laboratories (URLs) in Belgium, France and Switzerland
- Eight partner workshops.
- Several meetings of smaller partner groups on focused topics.
- A workshop (Oxford stakeholder workshop) involving expert stakeholders to verify whether the MoDeRn programme content was adequately designed to address their expectations, with an emphasis on developing repository monitoring programmes as well as progress on associated technological aspects of monitoring. The workshop results and provided feedback were incorporated into the remainder of the programme.
- A workshop (Troyes Monitoring Technologies Workshop) involving participants with technical expertise in monitoring in other industries such as oil and gas, mining and civil construction, including

involvement in other EC projects that are considering monitoring issues (MoDeRn, 2010a). The principal objective of the workshop was to identify techniques that could enhance the ability to monitor a repository,

- A workshop with stakeholders, which aimed to gain feedback on monitoring from regulators and advisory bodies (MoDeRn, 2011a).
- An international conference on monitoring in geological disposal of radioactive waste (MoDeRn, 2013a).
- Engagement with public stakeholder representatives from Belgium, Sweden and the UK, including a joint event with a number of these stakeholders at two underground research laboratories (URLs) in Switzerland.

Work in the MoDeRn Project was undertaken in a comprehensive and coherent programme of research structured into six interrelated work packages:

- **Work Package 1: Monitoring Objectives and Strategies:** Work Package 1 aimed to provide a clear description of monitoring objectives and strategies that (i) appear suitable in a given physical and societal context, (ii) may be implemented during several or all phases of the radioactive waste disposal process, (iii) appear realistic with respect to the capabilities of available monitoring technology, (iv) take into account feedback from both expert and public stakeholder interaction, and (v) provide information to support decision-making processes, while developing the licensing basis.

  Within the MoDeRn Project, programme challenges have been addressed by preparing a *reference framework* for monitoring activities in geological repositories. The reference framework identifies and discusses relevant issues that need to be considered during the development of a comprehensive monitoring programme, and describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders. The reference framework includes a structured approach to the development of a monitoring programme; this is referred to as the *MoDeRn Monitoring Workflow*. The reference framework aims to support radioactive waste management organisations (WMOs) in Europe and beyond as they further progress towards implementing geological repositories (MoDeRn, 2013b).

  As part of WP1, previous (national and international) work addressing monitoring in geological disposal was reviewed and the different national contexts of the participating partners was described, taking into account a variety of physical and societal contexts, and the different stages of the national disposal programmes (MoDeRn, 2010b). In addition, research into stakeholder engagement on monitoring has gathered feedback from both expert and non-expert stakeholder interactions, obtained through workshops, and other forms of dialogue (MoDeRn, 2012; 2013c).

- **Work Package 2: State-of-the-art and RTD of Relevant Monitoring Technologies:** The second work package focused on a description of the technical requirements on monitoring activities as well as an assessment of the state-of-the-art of relevant technology responding to these requirements (MoDeRn, 2011b, and MoDeRn, 2013d). It included the Troyes Monitoring Technologies Workshop (MoDeRn, 2010a). Technical research has been undertaken into innovative monitoring technologies that could address key challenges with EBS monitoring.

- **Work Package 3: *In situ* Demonstration of Innovative Monitoring Technologies:** The third work package aimed to develop *in situ* demonstrations of innovative monitoring techniques and provide a description of innovative monitoring approaches specifically responding to some of the design requirements of a repository. *In situ* demonstrations were undertaken in URLs in Belgium, France and Switzerland (MoDeRn, 2013c).

- **Work Package 4: Case Study of Monitoring at All Stages of the Disposal System:** The fourth work package was dedicated to a series of three case studies illustrating the process of mapping objectives and strategies onto the processes and parameters that need to be monitored in a given context, the possible design of corresponding monitoring systems, the use of monitoring to check compliance with the safety case, and possible approaches to prevent and detect failures in the monitoring system

- **Work Package 5: Dissemination of Results:** The fifth work package aimed at providing a platform for communicating the results of the MoDeRn Project. Two international meetings were managed through this work package: the stakeholders workshop with safety, regulatory and advisory authorities (MoDeRn, 2011a); and the international conference on repository monitoring (MoDeRn, 2013a). The work package also included implementation and maintenance of a project web site.

- **Work Package 6: Reference Framework:** The final work package consolidated results from the other work packages and provided a shared international view on how monitoring may be conducted at various stages of the disposal process.

The published reports from the MoDeRn Project are illustrated in Figure 1 and are available on the project website www.modern-fp7.eu.

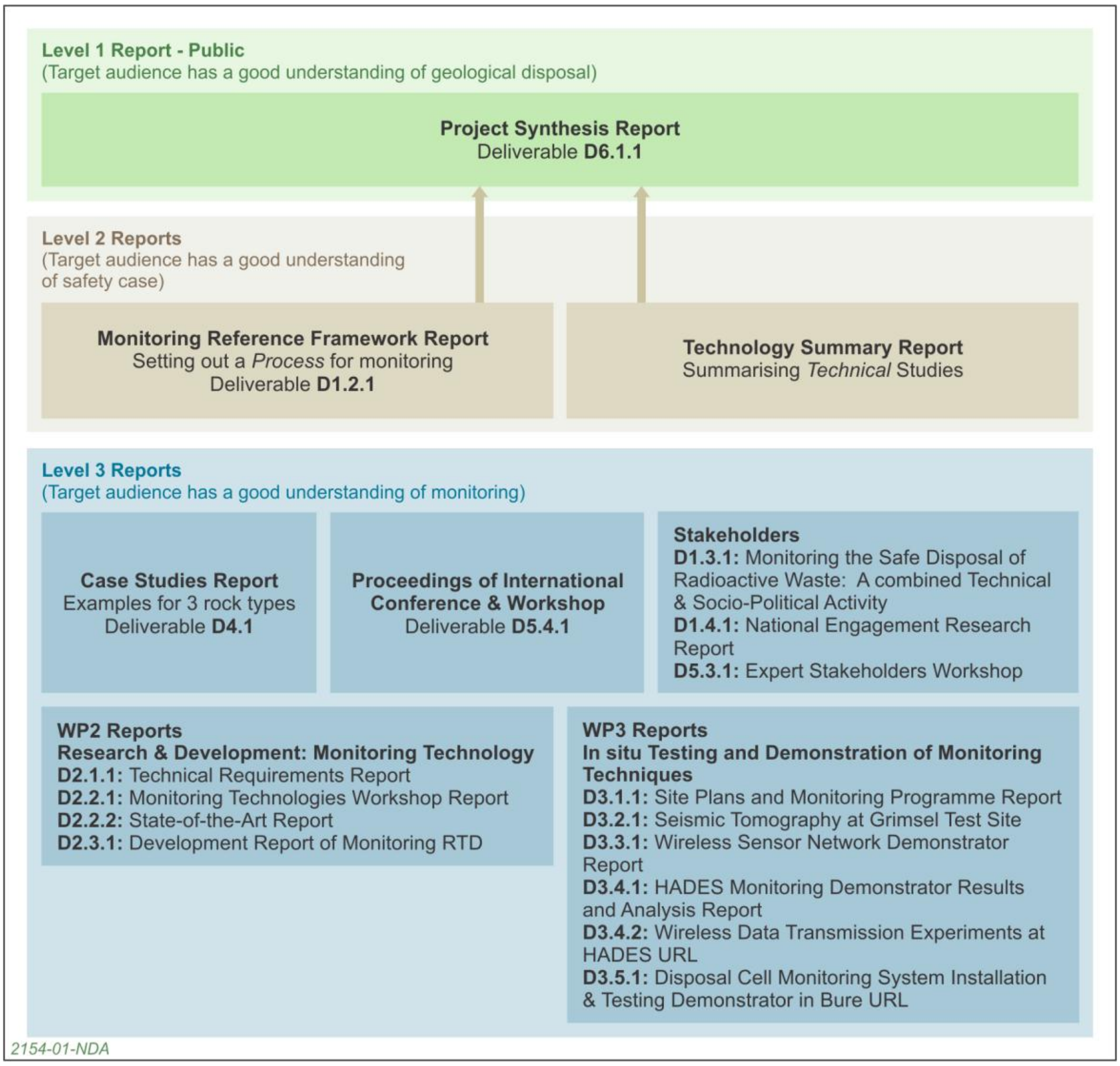

Figure 1: Hierarchy of published reports from the MoDeRn Project.

4. Description of the main S&T results/foregrounds

The work undertaken in the project is presented below in 4 chapters:

- A summary of the MoDeRn Monitoring Workflow and an introduction to the MoDeRn Reference Framework for repository monitoring.
- Technical aspects of repository monitoring, including a discussion of the current state-of-the-art of monitoring technology, and the outcome of specific research and demonstrator work undertaken at several URLs within the MoDeRn Project.
- A summary of the case studies that have been performed to test the MoDeRn Monitoring Workflow and to illustrate the application of monitoring technologies within such a framework. The use of monitoring to check compliance of repository performance with the safety case, and the ability to detect monitoring system failures are briefly presented in this chapter.
- A summary of the research into stakeholder participation in monitoring programmes within the MoDeRn Project.

4.1.Reference Framework for Repository Monitoring

Prior to the MoDeRn Project, guidance on the development of monitoring programmes at the international level was limited to general requirements and described how monitoring can support the implementation of geological disposal in a broad sense (IAEA, 2001; EC, 2004). The MoDeRn Project identified a need to develop more detailed information and illustrations, and to develop and propose a structured approach to provide guidance to national programmes on how to implement and use a monitoring programme. The information and the structured approach would build upon the existing general guidelines, but would be more focused on the actual implementation of a monitoring programme. It would also incorporate lessons learnt from those national programmes having already conducted monitoring or commenced development of a monitoring programme.

The MoDeRn Project provides advice on how monitoring might be integrated within a repository programme by proposing a Monitoring Reference Framework.

The MoDeRn Reference Framework identifies and discusses relevant aspects that need to be considered during the development of a comprehensive monitoring programme, and describes feasible monitoring activities, highlights remaining technological obstacles, illustrates the possible uses of monitoring results and suggests ways to involve stakeholders. The Monitoring Reference Framework provides advice to WMOs that can be used to support development of a monitoring programme that is consistent with their national repository programme, realistic to implement, and would provide information suitable for decision making.

The advice is illustrated by the MoDeRn Monitoring Workflow (Figure 2) a structured approach to developing, implementing and operating a monitoring programme. The themes developed more specifically in the MoDeRn Project are:

- How monitoring objectives may be developed and their role in the disposal process understood. In particular, how to develop the Main Objectives of a monitoring programme into clear information requirements related to key safety functions, and which can then be used to propose processes and parameters to be monitored.
- How monitoring systems may be designed and what strategies may help in meeting the monitoring objectives. These will include strategies to address technical limitations, with an outlook for further research and development (R&D), and, more generally, strategies to develop the potential for added value

from a monitoring programme as well as an assessment of its limitations for supporting decisions on the implementation of geological disposal.

- How monitoring should be addressed as part of the overall governance of the repository implementation process, guidance on how monitoring results would inform and thus contribute to management decisions, how they would be evaluated against prior expectations, and how monitoring results deviating from such prior expectations could be addressed.
- How monitoring might contribute to stakeholder confidence – to discuss how the evidence expected from testing the validity of the licence basis prior to closure, the process overall and the roles different stakeholders may play could contribute to enhancing confidence in the repository implementation process.

The Monitoring Reference Framework report (MoDeRn 2013b) develops the themes highlighted above in more detail and provides recommendations on how to develop them within the context of a national repository programme. This should enable implementers to build upon previously established understanding of monitoring, and the process should take full advantage of the more detailed understanding already developed in certain national repository programmes.

The Monitoring Reference Framework does not provide a description of a reference monitoring programme. Indeed, the project clearly recognises the diversity of national contexts and, as a result, the diversity of monitoring solutions that are likely to be developed. However, examples are provided to illustrate how the information developed in the MoDeRn Project can support development of a monitoring programme.

The MoDeRn Monitoring Workflow as part of the Reference Framework (Figure 2) illustrates the developed step-by-step process for identifying what is required from monitoring and developing those requirements into a defined programme through analysis of these requirements. The Workflow identifies three key stages in developing and implementing a monitoring programme:

1. Objectives and Parameters: Identification of the Main Objectives and sub-objectives, and relating these to processes and parameters to identify a Preliminary Parameter List for monitoring.
2. Monitoring Programme and Design: An analysis of performance requirements, available monitoring technology and overlaps/redundancy to design a monitoring programme.
3. Implementation and Governance: Conducting a monitoring programme and using the results to inform decision making.

The MoDeRn Monitoring Workflow envisages a top-down approach to the development of a monitoring programme, that starts from a high level (i.e. the Main Objectives), including engagement with all interested parties, and uses these to develop more detailed monitoring requirements. A top-down approach can be used to ensure comprehensiveness, transparency and traceability and should also help to ensure that a monitoring programme is properly focused on priorities. However, in practice, the development of a monitoring programme is expected to be iterative, i.e. result from several cycles of evaluation of the safety case.

Early development of monitoring programmes applying the process described in the Workflow should help the implementer and stakeholders to understand the approach to monitoring and provide a basis for engagement on monitoring programmes. All stages of the Workflow process are discussed in more detail in the MoDeRn Reference Framework report (MoDeRn, 2013b).

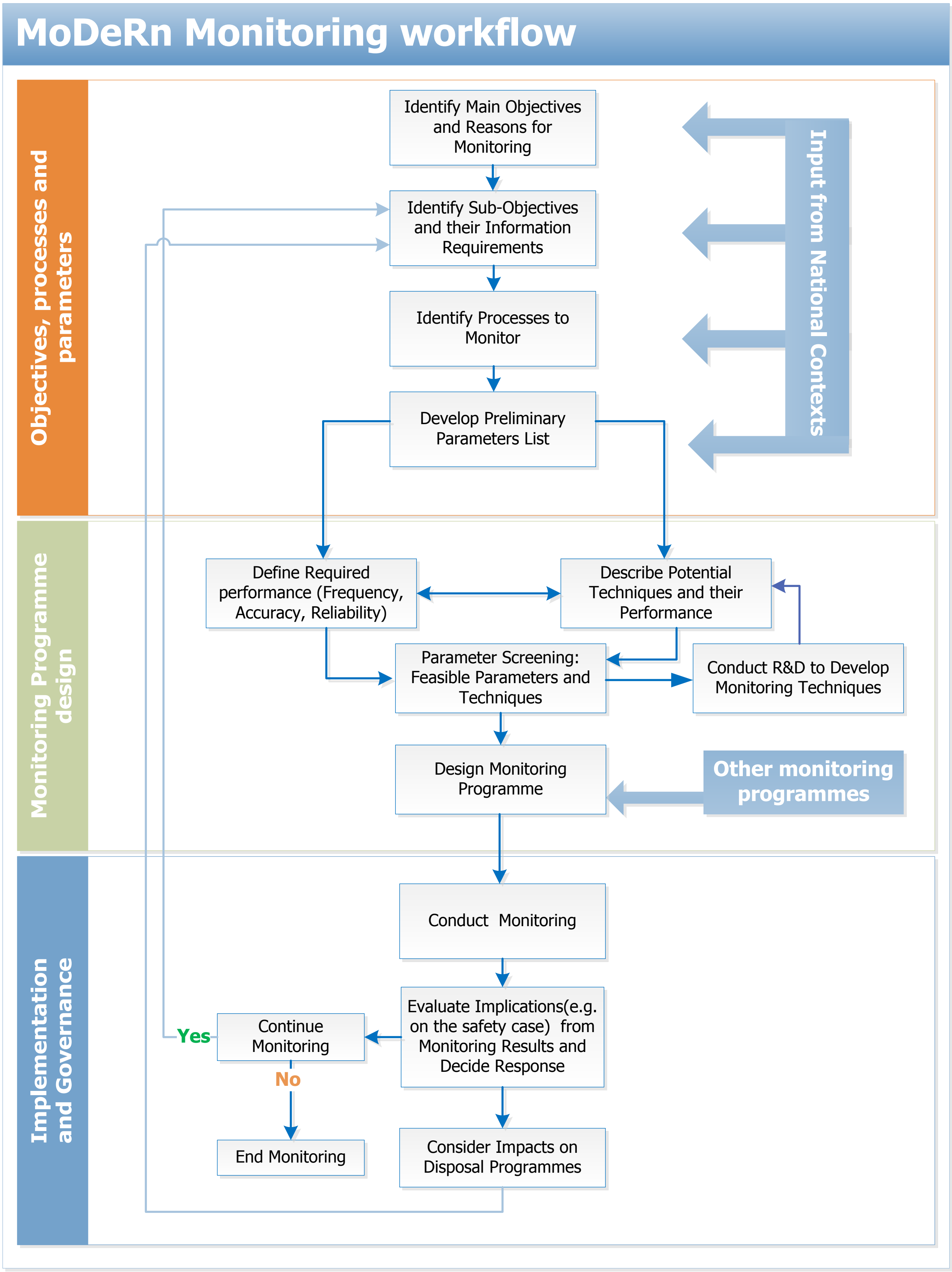

Figure 2: The MoDeRn Monitoring workflow

4.2. Technical aspects of repository monitoring

This chapter provides a summary of the technical research undertaken into monitoring technologies within the MoDeRn Project.

The first three sections provides an introduction to monitoring technologies by discussing some of the technical requirements and technical challenges posed by repository monitoring, and by summarising some of the lessons that can be taken from a consideration of the state-of-the-art in repository monitoring and in other related industries (e.g. oil and gas industry, carbon sequestration, mining and civil engineering). More detailed descriptions of the monitoring technologies can be found in the MoDeRn state-of-the-art report (MoDeRn, 2013d).

The fourth section summarises RTD work undertaken on monitoring technologies as part of the MoDeRn Project. There is a wide range of technologies available for repository monitoring. These include geophysical and remote sensing techniques that facilitate the acquisition of data on the general phenomena resulting from repository evolution. These phenomena include the surface manifestations of processes and events occurring within the repository, such as vertical displacement of the ground in response to first excavation (leading to subsidence) and then thermal expansion in response to the heat output from the waste (which leads to uplift).

In addition to technologies that can be used to model general phenomena, there are several innovative technologies that could be applied for direct monitoring of the near field, and these technologies include non-intrusive monitoring where signals are transmitted and/or acquired remotely from the near field, and in situ monitoring where measurements are taken in the near field and wireless data transmission systems are used to transfer the acquired data to receiver stations either within other (un-backfilled) parts of the repository or to the surface.

4.2.1. Technical Requirements and Technological Challenges

The MoDeRn Monitoring Workflow has been presented as an overall methodology for addressing the programmatic issues and challenges related to monitoring. There are also many practical issues and challenges related to the technology needed for monitoring. Technology is of key importance because it determines what can be measured, with what precision, and with what reliability over the long timescales and challenging conditions envisaged.

Monitoring technologies exist for monitoring the parameters that are likely to be of interest in understanding the evolution of repository systems. These parameters include temperature, mechanical pressure, hydraulic pressure, water content/saturation, salinity, radiation, displacement, deformation, humidity, gas concentration (oxygen, carbon dioxide, hydrogen and methane), gas pressure, pH, Eh, concentration of colloidal particles in solutions and alkalinity. However, the nature of the waste, geological environment and disposal concepts envisaged for disposal of radioactive waste place specific technical requirements on the capabilities of monitoring technologies that must be addressed before successful repository monitoring can be undertaken.

The environmental conditions in a repository are likely to be more aggressive to some monitoring equipment than in other applications, and are likely to exceed the conditions for which monitoring equipment was originally designed. This necessitates the development of specialised equipment to meet extremes in temperature, mechanical pressure, hydraulic pressure, water saturation, salinity, radiation and displacement.

Furthermore, as the rate of transient processes occurring in the near field is expected to be slow relative to the monitoring period, and because there is a requirement that monitoring should not compromise the passively safe design (IAEA, 2011), additional considerations need to be addressed in developing a monitoring programme, especially when the monitoring is concerned with near-field monitoring after the emplacement of waste and engineered barriers. These include developing compromises between access (boreholes, etc.) for data transfer and energy supply, versus the challenges of providing in situ power over long periods, for example to allow remote monitoring and wireless transmission of monitoring data. When considering the long timescales involved in monitoring, issues like drift of measuring devices and the need for calibration, reliability/longevity and the possibility for repair or replacement (without creating undue disturbances) is a relevant aspect that must be considered for the application in repository monitoring.

Development of specialised monitoring technologies and equipment for application in repository settings expands the options available for developing a monitoring programme. Technologies for repository monitoring can be based on:

- Use of available technologies that respond to the needs of repository monitoring.
- Development of specific adaptations of available technologies (e.g. to enhance resistance to environmental conditions).
- Development of new technologies.

The strategy for developing a monitoring programme also influences the technical requirements on monitoring equipment. This includes the use of pilot facilities and/or sacrificial cells, which may be decommissioned prior to the closure of a repository; more intrusive monitoring may be appropriate for these strategies.

4.2.2. State-of-the-Art in Monitoring Technologies

In order to provide an overview of the current capabilities of repository monitoring technologies, a state-of-the-art report has been compiled as part of the MoDeRn Project (MoDeRn, 2013d). The state-of-the-art report provides:

- A general introduction to the parameters potentially of interest for monitoring (the actual parameters of interest will depend on the specific monitoring programme), the components that might need monitoring, and the associated requirements and constraints.
- An overview of the state-of-the-art for technologies that may be used for repository monitoring, including a list of references for each monitoring technology considered.
- A summary of the advantages and disadvantages of each technology, and identification of R&D requirements to address the disadvantages.
- A conclusion on the feasibility and limitations of the technology for repository monitoring.

In the report, emphasis was placed on sensors, signal and data transmission, and local energy sources, because these are the aspects of monitoring technologies identified as most relevant to EBS monitoring, which is the focus of the MoDeRn Project. The information in the state-of-the-art report built on the existing knowledge and experience of the project partners, including experience on the strengths and weaknesses of the different monitoring technologies developed in experiments and in technology development projects in URLs. In addition, information from the Troyes Monitoring Technologies Workshop (MoDeRn, 2010a), and the outcome of RTD and demonstration activities (see Research and Technology Development (RTD page19), all of which were undertaken as part of the MoDeRn Project, were incorporated in the state-of-the-art report.

4.2.3. Monitoring State-of-the-Art in other related applications

As part of the MoDeRn Project, the Troyes Monitoring Technologies Workshop was held at the Université de Technologie de Troyes (UTT), France on 7-8 June 2010. The workshop brought together 55 experts from a range of organisations, including industry, WMOs and research institutes (MoDeRn, 2010a). The general aim of the workshop was to bring together monitoring specialists from a range of disciplines to present and discuss their work and experience in applying state-of-the-art monitoring techniques. The specific objectives of the workshop were to:

- Review recent developments in monitoring technologies.
- Stimulate a mutually beneficial exchange of experiences, applications and views between the radioactive waste management community and monitoring technology experts from other fields.
- Facilitate knowledge transfer, e.g. identify EC projects with a monitoring component.

The outcomes of the Troyes Monitoring Technologies Workshop are summarised below and are described in more detail in the Workshop report (MoDeRn, 2010a). This includes identification, at the time of the workshop, of the technologies under development or being applied in other industries that may have applications in repository monitoring, noting that some of the technologies discussed at the workshop are already being applied or developed within national and international radioactive waste management projects.

Wireless sensor networks (WSNs) consist of spatially distributed autonomous sensors used to monitor structures and/or environmental conditions (Römer and Friedemann, 2004). Transmission is generally considered through-air, with a lesser or greater ability to transmit through obstacles. Developments in WSNs and through-the-earth data transmission are of interest to repository monitoring as these technologies may support the transmission of monitoring data from the near field of the repository system without affecting the passive safety of the EBS. As such, research in this area has been undertaken within MoDeRn.

A fibre optic sensor is a sensor that uses an optical fibre either as the sensing element (intrinsic sensors), or as a means of relaying signals from a remote sensor to the electronics that process the signals (extrinsic sensors) (Measures, 2001; Yin et al., 2008). Optical fibres have a wide range of potential applications because they can operate under harsh environments, including environments with strong electromagnetic fields, high temperatures, explosive potential, aggressive chemical species or ionising radiation. The principal application for fibre optic sensors in repository monitoring is the measurement of parameters such as strain, pressure and/or temperature within the near field. Fibre optic sensors provide distributed monitoring and, as such would be suitable for monitoring the 3D parameter-field rather than the single location measured by traditional measurement devices.

Seismic interferometry uses cross-correlation techniques to map the velocity structure of the sub-surface, using background seismic signals (Campillo and Paul, 2002; Snieder, 2004; Snieder, 2006; Wapenaar and Fokkema, 2005). Changes in the velocity structure can be used to develop an understanding of the impact of processes on the physical properties of the sub-surface, and thereby to develop an understanding of the processes themselves. Future developments could allow monitoring of physical changes in the sub-surface (e.g. gas generation and migration, and increases in temperature), although this would be highly dependent on the geological environment.

Seismic reflection surveys provide information on the velocity structure of the sub-surface by recording the reflection of a known seismic source. Time-lapse three-dimensional (3D) seismics can be used to image the movement of fluids within the earth (European Association of Geoscientists and Engineers, 2003), e.g. a gas plume. Seismic reflection could be used to monitor gas generation and migration, although this would be highly dependent on the geological environment and disposal concept.

Acoustic emissions and microseismic (AE/MS) surveys monitor fracturing in rock and man-made materials through measurement of the seismic signals emitted when materials fracture (Young and Martin, 1993). AE/MS monitoring has the potential to monitor the mechanical evolution of the EBS following closure of a disposal cell, prior to closure of the access ways and service areas within a repository (i.e. to be used as part of a staged closure process).

Geotechnical monitoring will be required in geological repositories to determine the physical nature of the rock mass, and the rock mass response to excavation, emplacement of waste and closure of the facility (Bell, 2007). Geotechnical monitoring will contribute to confirming the host rock response to construction and operation, and thus may contribute to the demonstration of operational safety. In terms of the state-of-the-art in geotechnical monitoring recognised at the Troyes Monitoring Technologies Workshop:

- Strain monitoring using extensometers and tell-tales can now monitor millimetre-scale displacements in tunnels.
- Stress monitoring can detect the impact of the excavation on the in situ stress up to 100 m from the tunnel.

Surface monitoring using air-based and satellite-based systems can be used to develop an understanding of the changes to the ground as a result of repository development and to monitor for unexpected activity. Satellite-based optical imaging technology is readily available with a 50 cm resolution, and satellite-based corner reflector interferometric synthetic-aperture radar (CRInSAR) provides millimetre-scale monitoring of changes in ground elevation.

4.2.4. Research and Technology Development (RTD)

Innovative EBS monitoring technologies have been the focus of RTD work within the MoDeRn Project, and this work has brought the technical readiness of a range of potential technologies closer to that required for deployment within repository projects.

a. New algorithms for full waveform elastic inversion of seismic tomography

New algorithms for full waveform elastic inversion of seismic tomography data have been developed and practical methods for acquiring tomographic data have been developed through testing at Mont Terri and Grimsel. These developments enhance the ability to monitor a range of processes (e.g. saturation, and gas generation and migration) that affect the velocity structure of the near field. See MoDeRn (2013g) for further information.

- Potential use: As the EBS evolves, for example through resaturation, the generation and migration of gas, and, potentially, through displacement, the seismic signature will vary. Such variations could be detected through seismic tomography. Seismic tomography has, therefore, the potential to support the post-emplacement monitoring of the EBS
- Research results: The research undertaken within the MoDeRn Project has significantly advanced the potential for using seismic tomography to monitor the EBS:
    1. Experimental design: Criteria have been established for specifying the optimal spatial and temporal sampling strategies for EBS monitoring
    2. Validity of the acoustic approximation: Extensive numerical experiments revealed that the acoustic approximation used to translate seismic waves into a velocity structure is not adequate for monitoring radioactive waste repositories. Elastic inversion schemes should be used instead
    3. Non-linearity issues: research has identified where currently-available algorithms are expected to be successful and when they are likely to fail, due to the highly non-linear mathematical formulation of the transformation of the waveform information into a velocity model.
    4. Anisotropic inversions: Anisotropic and elastic waveform algorithms have been successfully developed, and initial synthetic inversions have been undertaken to demonstrate the suitability of using these new algorithms for monitoring sedimentary rocks using seismic tomography.
    5. Coupling problems: Sensor coupling to the host medium is a critical issue. An algorithm has been developed and successfully tested and can be used to reliably determine the coupling factors.

b. Micro-seismic Monitoring

Micro-seismic events are localised seismic phenomena that can originate spontaneously during stress release (or build-up) in the rock mass, for example after an excavation, and are the result of the mechanical response of the rock. They can also originate during the emplacement of the waste or be induced manually by generating small seismic oscillations using a hammer or another type of signal-generating source against the rock mass

- Potential use: Micro-seismic monitoring may allow monitoring of the near-field response to waste and EBS emplacement. This monitoring could be undertaken prior to the closure of the access ways and service areas in the repository.
- Research results: A new seismic hammer for application in microseismic monitoring has been developed. The hammer will enhance the ability to generate strong S wave signals, and thereby improve the feasibility of conducting shear wave monitoring of the near field. This will improve the potential to provide information on changes to the EDZ, e.g. the mechanical response to heating. (MoDeRn, 2013i).

c. High-frequency Wireless Data Transmission

Development of wireless data transmission methods would allow for data measured by sensors emplaced within the EBS to be relayed to receiving stations, and would, therefore, represent a method for monitoring the EBS without the need for data transmission using wires. There are several well-recognised limitations in applying wireless data transmission to repository monitoring. One important limitation, owing to the remote nature of the measurement devices and the long period required for monitoring repository systems, is the need to consider an autonomous power supply to the sensors and to the transmission units

- Potential use: Given the low penetration rates achievable for the transmission of data through rock at high frequencies, the potential use of this technology is mainly focused on monitoring of the near field following emplacement of the waste and EBS, prior to the closure of the access ways and service tunnels. However, this technology could also be used following closure of the access ways and tunnels, provided appropriate methods for relaying the monitoring information were developed.
- Research results:

  1. The transmission distances for high-frequency signals at four frequencies were tested in the laboratory, and in the field. In laboratory tests, signals at 868 MHz and 433 MHz were capable of passing through 50 cm of bentonite, 25 cm of salty water and 40 cm of argillite rock; transmission distances at 2.4 GHz were lower. Field tests demonstrated that transmission distances at 169 MHz were greater, about 3.5 m in clay-based rocks and greater than 5 m in saturated bentonite, and this frequency was adopted for the demonstration tests in the MoDeRn Project

  2. Research into power supply considered energy harvesting using thermal gradients and high-performance batteries. Harvesting of thermal gradients is not currently viewed as a feasible method for the supply of energy to wireless nodes, because the storage of power between transmissions is not currently feasible with existing super capacitors. Instead, the wireless nodes developed for the MoDeRn Project used a $Li\text{-}SOCl_2$ battery combined with some high performance capacitors, with an expected lifetime up to 20 or 25 years.

d. Long-distance Wireless Data Transmission

Work on long distance wireless data transmission within the MoDeRn Project has investigated the transmission of data using low-frequency magneto-induction techniques. The use of low-frequency magnetic fields overcome problems with strong signal attenuation by solid media that occur with high-frequency technologies. In magneto-induction, magnetic fields are generated by a loop antenna that propagates through the host rock or elements of the EBS. This provides a potential method for transmitting monitoring data through plugs, seals and dams, between different parts of a repository or from the repository to the surface.

- Potential use: Regarding distributed sensing, the optical fibre monitoring techniques show a lot of potential. Low-frequency wireless data transmission techniques can potentially be used to transmit data over small, medium and large distances (i.e. from distances of several metres to distances of several hundred metres). The main advantage of using low-frequency techniques is the low attenuation of the transmission signal by the host rock or elements of the EBS.
- Research results: The key result of this part of the MoDeRn Project is that data transmission over long distances through the underground by magneto-induction techniques is possible. The research was successful in demonstrating wireless transmission of data through 225 m of an electrically highly-conductive geological medium, at frequencies up to 1.7 kHz, using antennae with a radius of approximately 3.5 m. The optimum data transmission channels were between 1.4 kHz and 1.7 kHz. Data transmission was achieved at several frequencies with data rates up to 100 sym/s and bit error rates below 1%. Based on the demonstrated performance and analyses of the underlying processes, it was estimated that transmission of monitoring data to the surface can be realized with about 1 mWs of energy per bit of transmitted data. This would allow transmission of 1,000 sensor readings, with 1% precision, on a weekly basis for 100 years with the energy equivalent of two cell phone batteries.

e. Monitoring using Fibre Optic Sensing

Optical fibres can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fibre so that the quantity to be measured modulates the intensity, phase, polarization, wavelength or transit time of light in the fibre. Data can also be collected from unmodified optical fibres from the backscattering of light out from the fibre.

- Potential use: Optical fibres may be selected for monitoring because of the small size of the fibres and because of their inherent multiplexing capabilities - many sensors can be combined along the length of a fibre by using different wavelengths of light for each sensor, or by sensing the time delay as light passes along the fibre through each sensor. These qualities make optical fibres suitable for repository monitoring; they provide an efficient means of monitoring a range of parameters. The principal application for fibre optic sensors in repository monitoring is the measurement of parameters such as strain, pressure and/or temperature within the near field. Fibre optic sensors provide distributed monitoring and, as such, would be suitable for monitoring the 3D parameter-field rather than the single location measured by traditional measurement devices.
- Research results: The measurements that have been obtained so far using the SOFO gauges in the three boreholes show that these sensors are able to quantify displacements with a resolution of 1 µm. Based on other quality factors, such as repeatability, the expected accuracy of this system in general can be estimated to be less than 10 µm over 10 m. This would allow monitoring of strain with an accuracy assumed to be appropriate for repository monitoring.

The use of fibre optics to monitor temperature and strain in the three orthogonal directions in the half-scale test have demonstrated its potential as an in-situ monitoring technology that generates very little disturbance and limited intrusion to the surrounding concrete structure being monitored. However, the measurement instruments needed to interrogate the fibres require direct access to the fibres. This means that the fibres will need to penetrate the structure, a condition that could limit its applicability as monitoring technology in a repository. The performance of optical fibres will depend in part on the way it is installed. Further understanding of installation procedures is therefore required, not only to avoid damages of fibres and connectors during installation, but also to develop confidence in the measurement results.

f. Digital Image Correlation (DIC):

DIC is an optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images. This is often used to measure deformation (engineering), displacement and strain, Digital Image Correlation (DIC) and acoustic emission (AE) monitoring have been successfully used to detect crack initiation and growth during a half-scale test of the Belgian Supercontainer. (MoDeRn, 2013i).

- Potential use: This technique could be used to monitor for the onset and evolution of cracks in general and in particular within the supercontainer prior to backfilling, and, should spaces in the repository not be backfilled, over the long term
- Research results: The test partially conducted under the framework of MoDeRn and was still undergoing at the end of the MoDeRn project.

g. Corrosion Sensors

Corrosion sensors typically detect metal corrosion through changes in the electrical current of the medium of interest. The corrosion rate can be estimated through measurement of the voltage or current between a reference electrode and the metal being monitored.

- Potential use: Corrosion sensors could be used to undertake in situ monitoring of the corrosion of disposal overpacks.
- Research results Corrosion sensors that can measure in situ corrosion rates have been developed and tested in surface facilities. (MoDeRn, 2013i).

These developments have significantly increased confidence in the ability to monitor the evolution of the near field, following waste, buffer and backfill emplacement, through monitoring in adjacent tunnels, during the progressive closure of a repository, and even post-closure.

In addition, work in other industries is also increasing the feasibility of using a range of other technologies for repository monitoring. These include work on wireless data transmission systems, fibre optics, seismic interferometry, time-lapse 3D seismic surveying, AE/MS monitoring, geotechnical monitoring of underground mines, satellite-based imagery and satellite-based radar. Within the MoDeRn Project, links were established between researchers in geological disposal and those in other industries, and it is anticipated that these links will help the future development of monitoring technologies.

However, the technologies are still limited in their applicability. Although the work in MoDeRn has addressed some of the key concerns for repository monitoring, e.g. power supply and remote transmission of data, further developments are required to develop the more novel technologies from being feasible/novel to being standard techniques widely applied in repository environments. In addition, it remains for WMOs to define how these technologies will be employed within national programmes. Work on integrated repository monitoring systems is presented in the next section of this report. This work serves to illustrate further how the technologies discussed in this section of the report can be mapped to specific parameters relevant to the safety case.

4.3. Case studies

The objective of the case studies is to illustrate that an approach to monitoring key safety case events and processes, or key pre-closure management decisions, can be developed for specific contexts based on existing technologies or on technologies with a reasonable likelihood of development in time for deployment in repository programmes, while using the approach presented in the MoDeRn Workflow as discussed in “Reference Framework for Repository Monitoring” on page 13.

Three examples were selected in order to develop monitoring programme case studies for the three principal types of host rocks considered for geological disposal: salt, clay and granitic rocks. Each one of these case studies has specific and different issues that challenge the implementation of monitoring programmes.

All of the case studies considered the specific national context, and do not represent generic monitoring programmes that could be applied in other national programmes without further tailoring and modification to reflect the national context:

- The *salt host rock case study* selected focused on the development of a post-emplacement and post-closure monitoring programme for disposal of HLW in the Gorleben salt dome in Germany (Bollingerfehr *et al.*, 2011). It is related to the monitoring objective *support the basis for the long-term safety case*. The salt rock case study includes consideration of how a monitoring programme can be used to detect near-field evolutions that are inconsistent with the assumptions in the safety case.
- The *clay host rock case study* selected focused on the monitoring of HLW in a disposal cell prior to closure of the repository. This case study was based on the reference disposal concept for HLW in France (ANDRA, 2005). It is presented in Section 4.3, and is related to the monitoring objective *support pre-closure management of the repository*. In addition to a theoretical discussion of the monitoring programme, testing and demonstration of the proposed programme has been conducted in the Bure URL as part of the MoDeRn Project.
- The *granitic host rock case study* selected considers the monitoring of the reference concept for spent fuel in Finland, which is based on the KBS-3V concept (Posiva, 2012). The case study considers the monitoring of emplaced waste, buffer and backfill to support the licensing process. It is related to the monitoring objective *support the basis for the long-term safety case*.

One of the key challenges in developing a monitoring programme is to have confidence in the data acquired using the monitoring system. This requires that failures in the monitoring system can be detected and strategies implemented for distinguishing between data that can be used in support of decision making and data that should not be so used. This requires an approach to detecting monitoring system failure, where *monitoring system failure* is defined as *an instance when the outcome of implementing the monitoring system does not comply with the specified response to chemical and/or physical phenomena occurring in the repository*. Section 4.4 provides a discussion of monitoring system failure detection.

4.3.1. German Case Study: Salt Host Rocks

Based on the existing repository concept for the Gorleben site, a repository layout was designed for the borehole disposal option that considers the disposal of spent fuel casks as well as HLW casks in 300-m-deep vertical boreholes drilled from underground access drifts with a diameter of 600 mm. An option to develop a further three emplacement fields for radioactive waste with negligible heat generation has also been considered.

In 2010, the German Ministry for the Environment launched new safety requirements for the disposal of high-level heat-generating waste (BMU, 2010). With regard to monitoring, the following statement is included in the safety requirements:

> *"A monitoring and evidence preservation programme must be used during emplacement operations, decommissioning, and for a limited period following repository closure, in order to verify that the input data, assumptions and statements of the safety analyses and safety cases performed for the phases are valid. In particular, this measurement programme should record the impacts of the rock's thermo-mechanical reactions on the heat-generating waste, technical measures and the rock-mechanical behaviour."*

In Germany, a concept for the demonstration of safety, the *Safety Assessment Concept*, has been developed (Mönig *et al.*, 2012). The safety concept relies on siting to ensure confinement by the geological barrier, and demonstration of confinement of radionuclides by the waste and the engineered barriers, in particular the drift and shaft seals.

The safety concept is captured within a hierarchical structure of protection goals, safety assessment components and safety functions. This hierarchy allows a link to be established between the safety functions of the repository components and the protection goals.

In order to derive a list of processes and parameters against which the monitoring programme can be developed, the MoDeRn workflow was followed and each of the safety functions identified was analysed in turn to identify a Preliminary Parameter List. In the salt rock case study, the analysis also considered the potential locations at which monitoring data could be collected for each parameter of interest.

Based on the Preliminary Parameter List, a Monitoring Programme was developed. The monitoring programme design is based on monitoring of specific components of the EBS and also monitoring of the overall repository system, and is arranged in a way that is representative for the overall repository system.

Except for specific components of the EBS, monitoring is based on instrumentation of a single representative monitoring field. It is considered beneficial for the representative monitoring field to be the first to be filled with waste containers. This allows monitoring data to be gathered from this representative, sealed monitoring field while emplacement continues in the rest of the repository. The information collected in this manner could be used as a basis for forgoing monitoring in the rest of the repository, i.e. it provides sufficient confidence in the repeatability of performance making it unnecessary to monitor all emplacement areas.

Monitoring would be undertaken within deposition boreholes and within access tunnels. Monitoring locations would be distributed over the monitoring field. Measurements would be taken in the centre of the field to capture the greatest increase in temperature and other measurements would be taken towards the edge of the field to capture the greatest gradients in the thermo-mechanical response to waste emplacement.

In order to monitor the safe confinement of waste by the waste containers in the boreholes, the placement of a monitoring canister (sometimes referred to as a dummy canister) at the top of an emplacement borehole, directly below the borehole seal, is envisaged. A dummy canister would not contain waste. This monitoring canister contains the necessary hardware to collect and transmit monitoring data out of the borehole, and it monitors the conditions at the top of a borehole filled with containers containing HLW. Sensors to measure temperature, moisture, pore pressure, and total pressure would be placed on the outside of the monitoring canister.

The dimensions of the monitoring canister are chosen in a way that the gap between the monitoring canister and the borehole wall is only a few centimetres, and any fluid flow into or out of the borehole would be detected by the sensors on the outside of the canister. In this way, brine intrusion that may result in the migration of radionuclides from the waste containers/liner system to the sealing plug of the borehole can be detected.

The monitoring data would be transmitted via a wireless transmission system to the borehole cellar at the top of the borehole, used to store the power supply, data recording, and transmitting devices. In the current disposal concept, there are no special requirements on the backfilling of the borehole cellar, so this may be a suitable site for placing monitoring equipment. There would be a need, however, to demonstrate that degradation of the monitoring equipment in the long-term would not affect long-term safety.

In addition to borehole monitoring, monitoring of the geological barrier and of the overall repository closure system would be undertaken through testing of the performance of the backfill, drift and shaft seals. Backfill and drift seals monitoring are not discussed further here (see MoDeRn, 2013l for potential monitoring approaches).

The safety function of the shaft seal is to prevent or at least significantly slow down the inflow of water or brine from the overburden into the repository after its closure. Furthermore, in the event that radionuclides are mobilised during the post-closure phase, the function of the shaft seal is to retain these radionuclides in the repository. This ensures compliance with the conventional safety objective *protection of the groundwater against hazardous contaminants* as well as with the radiological protection goal *protection of the biosphere against radionuclides*.

Monitoring of the shaft envisages monitoring at several monitoring levels. Each level is equipped with total pressure and pore water pressure sensors as well as a data transmission unit consisting of a wireless transmitter and a long-life battery. The data transmission technology envisaged is based on the high-frequency wireless data transmission technologies described in the RTD chapter.

Monitoring to Check Compliance with the Safety Case

A key objective for a monitoring programme is to check that the system is performing within the bounds assumed in the safety case. Within the MoDeRn Project, an analysis of the German test case was undertaken to build confidence that it could be used to monitor processes that could contribute to altered evolution scenarios and thereby threaten the passively safe performance of the repository. Thirteen alternative evolution scenarios have been recognised within the German safety assessment (Buhmann, 2011; Rübel, 2011 and VSG, 2011). The ability for the monitoring system to detect the physical manifestation of each one of these scenarios was considered through a qualitative assessment. For twelve of the scenarios, monitoring could detect the physical manifestations of the scenario, i.e. the specified monitoring could detect the presence of brine as a result of the scenario occurring (in the safety case, brine is a prerequisite for radionuclide migration to occur). The other scenario involved the development of glacial channels; this scenario has a timeframe outside of monitoring and would be addressed through siting (e.g. through location of the repository at an appropriate depth). The results of the qualitative consideration of altered evolution scenarios are presented in MoDeRn (2013l).

In addition, a quantitative evaluation of the ability of the proposed shaft monitoring system to detect an alternative evolution scenario was undertaken. This concentrated on the requirement for the shaft seal to prevent or significantly slow down the inflow of water or brine from the overburden into the repository after closure. The altered evolution scenario evaluated the pore pressure evolution assuming that the shaft seal had been incorrectly constructed, and that the properties of the seal had been affected, resulting in an increase of the hydraulic conductivity of the bentonite plug. Whilst for the reference scenario almost no pressure reaction will be detectable during the first 100 years, an increase in pore fluid pressure of 1-3 MPa would occur within 100 years after closure for the altered evolution scenario, and these increases are readily detected using the pore pressure monitoring system.

4.3.2. French Case Study: Clay Host Rocks

In France, a final site has been identified for a repository for HLW, spent fuel and long-lived intermediate-level waste (LL-ILW) in Callovian-Oxfordian age indurated clay in north-eastern France, close to the site of the Bure URL. The reference approach for management of spent fuel in France is reprocessing, but some spent fuel may not be reprocessed and may require direct disposal.

The French case study focused on monitoring of the HLW disposal package, specifically the overpack of the disposal package, and, therefore, discussion in this section refers only to monitoring of parts of the repository designed for disposal of HLW. Further details of the case study can be found in MoDeRn (2013l).

The overall safety objective recognised in the French programme is to protect man and the environment from radionuclides and other hazardous contaminants contained in the disposed waste. The depth of the repository protects it from long-term surface erosion and climate evolution. The long-term protection of man and the environment implies control and understanding of the physico-chemical degradation of the waste and waste forms, of the processes by which radioactive elements and toxic chemicals are confined as close as possible to their source, and by control and understanding of potential long-term transfer paths. While a transient potential of gaseous transfer is recognised and transfer in solid form is possible in the event of human intrusion, emphasis is placed in the safety case on transfer by water, either in dissolved or in colloidal form.

Therefore, one of the key functions of the multiple barrier system is to limit radionuclide migration to the biosphere by means of water. This can be further broken down to yield the following fundamental safety functions that have to be realised after repository closure (ANDRA, 2010):

- First Safety Function (SF1): Counter water circulation.
- Second Safety Function (SF2): Limit radionuclide release and immobilise radionuclides in the repository.
- Third Safety Function (SF3): Delay and reduce concentration of radionuclide migration outside of disposal cells.

The French 2006 Programme Act (Loi, 2006) mandates that geological disposal shall be reversible for a period of no less than one century. Prior to closure, therefore, the repository must be managed according to a reversibility principle, including the ability to retrieve waste packages from disposal cells. Ease of retrieval relies, in part, on waste package integrity (retrieval operations of a damaged package might lead to substantial technical complications) as well as on the conditions in the disposal cell (e.g. quality of ground support and cell environmental conditions such as hydrostatic pressures). In addition, the surface dose rates of the HLW overpack should be limited to allow the package to be handled.

The example monitoring design developed as part of the MoDeRn Project focused on the contribution of monitoring to the verification of the basis for the expected performance of the HLW overpack. This includes both the long-term safety case and pre-closure management in association with the retrievability function.

Within the MoDeRn Project, a qualitative analysis of the safety functions described above was undertaken and allowed the identification of a preliminary parameter list that addresses the recognised processes influencing the evolution of the HLW overpack. An example programme for monitoring the HLW overpack has been developed within the MoDeRn Project, highlighting several on-going monitoring developments within the French programme.

The strategy envisaged for the monitoring programme is to undertake monitoring from several locations and to use different types of disposal cell. Monitoring of standard cells could be undertaken through instrumentation of the cell liner, instrumentation of the sealing plate and/or instrumentation of boreholes surrounding the disposal cells. Fully instrumented disposal cells are referred to as *witness structures* by ANDRA. In addition, *sacrificial cells* may be used to monitor parameters that cannot be monitored remotely. A sacrificial cell is one in which real waste is emplaced and monitored for a specific period, after which the waste is retrieved and disposed of separately, as discussed below. The sacrificial cells may have a reduced length, for example 25 m. The concept of sacrificial cells is considered by ANDRA to be similar to the pilot facility proposed in other countries, with the exception that sacrificial cells are planned to be in representative locations inside the main part of the repository. The distribution of the monitoring elements within the repository has also been considered as part of the monitoring programme example, and includes:

- Liner instrumentation: Monitoring of the liner would incorporate temperature and strain measurements, focused on checking of the expected temperature evolution assumed in the long-term safety case, and strain of the liner for purposes of reversibility. Much of the monitoring would be undertaken using distributed fibre optic sensors.

- Instrumented Sealing Plates: To detect the presence of water in the cell, the possibility, in some cells, of incorporating sampling lines attached to metallic plates at the accessible end of the cell is being considered. The speed of corrosion will be assessed using indirect measurements, for example through monitoring of the gas content in the cell using miniature spectrometers. The progressive establishment of an anoxic atmosphere would be monitored using sampling lines from the plug and by measuring oxygen concentrations in the air.
- Instrumented Boreholes Surrounding Disposal Cells***:*** In order to support checking of the evolution of the repository near field in response to waste emplacement, monitoring of temperature, humidity, interstitial pressure, strain and gamma radiation is envisaged in boreholes surrounding the HLW disposal cells. The boreholes would be within a few metres of the cells. The inclusion of gamma radiation monitoring is proposed in anticipation of stakeholder expectations for such monitoring.
- Monitoring in Sacrificial Cells: Collection of information on corrosion of the HLW disposal overpack is considered important within the framework of the ANDRA monitoring programme. It is currently envisaged that material coupons will be placed in sacrificial cells. These cells would also include monitoring for a range of relevant processes. Monitoring of sacrificial cells be undertaken for 15-30 years after waste emplacement, to detect transition towards low rates of corrosion will occur over several years to decades.

The overall design of the monitoring system would allow for a limited number of witness structures and sacrificial cells in each disposal module. Standard disposal cells would not be instrumented. A small number of *current structures* would also be included; these would contain more limited monitoring instrumentation than witness structures. The number of witness structures would be determined by the expected heterogeneity of the processes being modelled. It is envisaged that 2-3 sacrificial cells would be required.

An illustrative layout of the monitoring system has been developed within the MoDeRn Project, and this has focused on the distribution of monitoring systems that would be required for monitoring of the temperature evolution of the near field following waste emplacement. Witness structures would be implemented early during the development of the repository to maximise the duration over which monitoring can be undertaken.

The monitoring strategy anticipates the integration of an initial module constructed from witness cells distributed (i) in the core of the module and at its edge, (ii) along the length of the access tunnel (air intake and air return), and (iii) with respect to time (i.e. monitoring the first cells in which waste is emplaced rather than the last cells to be filled). With some witness cells able to monitor for a range of processes, a pooling of resources made it possible to restrict the number to eight witness cells (out of approximately 200 disposal cells in the case of the ANDRA (2009) architecture) within the initial waste disposal module. The number of witness cells will be amended over time as the monitoring programme is optimised.

The monitoring envisaged within the illustrative monitoring programme described above was evaluated in an integrated monitoring demonstration during the MoDeRn Project. This has focused on the ability to conduct monitoring of the cell liner and near-field rock around a specially excavated disposal cell constructed in the Bure URL, and also to test the emplacement of the monitoring system, i.e. to evaluate whether the cell liner monitoring system could withstand construction procedures and provide reliable monitoring results following construction. The cell used in the demonstration was 40-m long.

Within the framework of the MoDeRn Project, the monitoring of the demonstrator was undertaken for 300 days following installation of the network. Saturation of the annular space around the cell liner has been successfully monitored with the three sections furthest from the access tunnel achieving a saturation of 98%. The section closest to the tunnel has not saturated owing to the influence of the tunnel temperature.

Creep of the rock around the liner has been monitored. This monitoring has identified that rock creep results in convergence in the horizontal direction and divergence in the vertical direction. The initial annular space of 40 mm between the rock and the casing in the horizontal direction closed in less than a month.

The optical fibres were successfully installed with the exception of the external fibre intended to monitor for rock fall. This sensor is assessed to have been damaged owing to vibration during the installation process. No data has been acquired from this fibre.

Pressure monitoring in the borehole parallel to the disposal cell has been successful in monitoring pore pressure, including detection of an overpressure associated with the construction of a separate nearby cell.

Therefore, the disposal cell monitoring demonstrator has built confidence in the ability to monitor the thermo-mechanical evolution and retrievability function of a disposal cell. However, further developments in the monitoring technology are necessary, including development of approaches for monitoring the cell chemical evolution, development of installation methods for fibre optic cables, and testing of pressure sensors within the disposal cell; this was not feasible as full saturation was not achieved during the 300-day testing period available in the MoDeRn Project.

4.3.3. Finnish case Study: KBS-3V in Crystalline Host Rocks

A licence application was submitted for construction of a spent fuel repository to be built in Olkiluoto in Eurajoki, Finland, in December 2012. The repository design is based on the KBS-3V concept in which spent nuclear fuel is encapsulated in canisters made of cast iron and copper. The canister is emplaced in a vertical borehole in crystalline bedrock hundreds of metres below the surface and surrounded by a buffer of compacted bentonite.

According to the safety concept for the Olkiluoto repository, safe disposal is achieved first by long-term isolation and containment of the nuclear waste using multiple barriers until the waste no longer poses a risk, and second by ensuring that in the unlikely event of an early canister failure, safety is maintained by limiting and retarding the release and transport of radionuclides. Each component of the barrier system has one or several safety functions which describe its role in achieving the general goal of safe disposal. The barriers and their safety functions are:

- Canister: prolonged containment of the spent fuel.
- Buffer: primarily to provide favourable conditions for the canister to fulfil its safety function, and secondarily, to limit and retard the transport of radionuclides in the event of canister failure.
- Backfill: provide favourable conditions for the canisters and the buffer, limit and retard the transport of radionuclides, and contribute to the mechanical stability of the rock adjacent to the emplacement drifts.
- Host rock: physically isolate the spent fuel from the biosphere, impede (un)intentional human intrusion, provide favourable conditions for the previous barriers, and limit and retard the transport of possibly released radionuclides into the biosphere.

The geotechnical barriers (the canister, buffer and backfill) are associated with performance targets and the host rock contains target properties achieved through appropriate site selection. The performance targets and target properties are each linked to specific safety functions, and represent the parameters of relevance to this case study.

Posiva (2012) has undertaken an iterative and structured approach to identify monitoring targets involving the identification of processes that can lead to performance targets and target properties being missed. A screening process considered the potential for each identified process to significantly affect performance of the repository and is used to judge whether or not the process should be included in the monitoring programme (Miller *et al*., 2002). Processes were screened out of the monitoring programme if they were of low significance to safety or if it was judged to be unfeasible to monitor the process. Processes that were considered as being unfeasible to monitor *in-situ* were addressed by additional research activities, including laboratory experiments. The illustrative EBS monitoring programme developed within the MoDeRn Project focused on a programme for monitoring the bentonite barrier performance, and defined associated monitoring parameters.

In the KBS-3V concept, placing sensors within the bentonite buffer and bentonite backfill is judged to be not acceptable within the overall safety case. Therefore, the monitoring programme envisages development of a near-field monitoring system based on a disposal tunnel that does not contain real waste. Instead, the tunnel would be filled with dummy canisters. These would be heated, and would be made of the same materials, and have the same mass and dimensions as the waste canisters but would not contain any waste. The buffer and backfill would be emplaced as envisaged in the rest of the repository. At the end of the monitoring period, the canisters would be recovered to collect data on corrosion of the overpack, chemical changes in the bentonite and corrosion of steel auxiliary components.

Based on the processes and parameters, the monitoring system design contains sensors for monitoring temperature, total pressure, pore-water pressure and moisture content. This design is an example of how these specific parameters could be monitored based on available sensors and data transmission units, including recently developed systems. An approach for monitoring buffer displacement and uplift, canister displacement and *in situ* pH is still under development.

The envisaged monitoring scheme would include monitoring within and above the four deposition boreholes contained in the near-field monitoring system and in two additional locations within the bentonite backfill. In the proposed monitoring programme, all recorded data would be transmitted using a wireless data transmission system using electromagnetic waves.

For the current designs of the transmitters and sensors, one sensor could be attached on the outside of the transmitter unit. Its small size water-tightness up to a water pressure of 10 MPa allow installation in a deposition borehole. The transmission distance of this node is expected to be 25 m or more in saturated bentonite, and larger in unsaturated bentonite. The second, larger, node, which could have four sensors attached to the outside of the transmitter unit, could be used for an installation in the backfilled tunnel where sufficient space is available. Using these nodes, it is anticipated that the bentonite saturation process can be monitored by measuring swelling pressure, water content and relative humidity. Two different types of moisture sensors are proposed so that their measurement ranges overlap and in order to introduce a level of redundancy into the monitoring system.

Both of the nodes have one temperature sensor inside the transmitter unit for the necessary temperature correction. The life-time of each node is currently expected to be 10 years based on power being supplied by a lithium battery, a measurement frequency of once per day, and a data transmission frequency of once per week. The individual sensing units are small in length (240 mm) and diameter (60 mm). If emplaced in a longitudinal orientation in the buffer without placing them next to each other, its impact on buffer performance is assumed to be negligible, although this assumption will have to be tested within the safety case.

4.3.4. Detecting Failures in the Monitoring System

In order to support decision making during the stepwise implementation of geological disposal, there needs to be confidence in the monitoring data which might be used to support decision making. Accurate data acquisition requires a chain of sensors, cables, connectors, analogue-digital-converters, data-acquisition units, data-processing units, correction and calibration methods, and, in some cases data transmission units, all working to specification. Therefore, the quality of monitoring data does not only rely on the sensor itself, but also on the proper operation of each of the given components, and as it is the monitoring results and not the sensor readings that will be used for decision making, statements on data quality beyond the sensor level are required. These statements are part of method and procedure descriptions that have to be developed in order to quantify the performance of each applied system.

A failure in a monitoring system is defined as a specific circumstance that results in invalid monitoring data (data values that are influenced by factors other than those described by the method), i.e. the outcome of implementing the monitoring system does not comply with the specified response to chemical and/or physical phenomena occurring in the repository.

Failure modes can be classified as follows:

- Technical failures:
  - Total or partial sensor failures.
  - Failures of signal transmission.
  - Failures of signal conversion.
- Methodological failures:
  - Failure of sensor installation and placement.
  - Distortion of sample environment.
  - Unidentified cross-sensitivity.
  - Failure of correction methods (drift, cross-sensitivities).
- Procedural failures:
  - Loss of redundancy (i.e. simultaneous failure of several sensors).
  - Failure of any error detection and error correction procedures.

a. *Detecting Sensor Failure*

Failure detection methods for sensors include:

- Redundancy: The basic principal of redundancy is that more than one sensor measures the same phenomena and signal deviation is used to detect defective functional blocks (Weiler, 2001). Redundancy can be introduced on several levels, including the use of several sensors at the same location, the use of several sensors at comparable locations, and redundancy in data transmission systems.
- Known Relations: Error detection by means of known relations is a method that is based on diversity. Diversity, or *distinct functional redundancy*, is a special form of redundancy where two different methods are used for measuring the same parameter. An example of error detection integrated in a sensor element is a differential pressure sensor with redundant temperature measurement function (Schneider, 1996).
- Electrical Stimulation: The sensor element is directly stimulated by means of electrical impulses that – together with the measured variable – are processed by all subsequent components of the sensor system. In an accurately working sensor system, the electrical stimulation of the sensor element leads to a known

sensor response that can be detected in the output signal. A basic application of electrical stimulation is the measurement of the insulation resistance of thermocouples by measuring the resistance (DC or low-frequency AC) along the conductors.

- Reliability Indicators: Failure detection by means of reliability indicators uses certain features of a circuit/system or sensor to indicate the occurrence of, or evolutions that might lead to, a failure. These features are continuously monitored to detect if they exceed or fall below certain specified ranges/values which are only physically possible if an error occurs. Examples of reliability indicators are steady-state current measurements in so-called Complementary Metal Oxide Semiconductors (CMOS), integrated circuits or temperature measurements using thermocouples inside data acquisition systems to check for any deviating conditions within the system.
- Local Sensor Validation: The detection of local errors in a sensor system can be undertaken by analysing the unfiltered signal of the system as certain signal characteristics in the unfiltered output signal of a sensor system, e.g. spikes, may suggest a failure (Amadi-Echendu, 1994).
- Correlation: This method can be applied when sensors measure the same physical parameter and are placed in equivalent positions with respect to the measured object (e.g. measuring temperature at the same distance but in the opposite direction from a heat source in a medium with isotropic thermal conductivity). Then it is possible to evaluate whether the readings of one of those sensors are valid by directly correlating them with the readings obtained from the others. Indirect correlation can also be established between sensors measuring different parameters if they are embedded in media where these parameters are coupled.

In MoDeRn (2013l) an analysis is provided that identifies failure detection methods for different types of measurement, and which clearly identifies possibilities and limitations of failure detection methods with regard to long-term repository monitoring.

b. Detecting Data Transmission Failure

Failure of a monitoring method can also be the result of (incorrect) data transmission. Detecting data transmission failure is of particular relevance to the MoDeRn Project, given the consideration of wireless data transmission techniques in the project.

Three types of transmission failure mode are readily identified:

- General unit failure.
- Protocol errors (errors in the coding of software, which can be overcome through testing)
- Noise and/or interferences that alter the transmitted signal on its way from the transmitter to the receiver, e.g. channel interferences, signal distortion, or synchronization problems.

Assuming that data transmission in the case of repository monitoring is limited to binary digital data, data transmission errors are manifested by wrongly received bit values (i.e. *1* instead of *0* and vice versa). Transmission errors can be minimized by proper design, but not totally avoided owing to the random nature of noise and interferences. Quantification of the error probability is part of the performance description of a transmission method. Data transmission errors are quantified by the '*bit error rate'* (BER), and an example of the use of the BER to quantify data transmission performance has been applied in the MoDeRn Project as part of the development of low-frequency data transmission systems. The achievable BER is related to the signal strength. In repository monitoring, when supply of energy may be limited, the merits of a lower BER need to be balanced against the higher energy need.

Many error detection, elimination and correction schemes have been developed in order to detect, eliminate and correct errors in digital data streams, and, therefore, transmission errors do not necessarily result in incorrect data. All of these methods detect errors of the overall transmission chain, i.e. they do not depend on the specific localised cause of error. The simplest scheme is the use of a *parity bit* that is added to a group of bits and indicates if the number of ones in the group is even or odd. This allows the identification of single bit errors. More complex schemes exist that allows identification of the presence of multiple bit errors.

In cases where the error detection method has identified erroneous transmitted data, the accompanying data points can be eliminated. Elimination of incidental erroneous data might be a minor problem in many application cases, since monitoring data can consist of long timelines of slowly evolving processes, where incidentally missing data points are of no relevance. In the case of bidirectional transmission system, transmission errors can be notified to the transmitter station, allowing it to resend the missing data.

In addition to error detection methods, error correction methods can be used to restore the original data in the case of a transmission error. Error correction methods use comparable approaches to error detection methods, but are more complex because here, in order to restore the original data, the individual bit that causes the error has to be identified.

Error detection and error correction methods both make use of extra (redundant) data (checksum bits) that are added to the data stream, and therefore increase the amount of data to be transmitted. Simple error detection schemes like the parity bit involves a single additional bit for each group of data, while error correction schemes may increase the data stream significantly (e.g. 60% or more). As with the consideration for minimising the BER, the energy necessary to implement a certain error detection and/or correction method must be considered.

c. Detecting Overall System Failure

Additional options are available in order to avoid, detect and - if possible - correct monitoring system failures:

- By defining proper installation, testing and quality assurance procedures.
- By making use of overall system redundancy (in addition to sensor redundancy).
- By using cumulated information of different methods.

In industry, the operation of sensors and electronics in hazardous environments requires the use of intrinsically safe systems that are rated and approved for the specific environment. For the specific case of repository monitoring, especially for long-term monitoring of the EBS after emplacement of the waste, buffer and backfill, the method(s) of so-called *fail-safe sensors* as used in industry may be of value in developing reliable monitoring systems. These systems make use of error detection methods described above and apply these methods in a predefined, automated manner. Further details about fail-safe sensors and their working principles are described in MoDeRn (2013l).

Experience in failure detection has been developed in several URLs. For example, ANDRA uses the SAGD (Système d'Acquisition de Gestion de Données) data acquisition system in the Bure URL. The system provides a well-established example of an automated failure detection system that has been used for more than ten years.

d. Discussion of Detecting Failures in the Monitoring System

The overview of potential failure modes discussed above shows that, in numerous and widely varying safety-relevant areas, different methods to detect errors and failures have been developed, many of which are applicable to repository monitoring. These vary with respect to the degree of reliability that can be achieved, the technical efforts necessary and the special requirements of the particular application.

The relation between detection methods and failure modes gives a first idea of which failure modes may stay potentially undetected and which modes are less challenging (e.g. a simple sensor breakdown is easily identified by redundancy). It also shows what (combination of) measures/techniques are effective in addressing failure modes. By selection of principal techniques that are favourable with respect to failure detection, the ability to identify potential failures of the monitoring system can be improved. Understanding of the relation between failure detection and different techniques may also help to identify additional monitoring techniques or measures that can be applied in order to address as many failure modes as possible.

Robust methods and procedures that qualify all aspects of the performance of the applied monitoring systems are essential to allow the data to be used in decision making. Owing to the long timescales and the fact that sensors or other components of the monitoring equipment may be inaccessible, repository monitoring is challenging, and the possibility of failure detection will be an important aspect of the robust methods that need to be developed. When it comes to the detection of failures, several specific features of monitoring in waste disposal can be used:

- Evolution of parameters is usually slow, enabling efficient criteria to be defined for local failure detection systems.
- Redundancy can be applied easily and on different levels:
  - Redundant sensors in the same disposal component.
  - Sensors at different locations within, or distances from, a disposal component.
  - Repetitive monitoring of the same component in different parts of the disposal system.
  - Distinct functional redundancy.
- Correlations can be used because in most cases more than one parameter is measured, and some parameters have a constitutive relationship with each other.

e. Conclusions

Prior to the MoDeRn Project, limited development of EBS monitoring programmes had been undertaken for national repository programmes in Europe. Prior to the MoDeRn Project, guidance on the development of monitoring programmes at the international level included only general requirements describing how monitoring can support the implementation of geological disposal in a broad sense (IAEA, 2001; EC, 2004).

Within the MoDeRn Project, monitoring case studies have been developed for the three main types of host rock considered suitable for the geological disposal of radioactive waste. The case studies have demonstrated that monitoring programme designs can be established based on a structured analysis of the FEPs and safety functions considered in the safety case and to address pre-closure information requirements prescribed in regulations (e.g. to demonstrate reversibility).

Several strategies for overcoming well-known challenges to repository monitoring have been identified and proposed in the case studies. These include:

- The use of different types of monitored disposal cells in the French case, including sacrificial cells that will be decommissioned and from which waste will be retrieved during the closure of the repository.
- Monitoring strategies which focus on the monitoring of wastes emplaced during the first stages of operation, which allows information to be gathered and used in decision making during the subsequent stages of operation.

- The monitoring of disposal tunnels that do not contain real waste (KBS-3V example). Both the German and the KBS-3V cases envisage the use of dummy canisters, i.e. canisters with the same material properties, mass, dimensions and heat output as canisters containing waste, but which can be instrumented to allow monitoring of the near field.

The case studies have shown how several of the technological developments made within the project and reported in Chapter 3 of this report can be directly employed within repository monitoring programmes.

The case studies have allowed some aspects of the MoDeRn Monitoring Workflow to be tested using existing safety case and other national context information. All of the case studies were developed using an approach that is consistent with the MoDeRn Monitoring Workflow, i.e. an approach that includes identification of the main objectives and reasons for monitoring, identification of sub-objectives, processes and parameters through an evaluation of the safety case and other drivers (e.g. requirements of stakeholders identified through specific engagement and involvement activities), and the development of monitoring system designs based on an understanding of the performance requirements and techniques available. However, some steps in the Workflow were not used in the case studies. The required performance of the monitoring system was not specified as information to allow the performance to be specified was not available. In addition, the use of monitoring programme results in decision making was not assessed as the programmes were not implemented.

An analysis of monitoring system failure detection has demonstrated that there is a range of methods available for ensuring confidence in the data acquired by monitoring systems, even when these systems have to operate remotely for long timescales. Failure identification procedures should always be a key part of a monitoring system, especially when thinking about the use of monitoring results for decision-making processes.

There is a need to further develop and test monitoring programme designs that utilise a range of monitoring technologies and are related to specific monitoring sub-objectives (integrated monitoring systems) to demonstrate that the considerations related to monitoring programmes presented in this section can be implemented in actual repositories.

4.4. Stakeholder Involvement in Monitoring Programmes

Experience in the development of national programmes for the geological disposal of radioactive waste to date has demonstrated that developing and implementing a programme for geological disposal attracts considerable public interest and attention. In some cases, agreements have been reached among the affected parties. In others, proposals that have been advanced have met strong opposition from members of the general or affected public and their political representatives. Indeed, sometimes the anticipated opposition may appear so strong that proposals are never advanced at all (IAEA, 2007).

At the 44th Session of the IAEA General Conference (IAEA, 2000), it was recognised that:

- Technological solutions to the safe management of radioactive waste exist, but public acceptance is needed.
- A structured participatory process is needed for decision making.
- Consensus of all parties is unlikely and therefore a formal, transparent decision-making process with public participation is essential.
- The decision-making process needs to be step-wise, with the ability to reverse decisions at a later stage.

International guidance documents on monitoring of geological repositories (e.g. EC, 2004; IAEA, 2001) suggest that monitoring can potentially contribute to public acceptance by building confidence in the behaviour of a facility and can play a role in structured participatory processes for decision making. However, in order for monitoring programmes to effectively contribute to building public and stakeholder confidence, they must be able to answer stakeholders' expectations within the limits of the technical requirements on implementation of geological disposal. To know and understand these expectations, WMOs should engage with different stakeholders, from an early stage of repository development, and be transparent about the limits of monitoring (including what could realistically be expected in terms of evolutions in monitoring techniques).

In the MoDeRn Project, research was undertaken on public stakeholder involvement in repository monitoring that was directed at a better understanding of views on the nature and role of monitoring in geological disposal, and the governance of repository development and staged closure. By improving this understanding, it was expected that information and guidance could be identified that would support the future development of national or repository-specific monitoring programmes.

Consideration of participatory processes in repository monitoring was conducted through a range of activities:

- Interviews were conducted with 18 specialists employed by European WMOs (MoDeRn, 2012).
- A workshop was held with stakeholders in which representatives of other organisations (mainly regulatory agencies, but also with a limited number of participants from advisory bodies and public stakeholder groups) discussed the research activities of the MoDeRn Project and provided insights into stakeholder views on repository monitoring (MoDeRn, 2011a).
- Workshops involving public representatives from nuclear facility host communities were held in Belgium, Sweden and the UK. The participants in these workshops had varying degrees of engagement with, and knowledge of, radioactive waste management projects (MoDeRn, 2013c).
- A visit to the Mont Terri URL and the Grimsel Test Site in Switzerland was undertaken with a subset of the public representatives that participated in the host community workshops.
- Discussions on the role of stakeholder involvement in repository monitoring programmes were also held during the international conference on monitoring in geological disposal of radioactive waste (MoDeRn, 2013a).

The work was led by a team of social scientists with experience of, and expertise in, participatory approaches in geological disposal of radioactive waste. A summary of the overall programme of work on stakeholder involvement in monitoring programmes is provided in MoDeRn (2013c).

The key messages from the research are presented in this section. These messages are discussed in terms of views expressed by the stakeholders consulted on five key questions associated with monitoring:

- Why conduct repository monitoring?
- What should be monitored, where in the repository should monitoring data be acquired and how should monitoring be undertaken?
- Who should monitor?
- Over what period should repository monitoring be undertaken?
- What is the overall role of monitoring in repository governance?

Overall conclusions from the research into stakeholder involvement in repository monitoring and guidance on participatory processes are presented.

4.4.1. Views on Why Monitoring Should be undertaken

Technical reasons for monitoring include the provision of support to the post-closure safety case, demonstration of operational safety, and monitoring in support of EIA and safeguards. In addition, it is also expected by professionals in radioactive waste management that monitoring will provide information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence - for as long as society requires - that the repository is having no undesirable impacts on human health and the environment (EC, 2004). Monitoring is expected to support *public confidence* (IAEA, 2001; EC, 2004) and public *acceptability* (e.g. IAEA, 2011, p. 44).

The role of monitoring in providing assurance was explicitly mentioned by all of the technical specialists interviewed within the MoDeRn Project as one of the main drivers for monitoring. Distinctions were drawn in the way that this could be achieved for three different types of stakeholders:

- The implementer may see monitoring as a tool for assessing the performance of a repository and for contributing to quality assurance, i.e. supplying a means for the verification of both the repository system and the modelling behind it.
- Regulators may seek assurance that the repository monitoring programme has successfully incorporated specific societal expectations by being compliant with regulatory requirements, particularly in relation to requirements for operational safety and EIA.
- The public may make demands for transparency and oversight of repository development and staged closure including the provision of monitoring information.

The role of monitoring in supporting public confidence building was echoed in the workshop activities with local stakeholders in Belgium, Sweden and the UK. The Belgian group, for example, came to the conclusion that confidence building and *keeping guard* over the safety of the facility were the main reasons for monitoring. The UK group also identified stakeholder confidence in the safety of the repository as one of three reasons to monitor, the other two reasons being verification of compliance with prevailing regulations or standards, and *quality control* to support continuous refinement or improvement. Informing both the Belgian view on keeping guard and UK views on verification of continued safety is a notion of maintaining a watch over the repository.

Both local and national stakeholder representatives in Sweden discussed the importance of the timing and location of monitoring activities. The question of whether monitoring programmes carried out in URLs or pilot facilities during repository development can reduce the need for *in situ* monitoring of the actual repository was discussed. In both Sweden and Belgium, the argument was made by public participants that monitoring is needed *to know what happens in reality*. Confidence building through compliance monitoring and quality control thus seems to be a common reason for monitoring put forward by implementers, regulators and members of the public confronted with a geological repository programme.

A view commonly held by expert stakeholders is that the focus on assurance monitoring should be on *performance confirmation*. For example, this view was stated several times at the stakeholders' workshop (MoDeRn, 2011a). Because expert stakeholders rely on the safety case as the principal method for demonstrating confidence in the long-term (post-closure) safety of the disposal system, they consider that checks on whether or not the system provides adequate safety come from the development of the repository design, from the site selection and site characterisation activities, and from the safety strategy used in development of the safety case (IAEA, 2012).

Furthermore, the participants at the stakeholders workshop noted that an underpinning philosophy applied by implementers was that obtaining a licence for constructing and operating a repository is proof of a high degree of confidence in the safe performance of a repository, and hence, as required in IAEA requirements on geological disposal (IAEA, 2011), there would not be reliance on monitoring as a basis for ensuring safety (MoDeRn, 2011a, p.18). If monitoring is dedicated to helping stake out a path to passively safe waste packages, facilities and sites, then it must be dedicated to progressively reducing the need to repeatedly 'check-up' on safety. It must be dedicated to verifying the needlessness of continuing to look.

In contrast, the community stakeholders in the Belgian, Swedish and UK workshops, as well as in the MoDeRn stakeholder workshop made clear they expect a more critical assessment of safety. Like the technical specialists, they do not see monitoring in itself as contributing to the safety of the repository. They do, however, expect it to assess or check that safety is ensured. For that reason, they do not only require operator and expert assurance of safety, but also the additional assurance of (independent) monitoring - and (independent) control of that monitoring - for any evidence of exposure to harmful releases. Such an attitude is confirmed by literature on (environmental) risk and trust in experts and expert systems (e.g. Giddens, 1991; Irwin, 2008; and Simmons and Wynne, 1993).

At several occasions during the workshops with public stakeholders it was commented that the use of the term 'performance confirmation' came across as arrogant, and that it was inappropriate to take as a starting point the assumption that no problems can occur in future. Monitoring was thus considered a necessary action to remain *on guard*, but was only seen as effective if accompanied by a proper response plan or a Plan B should anything unexpected be detected. One of the public stakeholders' main concerns is that designing monitoring programmes solely for performance confirmation is likely to lead to implementers prioritising the monitoring of different parameters to those that might be most appropriate for registering unlikely and unexpected events.

4.4.2. Views on What, Where and How to Monitor

Among technical specialists there appears to be a widely held perception that public and stakeholder expectations are likely to focus on environmental monitoring in order to protect against human health impacts. A review of literature on public and stakeholder engagement in monitoring within the nuclear sector and in other contexts seems to corroborate this perception (Bergmans *et al*., 2012). However, there is also evidence that some stakeholders do not draw a distinction or express a clear preference between monitoring of different parts of the repository system; they expect implementers to develop a plan including specification of what, where and how monitoring would be undertaken.

From the engagement exercises conducted within the MoDeRn Project, it appears that local citizens are less concerned about what parameters are included in the monitoring programme or the exact locations where monitoring is conducted. What they did insist upon, however, was that repository monitoring programmes were as comprehensive as possible, and should have a broad scope, including both near-field and far-field monitoring. Both the Belgian and UK groups acknowledged the potential tension between potentially intrusive near-field monitoring and the integrity of barriers and seals that are required for passive safety. It was also considered to be important, most notably by the Belgian group, to continue searching for alternative parameters or techniques for processes that would be difficult to monitor with current technology, and to consider laboratory simulations as alternatives to near-field monitoring (e.g. in a post-closure situation).

4.4.3. Views on Who Should Monitor

For the participants in the different workshops it appeared self-evident that the implementer would be responsible for setting up and conducting the monitoring programme. They did, however, insist on additional mechanisms for control. Control by the regulator is one possible mechanism, but other forms of independent control are also seen as important in contributing to building confidence. An example of independent control is the environmental monitoring of the Waste Isolation Pilot Plant (WIPP) in New Mexico, US, which is being conducted by an independent agency, the Carlsbad Environmental Monitoring and Research Centre (CEMRC). CEMRC is funded by the implementer (the Department of Energy) through a grant process to respects its independence (see MoDeRn (2013a) for a paper on the monitoring work of CEMRC).

Indeed, in several cases found in the literature, different forms of environmental monitoring were commissioned or conducted by local institutional stakeholders, particularly local governments, including some examples that integrate this with monitoring of the socio-economic environment (e.g. Conway et al., 2009).

Dissatisfaction with or distrust of institutions has also led members of some communities to demand or even initiate participatory environmental monitoring, which involves local citizens in data collection (e.g. Vári and Ferencz, 2007; NEA, 2009). Both the literature review and the engagement activity conducted within the MoDeRn Project demonstrate the desire of members of the public and communities in many different contexts for active engagement with facility monitoring programmes.

4.4.4. Views on How Long to Monitor

For the technical experts, monitoring is primarily an activity dedicated to advancing and facilitating repository closure and confirming that the conditions outlined in the regulatory safety case have been achieved. Near-field monitoring following closure in particular was said by many of them to be unrealistic and even potentially counterproductive insofar as the techniques used could contribute to compromising barrier integrity. Nevertheless, many experts interviewed thought that there could be value in post-closure monitoring if it were needed to reassure other actors such as local communities, a position that is also expressed in international guidance (e.g. IAEA, 2011). It was furthermore recognised that although there is currently little evidence of statutory requirements for post-closure monitoring, it seemed possible that they would be introduced in some countries in the future in response to societal demands.

Evidence from the Belgian, Swedish and UK workshops confirmed that constructively engaged members of the public do have expectations and concerns regarding post-closure monitoring. What is less clear is the type of monitoring they would be expecting in the post-closure period, and where they might expect such monitoring to be based (i.e. monitoring of the near field, far field or the surface environment based on sensors located in the near field, far field or the surface environment). In the Swedish workshop, it was pointed out that even if post-closure monitoring is considered desirable, the technological innovation required to enable such monitoring is hardly likely to take place without the purposeful allocation of funds to related research and development. Community stakeholders were therefore concerned about post-closure safety but, unlike the technical experts, tended to see continued monitoring of some sort as being necessary not merely to confirm that the evolution of the repository system conforms to technical expectations, but to ensure that it continues to do so.

4.4.5. The Role of Monitoring in Repository Governance

For several decades now, one of the key principles informing the management and regulation of nuclear safety has been that of constant surveillance. This is first a political and moral principle which informs the practical design and development of nuclear activities; this principle is therefore an expression of what societies interpret nuclear safety to mean. Monitoring programmes focused on different types of nuclear activity are therefore ways of putting the moral principle of tireless vigilance into technical practice. This is particularly the case for nuclear installations such as power plants, fuel production plants, reprocessing plants, and storage facilities, as pointed out by nuclear scientist Alvin Weinberg, when he referred to the unusual degree of vigilance which had to be exercised over all programmes of nuclear power generation in order to guarantee safety (Weinberg, 1972). Geological repositories, incorporating the technical - and moral - principle of passive safety, can be understood as a way of trying to renegotiate the need for unremitting vigilance by delegating responsibility for safety to an engineered geological disposal system. The question then is how should the gradual transition from active human vigilance to passive safety without human intervention be organised? Weinberg (1972) believed that effective geological disposal reduced the need for vigilance to a minimum. However, the exploratory engagement with community stakeholders undertaken in the MoDeRn Project suggests that more is expected by many public stakeholders.

The principal of unremitting vigilance, as Weinberg (1972) reminds us, poses societal questions that cannot be answered from a technical-expert perspective alone (Weinberg 1972). Society will therefore have to decide what kind of human vigilance is needed and for how long it should continue. Nevertheless, for society to relinquish direct control of the wastes will require confidence in the repository system and trust in those responsible for designing, implementing, overseeing and regulating it. It may therefore be easier for national and local decision makers, and the communities that they represent, to commit to taking successive steps in repository siting, development, licensing, construction and operation if the contingent nature of their trust and commitment at each and every stage is acknowledged and the opportunity to influence plans is upheld.

In addition to providing confirmation of the assumptions, arguments, evidence and models upon which the safety case is based, therefore, there is another way in which monitoring can support public confidence. This is by the implementer accepting that monitoring could be undertaken to check that there are no uncertainties that have not been considered within the safety case, i.e. by using monitoring as a supporting argument in the safety case. Such a wider approach to addressing uncertainty is not without its risks, of course, in that it may appear to bring into question the premise of passive safety as the technological solution to the socio-technical problem of guaranteeing unflagging vigilance over long-lived radioactive waste. By introducing the notion of retrievability or reversibility into law, however, countries such as France are already moving towards an adapted socio-technical solution, one still directed towards achieving passive safety, but which recognises that this end point may be further away than initially planned, subject to a longer chain of socio-technical decision making, and that decisions made under the current socio-political framework may not be final. Such evolutions remind us that we inevitably pass the burden of decision making about final closure to subsequent generations. Acknowledging this requires that we think more specifically about the type of information, knowledge and skills that need to be passed on to future generations, and the role that monitoring might play in meeting the needs of future operators, regulators, decision makers and affected members of the public.

4.4.6. Conclusions on Stakeholder Involvement in Repository Monitoring

The national workshops and Swiss URL visits demonstrated that it is possible to discuss in a detailed manner monitoring issues with interested local stakeholders, even at an early stage in a repository programme. These activities furthermore revealed a mutual interest between participating technical experts and local stakeholders, leading to fruitful discussions considered beneficial and of interest by both parties.

The main conclusions from the work on stakeholder involvement in monitoring programmes are as follows:

- The opinion that monitoring should be a checking process rather than a confirmatory process was expressed by many stakeholders. Monitoring programmes are therefore likely to be viewed by some stakeholders as being more trustworthy if it is clearly communicated that they are designed from the perspective of challenging that repository behaviour is as expected, and if stakeholders are able to access clear information on how each aspect of repository performance is checked.
- Public stakeholders expressed a view that the checking of repository performance should be comprehensive and linked to an overall science programme. A continuation of research and development on repository monitoring techniques was expected. WMOs could ensure that this view is addressed by discussing with their stakeholders the role of monitoring during different phases of repository implementation, and by communicating the manner in which operational and long-term safety is assured.
- As anticipated, some public stakeholders do have expectations regarding post-closure monitoring, mainly in view of being able to prepare for (and respond to) unanticipated events or evolutions. Individual programmes will need to decide on ways to respond to this expectation. Additionally, communication of the understanding of remaining uncertainties, and a preparedness to allow options for monitoring to evolve and to respond to changes in the expected evolution of the repository (e.g. closure being postponed) could be beneficial to addressing stakeholders' expectations regarding long-term monitoring.
- Monitoring can be characterised as a socio-technical activity and could potentially contribute to building the confidence of public stakeholders in the safety of a particular repository project, though not by itself.

Of course, many other factors will also play a role in building stakeholder confidence, such as the approach to decision making, and the level of public and stakeholder engagement. Monitoring can contribute to repository governance if it can address expectations from stakeholders, if it is expressed as a practical commitment to maintain a watch over the repository performance, and if there is transparency about the limits of monitoring, including what could realistically be expected in terms of evolution in monitoring techniques.

References

Amadi-Echendu, J.E. and Zhu, H. (1994). Detecting Changes in the Condition of Process Instruments, IEEE Trans. on Instrumentation and Measurement, Vol 43, No 2.

ANDRA (2005). Dossier 2005 Argile.

ANDRA (2009). Options de réversibilité du stockage en formation géologique profonde. Internal report C.NT.AHVL.09.0005.

Bergmans A. (2012) Perspectives on Radioactive Waste Repository Monitoring: Confirmation, Compliance, Confidence Building, and Societal Vigilance, Technikfolgenabschätzung – Theorie und Praxis 12/2012; 21(3):22-28.

Bell, F.G. (2007). Engineering Geology. 2nd Edition. Elsevier Science & Technology.

BMU (2010). Safety Requirements Governing the Final Disposal of Heat Generating Radioactive Waste. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, Germany.

Buhmann, D. (2011). Vorläufige Sicherheitsanalyse Gorleben. Alternativszenarien aus wenig wahrscheinlichen FEPs; Zum Teil mit direkter Einwirkung auf eine ewB (Verwendeter Auszug aus der Datenbank; Stand: 18.07.2011). Draft version.

Campillo, M. and Paul, A. (2003). Long Range Correlations in the Diffuse Seismic Coda. Science, Vol. 299.

EC (2004). Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste. European Commission Project Report EUR 21025 EN, EC, Luxembourg.

European Association of Geoscientists and Engineers (2003). Petroleum Geoscience. 4D Seismic Technology Special Issue. Volume 9, Number 1.

Giddens, A. (1991). Modernity and Self-Identity. *Stanford, California: Stanford University Press.*

IAEA (2000). 3rd Scientific Forum: Radioactive Waste Management — Turning Options into Solutions. Report of the 3rd Scientific Forum to the 44th General Conference. International Atomic Energy Agency, Austria Centre, Vienna, Austria, 19–20 September 2000.

IAEA (2001). Monitoring of Geological Repositories for High Level Radioactive Waste. IAEA-TECDOC-1208, IAEA Vienna.

IAEA (2007). Factors Affecting Public and Political Acceptance for the Implementation of Geological Disposal. IAEA-TECDOC-1566, IAEA Vienna.

IAEA (2011). Disposal of Radioactive Waste. IAEA Specific Safety Requirements, No. SSR-5, IAEA Vienna.

IAEA (2012). The Safety Case and Safety Assessment for the Disposal of Radioactive Waste. IAEA Specific Safety Guide, No. SSG-23, IAEA Vienna.

Loi (2006). Loi de programme n° 2006-739 du 28 juin 2006 relative à la gestion durable des matières et déchets radioactifs.

Measures, R. (2001). Structural Monitoring with Fiber Optic Technology. Academic Press.

Miller, B., Arthur, J., Bruno, J., Hooker, P., Richardson, P., Robinson, C., Arcos, D. and West, J. (2002). Establishing baseline conditions and monitoring during construction of the Olkiluoto URFC access ramp, Posiva Report 2002-07.

MoDeRn (2010a). Monitoring Technologies Workshop Report, 7-8 June 2010 – Troyes (France). MoDeRn Project Deliverable D-2.2.1.

MoDeRn (2010b). National Monitoring Contexts Summary Report. MoDeRn Project Deliverable D-1.1.1.

MoDeRn (2010c). Site Plans and Monitoring Programmes Report. MoDeRn Project Deliverable D-3.1.1.

MoDeRn (2011a). Expert Stakeholders Workshop. MoDeRn Project Deliverable D-5.3.1.

MoDeRn (2011b). Technical Requirements Report. MoDeRn Project Deliverable D-2.1.1, www.modern-fp7.eu.

MoDeRn, (2012). Monitoring the Safe Disposal of Radioactive Waste: A Combined Technical and Socio-Political Activity. MoDeRn Project Deliverable D-1.3.1.

MoDeRn (2013a). Monitoring in Geological Disposal of Radioactive Waste: Objectives, Strategies, Technologies and Public Involvement. Proceedings of an International Conference and Workshop, Luxembourg, 19 – 21 March 2013.

MoDeRn (2013b). Monitoring Reference Framework Report. MoDeRn Project Deliverable D-1.2.1.

MoDeRn (2013c). National Engagement Experiments Report. MoDeRn Project Deliverable D-1.4.1.

MoDeRn (2013d): State-of-the-Art. MoDeRn Project Deliverable D-2.2.2.

MoDeRn (2013e). Technology Summary Report. MoDeRn Project.

MoDeRn (2013f). Development Report of Monitoring RTD. MoDeRn Project Deliverable D-2.3.1.

MoDeRn (2013g). Seismic Tomography at Grimsel Test Site. MoDeRn Project Deliverable D-3.2.1.

MoDeRn (2013h). Wireless Sensor Network Demonstrator Report. MoDeRn Project Deliverable D-3.3.1.

MoDeRn (2013i). HADES Demonstrator. MoDeRn Project Deliverable D-3.4.1.

MoDeRn (2013j). Wireless Data Transmission Demonstrator: from the HADES to the surface. MoDeRn Project Deliverable D-3.4.2.

MoDeRn (2013k). Disposal Cell Monitoring System Installation and Testing Demonstrator in Bure Underground Research Laboratory. MoDeRn Project Deliverable D-3.5.1.

MoDeRn (2013l). Case Study Report. MoDeRn Project.

Mönig, J., Buhmann, D., Rübel, A., Wolf, J., Baltes, B., Fischer-Appelt, K. (2012). Sicherheits- und Nachweiskonzept, Vorläufige Sicherheitsanalyse Gorleben AP4, GRS-277, ISBN 978-3-939355-53-3.

Posiva (2012). Monitoring at Olkiluoto – A Programme for the Period Before Repository Operation. Posiva Report 2012-01, Posiva Oy, Olkiluoto, Finland.

Römer, K. and Friedemann, M. (2004). The Design Space of Wireless Sensor Networks. IEEE Wireless Communications 11 (6): 54–61.

Rübel, A. (2011). Alternativszenarien aus den weniger wahrscheinlichen Ausprägungen wahrscheinlicher FEPs mit direkter Einwirkung auf die EWBs, VSG AP8.

Schneider, G. (1996): Selbstüberwachung und Selbstkalibration von Sensoren, atp-Automatisierungs-technische Praxis 38, Nr. 9 Sep. 1996, S. 9-17, R. Oldenbourg Verlag.

Simmons, P. and Wynne, B. (1993). Responsible Care: Trust, Credibility and Environmental Management. In: J. Schot & K. Fischer (Eds.). Environmental Strategies for Industry: International Perspectives on Research Needs and Policy Implications. Washington: Island Press.

Snieder, R. (2006). The Theory of Coda Wave Interferometry. Pure and Applied Geophysics, 163, 455-473.

Snieder, R. (2004). Extracting the Green's Function from the Correlation of Coda Waves: a Derivation Based on Stationary Phase. Phys. Rev. E, Vol 69, Issue 4.

Vári, A. and Ferencz, Z. (2007). Radioactive waste management in Hungary: changing approaches and conflicts. Journal of Environmental Assessment Policy and Management, 9/2 (2004): p. 185–209.

VSG (2011). Alternativszenarien aus abweichenden Betrachtungen zu spezifischen Annahmen, VSG: AP 8 "Szenarienentwicklung", Arbeitsdokument, 01.08.2011.

Wapenaar, K. and Fokkema, J. (2005). Green's Function Representations for Seismic Interferometry. Geophysics, Special Issue on Seismic Interferometry.

Weiler (2001): Selbsttest und Fehlertoleranz mit zugelassener milder Degradation in integrierten CMOS-Sensorsystemen, Dissertation, Gerhard-Mercator-Universität/Gesamt-hochschule Duisburg, Fachbereich Elektrotechnik, Essen.

Weinberg, A., 1972 : Social Institutions and Nuclear Energy. In: Science 177/4043 (1972), p. 27-34.

Yin, S., Ruffin, P. and Yu, F. (2008). Fibre Optic Sensors. CRC Press.

5. Use and dissemination of foreground

This part presents the terms of use and dissemination of the foreground arising from the Project and which the Project partners own, in accordance with their interests. The document gives a cumulative overview of the Project's dissemination activities and gives some information on patents registered and exploitable foreground generated within the Project.

5.1. Dissemination activities

5.1.1. Communication material

a. MoDeRn websites

The MoDeRn website (www.modern-fp7.eu) is accessible and structured between a public access section and an "Extranet" only available to MoDeRn partners, and restricted by a password. The public access section (launched in January 2010) is organised with separate pages providing information on the following: News, a project overview, work packages' description, presentation and contact details of partners, events and meetings, and links towards other FP7 related projects. The public part of MoDeRn website has been visited over 8615 times.

A specific website (http://www.modern-fp7.eu/monitoring-gdrw-2013/home/) was created for the conference. It provided the main channel of communication with conference attendants as well as with authors and presenters. It also allows download of papers abstracts and presentations delivered in during the conference as well as the Proceedings of the Conference.

b. Flyers/Brochure

A 2-3 pages project presentation (D-5.2.1) has been produced at early stages of the project to contribute to public communication and was published on the project website. This document has been be updated following each reporting period.

In addition, a "project presentation flyer" (2 pages) was distributed to participants during the RTD Workshop (June 2010). A Standard PowerPoint presentation has also been proposed to partners to be used and adapted to their dissemination activities.

A project presentation was produced at the beginning of the project to be published by the EC in "Euratom FP7 Research & Training Projects", volume 2.

5.1.2. Workshops organised or co-organised by MoDeRn with external participants

a. MoDeRn RTD workshop, 7-9th June 2010, Troyes, France

This RTD workshop on Monitoring Technologies was held at the Université technologique of Troyes (France) on the 7-9th June 2010. 55 Participants from a range of research and industrial disciplines met to discuss potential applications to monitor geological repositories for radioactive waste. The workshop proceedings are available on MoDeRn website.

b. Expert Stakeholders workshop, Oxford, (UK), 4-5th May 2011

Thirty-one participants attended the meeting, including representatives from: Regulatory organisations in Belgium, Finland, Switzerland and the United Kingdom, advisory bodies in the UK, a public stakeholder group in Germany, the Belgian agency for radioactive waste and enriched fissile materials (ONDRAF/NIRAS), and MoDeRn Partner organisations.

c. International conference on repository monitoring, Luxembourg, 19-21 March 2013

The conference attracted 120 persons, 84 (69%) from outside the project. 18 countries were represented. To advertise and inform on this conference, a website was developed: http://www.modern-fp7.eu/monitoring-gdrw-2013/home/ as well as a flyer and a poster.

d. Workshops involving public representatives

Workshops involving public representatives from nuclear facility host communities were held in Belgium, Sweden and the United Kingdom. The participants in these workshops had varying degrees of engagement with, and knowledge of, radioactive waste management projects.

A visit to the Mont Terri URL and the Grimsel Test Site in Switzerland was undertaken with public representatives that participated in the host community workshops.

5.1.3. List of scientific (peer reviewed) publications

a. Period 1

Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Permanent identifiers[1] (if available)	Is/Will open access[2] provided?
Appraisal of waveform repeatability for crosshole and hole-to-tunnel seismic monitoring of radioactive waste repositories 10.1190/1.3479552	Marelli S.	Geophysics	5/75	Society of Exploration Geophysicists ISSN 0016-8033		September - October 2010	Q21-Q34		
Geophysics applied to nuclear waste disposal problems in Switzerland	Spillmann T.	Near Surface Geophysics	first break volume 28	EAGE Publishing BV 1569-4445		08/2010	39-50		
Recent advances in optimized geophysical survey design	Maurer H.	Geophysics	5/75	Society of Exploration Geophysicists 0016-8033		01/09/2010	75A177 - 75A194		

[1] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[2] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

b. *Period 2*

Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Permanent identifiers[3] (if available)	Is/Will open access[4] provided ?
Exploitation of the data information content for elastic waveform inversions 10.1190/GEO2011-0184.1	Edgar Manukyan	Geophysics	2 / 77	Society of Exploration Geophysicists ISSN 0016-8033		01/03/2012	R105 - R115		
Monitoring of radioactive waste –potential changes of elastic properties within a repository during water saturation: Geophysics, in press.	Manukyan, E	Geophysics				2012	In press		
Receiver coupling effects 1/77in seismic waveform inversions, doi:10.1190/geo2010-0402.1	Maurer, H. R	Geophysics	1/77	Society of Exploration Geophysicists 0016-8033		01/01/2012	R57 - R63		
2.5-D frequency-domain seismic wave modeling in heterogeneous, anisotropic media using a Gaussian quadrature grid technique, 10.1016/j.cageo.2011.06.005	Zhou, B	Computers & Geosciences	39	Elsevier		February 2012	18-33		

3 A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

4 Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

C. *Period 3*

Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Permanent identifiers[5] (if available)	Is/Will open access[6] provided ?
Non-intrusive seismic monitoring of high-level radioactive waste repositories.	Maurer H.R	*SEG Technical Program Expanded Abstracts*	*2012*	*Society of Exploration Geophysicists 1052-3812*	Las Vegas, U.S.A..	*2012*	*1-5*		
Validity of the acoustic approximation in full waveform seismic crosshole tomography	Marelli S	Geophysics	*3/77*	*Society of Exploration Geophysicists ISSN 0016-8033*		*17/09/2012*	*R129–R139*		
Seismic monitoring of radioactive waste repositories	ManukyanE	Geophysics	*6/77*	*Society of Exploration Geophysicists ISSN 0016-8033*		*01/11/2012*	*EN73 - EN83*		
Laboratory measurements of the longitudinal and transverse wave velocities of compacted bentonite as a function of water content, temperature, and confining pressure.	Tisato N.	Journal of Geoph. Res	*Volume 118, Issue 7*	*American Geophysical Union*		*25/07/2013*	*3380–3393*		
Report on "MoDeRn International Conference", Journal of Nuclear Fuel Cycle and Environment	Hiromi TANABE	Journal of Nuclear Fuel Cycle and Environment	*Vol.20 No.1*				23-27		
Perspectives on Radioactive Waste Repository Monitoring: Confirmation, Compliance, Confidence Building, and Societal Vigilance	Bergmans A.	*Karlsruhe Institute of Technology*		*Editors TATuP ISSN 1619-7623*		*12/2012*	*22-28*		

[5] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[6] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

5.1.4. List of dissemination activities

a. Period 1

Type of activities[7]	**Main leader**	**Title**	**Date/Period**	**Place**	**Type of audience**[8]	**Countries addressed**
Publication	All + EC	Euratom FP7 Research Projects & Training Volume 2, 2010 Brussels (Belgium)	*2010*	*EU*	Scientific Community; Industry; Civil Society; Policy makers	EU
Oral presentation	UA	Opening up technical issues to (local) stakeholders: Monitoring as a socio-technical combination	Oct. 2009	CARL Workshop, Cumbria	Scientific Community; Industry; Civil Society; Policy makers	EU
Oral presentation	ANDRA	Presentation of MoDeRn project	April 2010	Internal Andra meeting, GL R&D moyens et stratégie d'auscultation Châtenay-Malabry (France)	Scientific Community; Industry	FR
Poster	ANDRA, EURIDICE, ETHZ, NDA	*MoDeRn Project: Monitoring Developments for Safe Repository operation and staged closure*	29th - April 1st, 2010	Clays in Natural & Engineered Barriers for Radioactive Waste Confinement" 4th international meeting, March, Nantes, France	Scientific Community; Industry	international
Oral presentation	RWMC	Study on monitoring in the MoDeRn project supported by co-funding from Euratom	September 2010	2010 Fall Meeting of AESJ - Hokkaido (Japan)	Scientific Community; Industry	international
Presentation	ETH Zurich	Geophysics applied to nuclear waste disposal investigations in Switzerland	2010	EAGE, Barcelona 14 - 17 June 2010	Scientific Community; Industry	international
Presentation	ETH Zurich	Receiver coupling effects in seismic waveform inversions. Geophysics	October 2010	Society of Exploration Geophysics Meeting, Denver, U.S.A. 17-22 October 2010	Scientific Community; Industry	international
Presentation and paper	Andra	*MoDeRn Monitoring Developments for safe Repository operation and staged closure*	7th June 2010,	RTD workshop on monitoring technologies Université de technologie de	Scientific Community; Industry	EU

[7] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[8] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

				Troyes, France		
Presentation and paper	ETH Zurich	*Seismic Monitoring of a Simulated Radioactive Waste Repository During Water Saturation*	6-8 September 2010	Near Surface 2010, 16th European Meeting of Environmental and Engineering Geophysics, Zurich, Switzerland.	Scientific Community; Industry	EU
Presentation and paper	ETH Zurich	S. Marelli, E. Manukyan, H.R. Maurer, A.G. Green and S.A. Greenhalgh, *Appraisal of Waveform Repeatability and Fidelity for Crosshole Seismic Monitoring of Potential Radioactive Waste Reposit*	6-8 September 2010	Near Surface 2010, 16th European Meeting of Environmental and Engineering Geophysics, Zurich, Switzerland.	Scientific Community; Industry	EU
Presentation and paper	ETH Zurich	H.R. Maurer, S.A. Greenhalgh, S. Marelli, E. Manukyan and A.G. Green, *Combined Seismic, Waveform Inversion for Source Functions, Medium Parameters and Receiver Coupling Factors*	6-8 September 2010	Near Surface 2010, 16th European Meeting of Environmental and Engineering Geophysics, Zurich, Switzerland.	Scientific Community; Industry	EU
Poster	ETH Zurich	Seismic Monitoring of a Simulated Radioactive Waste Repository During Water Saturation	6-8 September 2010	Near Surface 2010, 16th European Meeting of Environmental and Engineering Geophysics, Zurich, Switzerland.	Scientific Community; Industry	EU
Presentation and paper	ETH Zurich	Maurer, H. R., S. A. Greenhalgh, S. Marelli, E. Manukyan, and A. G. Green, 2010, *Systematic errors in waveform inversions caused by variable receiver coupling*	2010	Society of Exploration Geophysics (SEG) Meeting (Denver, U.S.A., 2010)	Scientific Community; Industry	international

b. Period 2

Dissemination activities directly linked to MoDeRn project

Type of activities	**Main leader**	**Title**	**Date/Period**	**Place**	**Type of audience**	**Countries addressed**
Oral presentation	*ANDRA*	*Monitoring Developments for Safe Repository Operation and staged Closure – The International MoDeRn Project, 12040 Abstract*	*February 2012*	Waste Management 2012,Phoenix, USA *26/02 - 01/03/2010*	Scientific Community; Industry	international
Oral presentation	*DBE TEC*	Development of a theoretical monitoring system design for a HLW repository based on the "MoDeRn Monitoring Workflow (A case study), 12044 Abstract	*February 2012*	Waste Management 2012,Phoenix, USA *26/02 - 01/03/2010*	Scientific Community; Industry	international
Oral presentation	*EURIDICE*	Seismic monitoring at the underground nuclear research laboratory in Mol, Belgium, 12461	*February 2012*	Waste Management 2012,Phoenix, USA *26/02 - 01/03/2010*	Scientific Community; Industry	international
Oral presentation	*NDA*	*EC MoDeRn project: In-situ Demonstration of Innovative Monitoring Technologies for Geological Disposal,* 12053 Abstract	*February 2012*	Waste Management 2012,Phoenix, USA *26/02 - 01/03/2010*	Scientific Community; Industry	international
Oral presentation	*UEA*	*A Socio-Technical Perspective on Repository Monitoring*, 12229 Abstract	*February 2012*	Waste Management 2012,Phoenix, USA *26/02 - 01/03/2010*	Scientific Community; Industry	international
Presentation and paper	NRG	*Wireless transmission of monitoring data out of the HADES underground laboratory*	*February 2012*	Waste Management 2012,Phoenix, USA *26/02 - 01/03/2010*	Scientific Community; Industry	international
	SNL	F.D. Hansen, Repository Performance Confirmation-12119 Abstract	*February 2012*	Waste Management 2012,Phoenix, USA *26/02 - 01/03/2010*	Scientific Community; Industry	international
Oral presentation	UA	Findings from the MoDeRn Project: Indications of stakeholder expectations regarding monitoring - What, how, and who to involve?	*November 2012*	ENSI workshop	Regulator and civil society representatives	CH

Dissemination activities related to general activities of the partners on monitoring issues

Type of activities	Main leader	Title	Date/Period	Place	Type of audience	Countries addressed
presentation	GSL, NDA, ETH Zurich	Monitoring Geological Disposal Facilities	*18-20 October 2011*	Geological Disposal of Radioactive Waste: Underpinning Science and Technology (Loughborough, UK)	Scientific Community; Industry	EU
Training	DBE Technology	Monitoring of HLW repositories – objectives, needs and technologies	November 2011	ITC Training Course on practical aspects of repository engineering for disposal of spent fuel/HLW in sedimentary environments, Peine (Germany)	Scientific Community; Industry	DE
Thesis	ETH Zurich	Edgar Manukyan, *Seismic monitoring and elastic full waveform inversion investigations applied to the radioactive waste disposal issue*, ETH Zurich, Diss. ETH No. 19822, 2011	2011	PhD thesis, E. Manukyan (Switzerland, 2011)	Scientific Community; Industry	CH
Thesis	ETH Zurich	Stefano Marelli, *Seismic imaging of temporal changes in underground radioactive waste repositories: Surveillance requirements and full waveform inversion issues*, ETH Zurich, Diss. ETH No. 20040, 2011	2011	PhD thesis, S. Marelli (Switzerland, 2011)	Scientific Community; Industry	CH
Publication	Sandia	*Repository Performance Confirmation*	October 2011	SANDIA REPORT SAND2011-6277 October 2011	Scientific Community; Industry	US

c. Period 3

Type of activities	Main leader	Title	Date/ Period	Place	Type of audience	Countries addressed
Presentation	ETH	Seismic tomography in an argillaceous and crystalline rock formation	Oct, 16, 2012	IAEA workshop at Mont Terri, GM-A (Geophysical monitoring)	Scientific Community; Industry	international
Poster	AITEMIN, et al	State-of-the-art of monitoring technology for repositories: Outcome of MoDeRn project based on instrumentation performance obtained from long-term experiments	October 22-25, 2012	Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. 5th International meeting. Montpellier (France)	Scientific Community; Industry	international
Poster	AITEMIN, ENRESA	New wireless data transmission system based on high frequency radio communication: Design, development and testing results under repository conditions	October 22-25, 2012	Clays in Natural and Engineered Barriers for Radioactive Waste Confinement. 5th International meeting. Montpellier (France)	Scientific Community; Industry	international
Poster	NRG	T.J. Schröder and J. Hart. *Wireless transmission of monitoring data out of the HADES underground laboratory*. Abstract for poster presentation	22-25 October 2012	Clays in Natural and Engineered Barriers for Radioactive Waste Confinement conference, Montpellier, France	Scientific Community; Industry	international
Presentation	ETH	Non-intrusive seismic monitoring of high-level radioactive waste repositories	Nov 6, 2012	Annual meeting of the Society of Exploration Geophysics	Scientific Community; Industry	international
presentation	UA (with input from UEA and UGOT)	A. Bergmans, Perspectives on geological repository monitoring: confirmation, compliance, confidence building and societal vigilance	24/01/2013	EURIDICE exchange meeting “Instrumentation and monitoring in radioactive waste repository research” (Mol, Belgium)	Scientific Community; Industry	BE
paper + oral presentation	NRG	T.J. Schröder, E. Rosca-Bocancea, and J. Hart: *Wireless Transmission of Monitoring Data out of an Underground Repository: Results of Field Demonstrations Performed at the HADES Underground Laboratory*.	February 24-28, 2013,	Waste Management 2013 Conference, Phoenix, Arizona, USA	Scientific Community; Industry	international

Presentation	ETH	Monitoring High-Level Radioactive Waste Repositories with Non-intrusive Seismic Methods Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
Paper & Oral Presentation	DBE Tech, Euridice, ANDRA, NRG, AITEMIN, RWMC, Posiva	M.Jobmann, J. Verstricht, S. Lesoille, G. Hermand, T.J. Schröder, J. Hart, I. Bárcena, K. Susuki, J. Lahdenperä MoDeRn – A Case Study Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
Article	RWMC	Activity of the MoDeRn Project, an International Collaborative Study on the Monitoring of Geological Disposal	June, 2013	Radioactive waste management funding and research center topics, No.106, p.4-8, in Jap.	Scientific Community; Industry	JP
Presentation	NDA	The EC MoDeRn Project	3/04/2013	NDA Radioactive Waste Management Directorate	Scientific Community; Industry	UK
Presentation	AITEMIN	New wireless data transmission system based on high frequency radio communication: design, development and testing results under repository conditions Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
Presentation	AITEMIN	State of art of monitoring technology for repositories: instrumentation performance obtained from long duration experiments Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
Presentation & paper	UA, UEA and UGOT	A. Bergmans, M. Elam, P. Simmons, G. Sundqvist, Different Views on Monitoring and the Governance of Repository Development and Staged Closure Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
presentation	NDA, GSL	Development of the UK's Geological Disposal Facility Monitoring Programme.	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
Presentation	Andra	N. Solente, Overview of the MoDeRn project: A Reference Framework For Developing A Monitoring Programme Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
paper + oral presentation	NRG	T.J. Schröder and J. Hart. *Wireless Transmission of Data from the HADES Underground Laboratory to the Surface*. Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop,	Scientific Community; Industry	international

				Luxembourg		
Presentation	EURIDICE	Areias L., Sol H., Jun G., Pyl L., Van Marcke P.,Coppens E., Verstricht J., Villers L., and Van Cotthem A. (2013), Application of DIC to detect the onset of cracking in the concrete buffer of the Belgian Supercontainer	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
Presentation	EURIDICE	Areias L., Kursten B., Druyts F., Gens R., Van Marcke P., Verstricht J., Villers L. Van Cotthem A., and De Wilde D. (2013), Reduced scale tests to assess corrosion of steel overpack in the Belgian Supercontainer Abstract	19-21 March 2013	The MoDeRn International Repository Monitoring Conference and Workshop, Luxembourg	Scientific Community; Industry	international
paper + oral presentation	NRG	T.J. Schröder, Ec. Rosca-Bocancea, and J. Hart *Wireless data transmission from wireless data transmission from deep geological disposal facilities to the surface.*	April 28 - May 2, 2013	14th International High-Level Radioactive Waste Management Conference, Albuquerque, New Mexico,	Scientific Community; Industry	international
Presentation & abstract	UEA (with input from UA and UGOT)	Simmons P., Bergmans A., Elam M., Sundqvist G., Expert and Lay Constructions of Repository Monitoring in the Geological Disposal of Radioactive Waste	28-31 Aug. 2013	ESA 2013, 11th European Sociological Association Conference - Crisis, Critique and Change Torino -	Scientific Community; Industry	EU
Presentation	EURIDICE	Areias, L., Troullinous, I., Iliopoulos, S., Voet, E., Pyl, L., Lefevre, C., Verstricht, J., Van Ingelgem, Y., Coppens, E. and Van Marcke, P. (2013). Instrumentation and monitoring aspects of a ½-scale test to evaluate the feasibility of the Belgian Supercontainer,	September 8-12, Brussels	15th ASME 2013 International Conference on Environmental Remediation and Radioactive Waste Management, ICEM2013	Scientific Community; Industry	International
presentation	Andra	*N. Solente*, Monitoring Developments for safe Repository operation and staged Closure: The International MoDeRn Project	14-17 October 2013	EURADWASTE'13, Vilnius	Scientific Community; Industry	EU
Presentation & paper	UA (with feedback from UEA and UGOT)	Bergmans A., Andersson K., Opening up the technical: Involving stakeholders in developing repository programmes	14-17 October 2013	EURADWASTE'13, Vilnius	Scientific Community; Industry	EU
Short video	EURIDICE	Belgian Supercontainer half-scale test no. 2. Video shown at Euradwaste '13	14-16 October 2013	Euradwaste'13 8th EC Conference on the Management of Radioactive Waste Vilnius, Lithuania.	Scientific Community; Industry	EU
Presentation	AITEMIN	Results of the "call for ideas" on repository monitoring	29-30th October 2013	4th IGD-TP Exchange Forum. Prague (Czech republic)	Scientific Community; Industry	EU

Presentation	AITEMIN	Short range data transmission for repository monitoring: Technology status and required R&D	29-30th October 2013	4th IGD-TP Exchange Forum. Prague (Czech republic)	Scientific Community; Industry	EU
Oral presentation	NRG	T.J. Schröder. Monitoring in Waste Disposal - NRGs' contribution to MoDeRn and lessons learned	29-30 October 2013	IGD-TP Exchange forum 4 (EF4) meeting, Prague	Scientific Community; Industry	EU
Oral presentation	UA, UEA	A. Bergmans, The role of social science in further research on monitoring for GD	29-30 October 2013	IGD-TP Exchange forum 4 (EF4) meeting, Prague	Scientific Community; Industry	EU
Oral presentation	GLS	M. White, MoDeRn Project: Lessons Learned and Further Work Requirements	29-30 October 2013	IGD-TP Exchange forum 4 (EF4) meeting, Prague	Scientific Community; Industry	EU
Presentation	EURIDICE	Areias, L., Iliopoulos, S., Verstricht J. (2013). Recent experience with the use of DIC and AE to monitor surface cracking in a cylindrical concrete buffer	29-30 October 2013	IGD-TP Exchange forum 4 (EF4) meeting, Prague	Scientific Community; Industry	EU

5.2.Patents and exploitable foreground

Not applicable

6. Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*	
Grant Agreement Number:	232598
Title of Project:	Monitoring Developments for safe Repository operation and staged closure
Name and Title of Coordinator:	Nicolas SOLENTE, scientific coordinator

B Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***No***
2. Please indicate whether your project involved any of the following issues (tick box) :	
RESEARCH ON HUMANS	
• Did the project involve children?	NO
• Did the project involve patients?	NO
• Did the project involve persons not able to give consent?	NO
• Did the project involve adult healthy volunteers?	NO
• Did the project involve Human genetic material?	NO
• Did the project involve Human biological samples?	NO
• Did the project involve Human data collection?	NO
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	NO
• Did the project involve Human Foetal Tissue / Cells?	NO

• Did the project involve Human Embryonic Stem Cells (hESCs)?	NO
• Did the project on human Embryonic Stem Cells involve cells in culture?	NO
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	NO
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	NO
• Did the project involve tracking the location or observation of people?	NO
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	NO
• Were those animals transgenic small laboratory animals?	
• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	NO
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	NO
DUAL USE	
• Research having direct military use	NO
• Research having the potential for terrorist abuse	NO

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator		2
Work package leaders		6
Experienced researchers (i.e. PhD holders)	6	23
PhD Students		2
Other	10	10

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men:	

D	Gender Aspects		
5.	**Did you carry out specific Gender Equality Actions under the project?**	○ ●	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not effective at all — Very effective
❑	Design and implement an equal opportunity policy	○ ○ ○ ○ ○
❑	Set targets to achieve a gender balance in the workforce	○ ○ ○ ○ ○
❑	Organise conferences and workshops on gender	○ ○ ○ ○ ○
❑	Actions to improve work-life balance	○ ○ ○ ○ ○
○	Other:	

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

● No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

○ Yes- please specify

● No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

● No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

○ Main discipline[9]: 1.4 , 2.2 , 5.4

○ Associated discipline[9]: 2.1, 2.3

○ Associated discipline[9]:

G Engaging with Civil society and policy makers

11a	**Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)*	● ○	Yes No

[9] Insert number from list below (Frascati Manual).

11b	**If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?** ○ No ○ Yes- in determining what research should be performed ● Yes - in implementing the research ● Yes, in communicating /disseminating / using the results of the project

11c	**In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?**	○ ●	Yes No

12.	**Did you engage with government / public bodies or policy makers (including international organisations)**
	● No ○ Yes- in framing the research agenda ○ Yes - in implementing the research agenda ○ Yes, in communicating /disseminating / using the results of the project

13a	**Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?** ● Yes – as a **primary** objective (please indicate areas below- multiple answers possible) ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible) ○ No

13b If Yes, in which fields?

~~Agriculture~~ ~~Audiovisual and Media~~ ~~Budget~~ ~~Competition~~ ~~Consumers~~ ~~Culture~~ ~~Customs~~ ~~Development Economic and Monetary Affairs~~ ~~Education, Training, Youth~~ ~~Employment and Social Affairs~~		**Energy** ~~Enlargement~~ ~~Enterprise~~ **Environment** ~~External Relations~~ ~~External Trade~~ ~~Fisheries and Maritime Affairs~~ ~~Food Safety~~ ~~Foreign and Security Policy~~ ~~Fraud~~ ~~Humanitarian aid~~		~~Human rights~~ **Information Society** ~~Institutional affairs~~ ~~Internal Market~~ ~~Justice, freedom and security~~ ~~Public Health~~ ~~Regional Policy~~ **Research and Innovation** ~~Space~~ ~~Taxation~~ ~~Transport~~	

13c If Yes, at which level? ● Local / regional levels ● National level ○ European level ○ International level	

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	
To how many of these is open access[10] provided?	
How many of these are published in open access journals?	
How many of these are published in open repositories?	
To how many of these is open access not provided?	
Please check all applicable reasons for not providing open access:	
❑ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[11]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*		
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	
	Registered design	
	Other	
17. How many spin-off companies were created / are planned as a direct result of the project?		**0**
Indicate the approximate number of additional jobs in these companies:		

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑	Increase in employment, or	❑	In small & medium-sized enterprises
❑	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	❑	None of the above / not relevant to the project
❑	Difficult to estimate / not possible to quantify		

[10] Open Access is defined as free of charge access for anyone via Internet.
[11] For instance: classification for security project.

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	☒

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes ● No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ● No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

❑	Press Release	❑	Coverage in specialist press
❑	Media briefing	❑	Coverage in general (non-specialist) press
❑	TV coverage / report	❑	Coverage in national press
❑	Radio coverage / report	❑	Coverage in international press
☒	Brochures /posters / flyers	☒	Website for the general public / internet
❑	DVD /Film /Multimedia	☒	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

❑	Language of the coordinator	☒	English
❑	Other language(s)		

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]