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
Foreword

Support from the European Commission (EC) to research on the management and disposal of radioactive waste stems from the European Atomic Energy Community (EURATOM) Treaty, which was signed in 1957. Since 1975, the EC has continuously supported research in the field.

One of the requirements of the research programmes is to promote dissemination and use of the results in the European Union (EU) Member States and to promote international cooperation in research activities. With this in mind, in the present Framework Programme 2007-2013, the EC has requested from all the large and key projects it is funding in geological disposal, that they organise a final conference in order to present and discuss the results obtained. The Monitoring Developments for Safe Repository Operation and Staged Closure (MoDeRn) project is one of these key projects and because of its specific importance and international dimension the EC decided to host an international conference and workshop on monitoring in geological disposal of radioactive waste. The conference and workshop received support from the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA), Integration Group for the Safety Case (IGSC).

On the topic of monitoring, one could say that activities on this specific issue at European and international level started only fairly recently compared to other research and development activities. At an EC level, it started in 2001 with the Thematic Network on Monitoring, which is available for download from the EU bookshop http://bookshop.europa.eu. In the meantime, the International Atomic Energy Agency (IAEA) produced, in 2001, Technical Document guidance on monitoring and later in 2006 it issued safety requirements for the geological disposal of radioactive waste including the need for a monitoring strategy. The 2006 requirements were updated in 2011. The NEA for its part launched the reversibility and retrievability project in 2007. Reversibility and retrievability issues are closely linked with monitoring.

Many national programmes have also worked on the issue in parallel, starting from the launch of a performance confirmation programme for the Waste Isolation Pilot Plant in the United States back in 1983, to the international workshop on repository monitoring strategies hosted by the Radioactive Waste Management and Funding Centre (RWMC) of Japan and United Kingdom Nirex in Geneva, in 2007, and others. The Geneva workshop laid the foundation for future activities, based on which the MoDeRn project was prepared for submission to EC funding.

Many aspects of monitoring have been addressed until now but it seems that many of us still do not feel at ease with the issue. The question is: what do we really want monitoring for and is it technically feasible? Would we implement monitoring for performance confirmation, for compliance with regulatory requirements, for decision making, for confidence building or because of public concern and societal demand?

In calling for this project in 2008, the EC was asking somehow to address these questions: what, why, how, when and for how long? Recognising the importance of public involvement on the topic, the EC had also asked the project to involve and seek input from local stakeholders and the public concerned by repository projects.

I hope that the MoDeRn project and this international conference will have contributed to clarifying the issues and making progress on the different aspects of monitoring.

Christophe Davies

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*EC project officer for the MoDeRn project and other projects in the field of radioactive waste management – geological disposal.*
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1. Introduction

Elizabeth Harvey and Matthew White (Galson Sciences Ltd)

1.1 Background to the MoDeRn Project

Long-lived radioactive waste must be safely isolated and contained for long periods. Current radioactive waste management programmes are focused on disposal in geological repositories as the most appropriate strategy for ensuring the long-term safety of people and the environment.

A successful strategy for radioactive waste disposal should address both technical and societal needs, and monitoring has the potential to contribute to both of these aspects. It can underpin a repository safety strategy and the quality of the engineering design, it can contribute to public and stakeholder understanding of processes occurring in the repository, and hence, it can be used to build confidence in geological disposal. Monitoring therefore plays an important role in enabling waste management organisations to work towards the safe and accepted implementation of geological disposal.

The role of monitoring through the staged implementation of geological disposal has been considered on an international basis through production of an International Atomic Energy Agency (IAEA) Technical Document (TECDOC) on monitoring of geological repositories (the IAEA Monitoring TECDOC) [1] and by the European Commission (EC) within a Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste (the Monitoring ETN) [2]. These two documents have described how monitoring can support the implementation of geological disposal in a broad sense.

Building on these activities, the European Commission (EC) is co-financing the MoDeRn (Monitoring Developments for Safety Repository Operation and Staged Closure) Project, within its 7th Euratom Framework Programme (FP7). The project, which started in May 2009, and which runs until later in 2013, involves 18 partner organisations drawn from across Europe, Japan and the United States (US), including:

- National radioactive waste management organisations.
- Organisations with specialist technical monitoring expertise.
- A specialist radioactive waste management consultancy.
- Organisations with social science expertise, including understanding of the interfaces between technical and societal needs, and understanding of stakeholder engagement in the context of radioactive waste disposal.

The MoDeRn Project aims to further develop understanding of the role of monitoring in staged implementation of geological disposal to a level of description that is closer to the actual implementation of monitoring. Key objectives of the project are to provide a reference framework for the development and implementation of a monitoring programme, including associated stakeholder engagement, and to consider the role and technical feasibility of using a range of monitoring technologies within the reference framework, particularly during the period following emplacement of waste packages in a repository (the "post-emplacement period").
Activities within the MoDeRn Project consider a range of strategic, technical and social issues associated with monitoring, and are structured into six inter-related work packages (WPs):

- WP1: Monitoring objectives and strategies.
- WP2: State-of-the-art, and research and technological development (RTD) of relevant monitoring technologies.
- WP3: *In situ* demonstration of innovative monitoring techniques.
- WP4: Case study of monitoring during all stages of the disposal process.
- WP5: Synthesis and dissemination of MoDeRn Project results.
- WP6: Reference framework for repository monitoring.

### 1.2 Objectives of the Conference and Workshop

A key activity under WP5 of the MoDeRn Project is to hold an international conference on repository monitoring under the auspices of the EC. This conference, entitled “Monitoring in Geological Disposal of Radioactive Waste: Objectives, Strategies, Technologies and Public Involvement”, and hereafter referred to as the “International Conference and Workshop on Repository Monitoring”, was held on 19-21 March 2013 at the EC’s offices in Luxembourg. The objectives of the conference and workshop were as follows:

- To present and discuss the results of the MoDeRn Project, as part of ensuring wide dissemination of this EC-funded work.
- To invite further input to the issues being considered in the MoDeRn Project.
- To discuss how monitoring can be used to inform the disposal process, respond to regulatory requirements, and contribute to enhancing confidence in, and acceptance of, geological disposal of radioactive waste.

The conference took place on the afternoon of 19 March and the morning of 20 March and included oral presentations and plenary discussion under three themes, as well as a poster session covering all three themes. This was followed by a series of six workshops, which were held on the afternoon of 20 March and the morning of 21 March, with the objective of providing an opportunity for further discussions on the conference topics and to investigate whether a shared understanding of repository monitoring can be developed. The key conclusions from each workshop were presented and discussed during a final plenary session later on the morning of 21 March 2013. The conference and workshop were attended by 133 participants from 20 countries.

### 1.3 Scope of the International Conference on Repository Monitoring

The conference was organised around the following three themes:

- Theme 1: Monitoring – Implementers’ perspectives: Programmes and case studies on repository monitoring.
• Theme 2: Monitoring – The wider perspective: Regulatory and stakeholder viewpoints.

• Theme 3: Monitoring technologies: Feasibility and limitations.

Twenty five oral presentations and seventeen poster presentations were spread across seven plenary conference sessions under these three themes, as illustrated in the conference timetable provided in (Fig. 1.1). A detailed conference programme is provided in Appendix A.

1.4 Scope of the Associated Workshops

Six workshop sessions were held, in three parallel tracks. These focused on:

• How to monitor, including discussion of technical feasibility and the limitations of existing monitoring technologies (Workshop 1, Track 1).

• Why to monitor, including discussion of the driving forces for monitoring and why monitoring is required (Workshop 1, Track 2).

• When and how long to monitor for, including discussion of the role of post-closure monitoring and associate stakeholder views (Workshop 1, Track 3).

• How to use monitoring results, including discussion of the role of monitoring within decision making and governance (Workshop 2, Track 1).

• Who should be involved in monitoring, including discussion of the different roles and responsibilities that the different actors involved in monitoring could adopt (Workshop 2, Track 2).

• What and where to monitor, including discussion of the parameters that could be included within a monitoring programme, the spatial distribution of monitoring locations and underlying justifications for approaches suggested (Workshop 2, Track 3).

MoDeRn Project partners acted as the chair person and rapporteur for each of these workshops.
Figure 1.1: Summary timetable for the International Conference and Workshop on Repository Monitoring.
1.5 Structure of these Proceedings

These proceedings of the International Conference on Repository Monitoring incorporate the following components:

- An independent analysis and synthesis of the conclusions arising from discussion at the conference and workshop (Section 2), based on the observations of an independent expert in the geological disposal of radioactive waste (Alan Hooper) who had not been previously involved in the MoDeRn Project, and who acted as the “general rapporteur” for the conference.

- A record of the key points raised and discussed during plenary conference sessions (Section 3) and associated workshops (Section 4).

- A list of references associated with Sections 1 to 4 (Section 5).

- A detailed conference programme (Appendix A).

- A list of registered participants in the International Conference on Repository Monitoring (Appendix B).

- Full papers for each of the oral and poster presentations submitted to the conference (Appendix C).

Section 2 of these proceedings was prepared by the conference general rapporteur. The discussion in this section reflects the general rapporteur’s independent analysis of the event, and does not necessarily reflect the opinions of the MoDeRn Project. Papers provided in Appendix C were prepared by the listed authors. The rest of these proceedings were prepared by Galson Sciences Ltd, on behalf of the MoDeRn Project partnership, as a factual record of discussion.
2. An Overview of the Important Outcomes from the MoDeRn International Conference

Alan Hooper, Visiting Professor of Repository Science and Engineering, Imperial College, London (Independent General Rapporteur)

2.1 Introduction

Monitoring in geological disposal was, until relatively recently, a topic that was treated with apprehension in many radioactive waste management programmes. This was in large part because of a possibility that it implied a need to monitor a repository in the period after closure to somehow prove that it was performing satisfactorily. This in turn could be linked with the hypothetical proposition that long-term safety would rely upon continued human actions and possible intervention, in contradiction of various international and national statements on safety requirements for geological disposal.

Whereas the relationship of monitoring to long-term safety remains an area of lively debate, as evidenced at the conference, successive international initiatives culminating in the Euratom MoDeRn Project have promoted a systematic analysis of the role that monitoring can play in implementing safe geological disposal of long-lived, high-activity radioactive wastes. This progress has been made not least because of the involvement of other players alongside the organisations responsible for implementing disposal. The conference provided a showcase for some of the outputs from the MoDeRn Project but additionally received valuable inputs from other contributors. Formal presentations and contributions to discussions were made with great honesty, exposing the problematic nature of the topic of monitoring rather than ignoring it.

As a matter of practicality, the formal presentations at the conference were structured around the three themes of, respectively: the implementers’ perspective; the wider (regulatory and stakeholder) perspective; and monitoring technologies. This disaggregation of the overall topic made it difficult to place some of the information in an appropriate context, although material provided to delegates illustrated a workflow for the Project that could be seen as an approach to integration of the various inputs. A philosophical point established in the introduction to the conference and reaffirmed by various speakers was that monitoring can be characterised as a socio-technical activity in that it can provide a visualisation of what is meant by safety to non-technical members of society and potentially build confidence as a practical commitment to maintain vigilance. However, it was difficult to determine the societal context of some of the technical inputs to the conference. Conversely, from the information presented at the conference, the MoDeRn Project has generated some valuable inputs from stakeholders, for example that monitoring has the potential to build confidence, but subject to constraints such as monitoring being clearly related to showing compliance (with regulatory and other standards or requirements) and to system optimisation. Therefore, it is to be hoped that a successful integration of the outcomes from the technical and societal work packages will take place in finalising the reporting of the Project.

2.2 Definition and Purpose of Monitoring

A range of views was evident on the meaning of monitoring and therefore of its purpose. However, delegates at the conference generally accepted that it was not fruitful to argue whether a specific activity should be defined as a monitoring activity or otherwise. It was very helpful to have a view of the draft IAEA Safety Guide DS357: Monitoring and Surveillance of Radioactive waste Disposal Facilities. Noting that the safety guide applies to all types of radioactive waste disposal system, this defines monitoring as “Continuous or periodic observations and measurements to help evaluate the
behaviour of the components of a waste disposal system and the impact of the waste disposal system on the public and environment”. Surveillance is additionally defined as “Physical inspection of a waste disposal facility in order to verify its integrity to protect and preserve the safety barriers”. The two IAEA definitions appeared to be combined in the minds of most participants as a broader definition of monitoring. The draft of the International Commission on Radiological Protection’s publication *ICRP-122: Radiological Protection in Geological Disposal* introduces the idea of “oversight” as a form of control even after the repository is closed and which involves monitoring of more than technical parameters. It is envisaged by the ICRP that, with the passage of time after closure of a repository, society would play an increasingly important role in such oversight.

In the keynote address to the conference *Monitoring and Long-term Safety* (P. Zuidema, Nagra, Switzerland) it was proposed that monitoring can:

- Provide specific technical information to implement geological disposal.
- Provide important inputs to the scientific and technological basis for geological disposal.
- Provide information for society that helps the interaction between technical experts and society.

This set of purposes of monitoring is very much in line with the thrust of the draft IAEA Safety Guide and its statement that monitoring should be driven by and inform the safety case. It implies a focus on the monitoring of technical aspects of a geological disposal system, whereas the ICRP draft publication appears to imply monitoring of non-technical aspects also. These are not mutually exclusive positions; the monitoring of non-technical aspects after closure of a disposal facility is generally accepted as an important element of an institutional control period that is expected in most national programmes.

### 2.3 A Systematic Framework

The value of establishing a framework in which to discuss the role and objectives of monitoring became clear in the initial stages of the conference. Based on the stepwise implementation of geological disposal, it helps to overcome differences in terminology and of focus in different national programmes to consider that monitoring is necessary in each of the following stages that support decision-making:

- Site selection (e.g. monitoring seismicity, geodesy).
- Site investigation (e.g. monitoring ecology, hydrology, hydrogeology).
- Design of engineered barrier system (e.g. monitoring prototypes in an underground research laboratory (URL) or mock-up facility).
- Construction (e.g. monitoring response of host rock to excavation of tunnels etc.).
- Operation (e.g. monitoring emplaced wastes and engineered barriers).
- Closure (e.g. monitoring of engineered sealing systems).
• Post-closure institutional control (e.g. monitoring conditions at the surface according to any regulatory or societal requirements).

Both the approach to monitoring according to this stylised schedule and the objectives of the monitoring are clearly dependent upon respective national policies, implementation plans and repository concepts. For example, the Swiss national programme envisages a pilot facility where real wastes will be emplaced specifically for the purpose of monitoring. The French national programme has to meet a requirement for reversibility until repository closure, necessitating long-term monitoring of the engineered disposal system after waste emplacement.

Also in the early stages of the conference, there was a clear consensus from presentations and discussions that a systematic approach to defining the link between monitoring activities and long-term safety is helpful to implementers, regulators and stakeholders. Well-chosen examples showed that it is practicable to start with the safety functions of the various barriers in the multiple barrier system and then to identify the processes that are involved in the delivery of each safety function, for example by using a features, events and processes (FEPs) database appropriate to the system under consideration. The ability to measure the parameters that characterise these processes as part of a monitoring programme can then be considered in turn.

2.4 Confidence Building

Confidence building is an important theme of the MoDeRn Project and this was emphasised at the conference. Presentations of work carried out as part of the project showed that, by commissioning relevant social scientific research, it has gone beyond simply asserting that monitoring per se will build or assure confidence in the minds of stakeholders. Additionally, valuable insights were afforded by presentations on the views of stakeholders in specific disposal projects (Mol / Dessel Partnerships in the framework of short-lived LLW/ ILW disposal in Belgium, and the local community for the Waste Isolation Pilot Plant at Carlsbad, New Mexico, USA).

An important aspect to note from all the relevant information presented, including an analysis of the socio-technical nature of monitoring, is that monitoring cannot be considered in isolation from the governance of waste disposal. The roles, responsibilities and behaviour of the relevant organisations will strongly determine whether monitoring can play a role in confidence building. There was general agreement that monitoring has the potential to build confidence, but that realising this potential is subject to a number of conditions. Conditions might include establishing a relationship with compliance and optimisation and establishing appropriate governance arrangements within which the time and dimensional space to be covered by monitoring can be discussed and agreed. Such conditions may vary for individual groups of stakeholders. The merit in engaging with a locally-based partnership at the earliest opportunity was clear both from the more theoretical analyses and from the experience of real projects.

Many significant points emerged during the conference concerning the expectations of stakeholders in relation to monitoring, three of which are highlighted for the purposes of this section of the summary.

i. Stakeholders expect monitoring to test compliance with relevant regulations and standards, thereby providing some level of assurance that the facility is safe at the time of monitoring and will continue to be safe in the future. This supports a general agreement on the necessity for society to be satisfied with a programme of environmental monitoring along the lines of those programmes routinely carried out currently at nuclear sites (for example
measuring radioactivity in environmental samples, including foodstuffs, soils, water and air), which would continue after operations had been completed and the disposal facility had been closed.

ii. Additionally stakeholders expect that monitoring will be used to inform optimisation of the facility; this is particularly strongly manifested when a local partnership such as the Mol/Dessel partnerships are engaged with the implementer in discussions of facility design.

iii. Finally, there is the expectation that a monitoring programme will be comprehensive, not least in the sense of being able to identify unexpected behaviour. It follows from this finding that stakeholders expect the implementer to be willing and able to respond to the results of monitoring, for example by retrieving waste if appropriate.

It seems that the respective views of the different actors in relation to uncertainties, and how they are to be treated, underpinned many of the findings from stakeholder groups. Very possibly fuelled by the use of jargon such as “performance confirmation” or “demonstration experiments”, the impression has been given that technical experts have a closed mind to the possibility that systems or sub-systems will behave differently from the manner intended or modelled. Therefore an important contribution can be made to confidence-building in relation to a monitoring programme if the programme is presented in the context of the classical scientific method of testing.

Independent regulation is an important aspect of confidence-building and the role of the regulator in monitoring the implementing organisation’s monitoring activities was emphasised. A possible tension is recognised between stakeholders’ expectations of monitoring after repository closure and the current expectations of regulators. As discussed in the following section, in general regulators have an expectation for monitoring to support the safety case and for this to be achieved principally in the period up to the time when an application is made to close the repository. Thereafter monitoring requirements would be to support post-closure institutional control of the repository site until it would be decided that such control is no longer necessary. Currently there appear to be no known regulatory requirements for specific monitoring activities after repository closure, although some regulatory bodies have clearly stated a requirement for such monitoring and associated systems and in some cases are giving the topic further consideration, which may lead to specific requirements on the objectives and duration.

2.5 Post-closure Monitoring

One generally accepted principle, as stated clearly in *Monitoring Requirements in the Swiss Regulatory Framework (A.-K. Leuz et al., ENSI, Switzerland)*, that monitoring activities should not adversely affect the passive safety barriers of a repository and therefore potentially impair safety, applies equally to the post-closure period. However, beyond this, whereas there is a reasonable level of agreement both between the various actors and between different groups of technical experts as to what types of monitoring activities can and should be conducted in the stages leading up to the time of closure of a disposal facility, there is not such unanimity of view for the time after closure. The role and objectives of post-closure monitoring are recognised as requiring further consideration in some national programmes. As expressed clearly at the conference, poorly conceived undertakings to carry out post-closure monitoring as some means of confirming the long-term safety case presents difficulties for the regulator. Once the designated disposal activities have been completed and the relevant actors have determined that the isolation and containment multi-barrier system should be fully established, it is for the regulator to judge whether the arguments presented in a long-term safety case are sufficiently substantiated to allow the closure of the facility.
Therefore the necessary level of substantiation of the safety arguments, including modelling of the long-term evolution of the facility, must rely on information already available and cannot rely upon the promise of future results from a monitoring programme.

The draft IAEA safety guide presents the position (for geological disposal) that monitoring after closure is rather for the purpose of public reassurance than for ensuring the performance of the disposal system. Although perhaps a little stark in its presentation, this hints at the questions concerning post-closure monitoring posed by a regulator at the conference, namely “Why, for who and how long?” The stakeholder views expressed at the conference already go some way to answering these questions in principle at least. However, the important conclusion that can be drawn from the conference workshops is that currently it is neither practicable nor necessary to have detailed, definitive answers to the questions. Furthermore, it may be that we can never a priori formulate definitive answers and that these questions frame an ongoing dialogue between the various actors. The MoDeRn Project is successfully laying out the technological and societal possibilities such that these can then be discussed between the relevant actors in national programmes, as is envisaged by the Finnish regulator STUK.

In the absence of the specification of a detailed post-closure monitoring programme there does appear to be an issue in the event that the design, construction and operation of a disposal facility might preclude monitoring activities that are subsequently identified as required. However, there is a generally agreed requirement to be able to show, through test monitoring, that the “initial state” of the disposal facility, as described at the time of closure in the long-term safety case, has been achieved. Substantial provisions for monitoring are likely to be established in meeting that requirement.

2.6 Monitoring Technologies

Under the MoDeRn Project, impressive progress has been made in developing and analysing the capabilities of monitoring technologies in each of the fields of measurement probes and methods, data transmission, and energy supply. The physical limitations on the various technologies are much better understood as a result, for example the distances over which various types of signals can be reliably transmitted, the influence of the host rock-water system, and the energy demand of various technologies. Some problems remain to be investigated, for example the reliability of technologies operating in the radiation field presented by emplaced radioactive wastes.

A key challenge that the technologies have to meet is that monitoring should not impair the safety of a disposal facility. This is seen as precluding the use of cables to carry signals from the wastes and engineered barrier system back to the surface and has led to a focus on wireless transmission of data; the technologies explored to date have relied on radio frequencies while the non-radio alternatives do not look promising. The long timescales of interest in geological disposal, even in relation to monitoring relatively short-term transients in the disposal system, are greater than those covered by our experience of any of the technologies of interest. Furthermore some technologies require access to measurement points obtained by open boreholes to depth, which is potentially problematic if such monitoring is envisaged in the post-closure period or if borehole sealing is considered to be an issue.

Nevertheless, valuable information has been, and continues to be, obtained from monitoring large scale tests of excavations and engineered barrier systems in underground research laboratories, using some of the most recently developed monitoring technologies. Coupled with the more fundamental studies on the physical science of monitoring technologies, this experience can be used
to point to the most promising areas for further research and development, thereby presenting a picture of the possibilities that can be pursued.

Despite the considerable progress that has been made, it appeared unlikely that current monitoring technologies will be developed such that they can be relied upon to function for the nominal period of 100 years considered in the case studies of repository evolution in the MoDeRn Project.

2.7 Important Considerations in a Monitoring Programme

Transferability of information
In order that monitoring activities carried out in successive stages of implementation of a disposal facility can fulfil the role of supporting the eventual long-term safety case, the transferability of the information obtained needs to be understood. The Swiss national programme exemplified how monitoring information on the behaviour of the engineered barrier system (EBS) in a generic URL might be transferred to the design for a site-specific disposal facility. The legislation for the development of the disposal facility itself at the selected site envisages monitoring in a test area whereby the safety-relevant properties of the EBS and host rock must be tested in support of the safety case. In the subsequently developed pilot facility, the behaviour of representative waste, backfill and host rock is required to be monitored over a long period such that it is readily transferable to the processes occurring in the main disposal area and ultimately supports the decision to close the facility.

The requirement for transferability of monitoring information was raised consistently by implementers, regulators and stakeholders but its implications were not much discussed at the conference. The observation, in connection with the monitoring strategy for the French “Cigeo Repository”, that the homogeneity of the properties of the host-rock formation is important for developing a practicable monitoring programme merits attention. It is likely to be problematic to transfer monitoring information obtained from one location in the engineered system to infer the evolutionary behaviour of un-monitored parts of the system elsewhere when a repository is located in a heterogeneous host rock. As is already recognised in site characterisation programmes, the implementer would need to exercise caution in considering transferability of monitoring information for host rocks with spatially heterogeneous processes and properties, where possible taking account of the influence such heterogeneity could have on the variability of any parameter to be monitored.

Transient conditions
A favourable host rock for a disposal facility is typified by the property of low hydraulic conductivity. This desirable property will cause processes such as the saturation of the components of engineered barrier systems (EBS) by inflowing groundwater to occur very slowly. Furthermore, heterogeneity in the rock local to the EBS and/or in the interfaces between the EBS and host rock will cause such saturation to occur at different rates at different locations. It is noticeable that the saturation process is frequently cited as one that should be monitored, purportedly to demonstrate that the system is showing its expected evolution. However, the conference received a striking example of the risks of making such assertions.

The example concerned the monitoring of the evolution of stresses and pore pressures in and around a sealing dam installed in the German ERAM Repository. It has to be recognised that this does not represent an idealised situation, such as might be achieved in a future disposal system designed and operated in accordance with current knowledge and experience. Nonetheless, the conclusions from the monitoring carried out to date include that there are inhomogeneous distributions of
permeabilities, stresses and pore pressures in the contact zone between the engineered dam and salt host rock so that the monitored pore pressures and normal stresses are influenced by local conditions. Furthermore, “many challenges arise in the analysis and interpretation of the captured values even with the careful planning of the measurement programme and installation of the devices”. It was reasonably concluded that homogenisation of properties might occur eventually but that this cannot be predicted with confidence from the information obtained.

This valuable example fits very well with the messages in the keynote address concerning the societal aspects of monitoring, namely that interpretation of monitoring data in the context of overall system behaviour is the other half of building confidence, and that to inspire confidence through monitoring the inherent limitations must be recognised and explained. These statements in the keynote address were made in the context that even the attainment of steady-state conditions in the near field of a disposal system is unlikely to be realised over timescales that are short enough to allow it to be monitored; therefore monitoring is restricted to the measurement and observation of transients which need to be strong enough to provide clear indicators of the system evolution. The monitoring of transient conditions themselves can be of great value during the period prior to closure of a repository, for example providing information on temperature rises as a result of the radiogenic heat-loading in emplaced high-level waste and its effects on the disposal system and geological environment.

2.8 In Conclusion

In line with the position of the participants in the MoDeRn Project, there will be no single, international prescription that national programmes can take as the basis for the design of a monitoring programme. The national waste inventory, disposal concept, governance arrangements, regulations, and societal values and norms will establish the necessary context and input. Nonetheless, in line with the objectives of the MoDeRn Project, this conference provided much of the information required to establish the framework for designing a national monitoring programme.

There appears to be a reasonable degree of consensus between all the interested parties concerning the role and objectives of monitoring in supporting step-wise decision making up to the point of closure of a disposal facility, and there is also a shared understanding of the issues that should be further discussed in relation to the post-closure period. The expectations of stakeholders are expressed in different terms to those often used by implementers but in fact there appear not to be fundamental differences. The same important aspects that apply to implementation of geological disposal overall, such as governance arrangements and the ability of stakeholders to have access to information and to influence decisions, apply equally strongly in the area of monitoring.

The inputs made by regulators proved invaluable and it is encouraging that national regulatory bodies in some of the more advanced programmes are planning to give monitoring, particularly in the post-closure period, more detailed consideration. It is recommended that these regulatory bodies should, if possible, be involved in any ensuing international initiative in this area.

A matter not specifically considered under the auspices of the MoDeRn Project concerns the practical reality of funding monitoring activities, particularly in the long term after repository closure. It might be worthwhile to analyse how this matter is dealt with in national plans, particularly as reflected in the planning information provided to international organisations, to determine whether it requires further consideration.
3. Record of Conference Plenary Discussion

Elizabeth Harvey (Galson Sciences Ltd)

This section provides a factual record of discussion during the International Conference on Repository Monitoring, for each of the three themes of the conference. For each theme, the papers presented under the theme are listed, and a reference is given to the paper numbers. In these numbers, “S” refers to the conference session in which the paper was presented. “O” refers to an oral presentation (associated full papers can be found in Appendix C.1, C.2, C.3, C.5, C.6D and C.6T) and “P” refers to a poster presentation (associated full papers can be found in Appendix C.4). This is followed by a summary of the key points discussed during plenary sessions associated with each theme.

3.1 Theme 1: Monitoring – Implementers’ Perspectives: Programmes and Case Studies on Repository Monitoring

The following oral presentations were delivered during Session S2 of the International Conference and Workshop on Repository Monitoring:

- S2O1: Michael Jobmann (DBE-TEC, Germany) presented a summary of monitoring case studies carried out under the MoDeRn Project.

- S2O2: Steve Wagner (Sandia National Laboratories, USA), described the development and use of conformation monitoring programmes in association with radioactive waste repositories in the US.

- S2O3: Stephane Buschaert (Andra, France), set out the monitoring strategy for a French reversible waste disposal facility.

- S2O4: Assen Simeonov (SKB, Sweden), described the proposed approach to monitor the repository for spent nuclear fuel in Sweden.

- S2O5: Brendan Breen (NDA, UK), summarised the approach taken to develop the monitoring programme for a UK geological disposal facility.

The following poster presentations were delivered during Session S4 of the International Conference and Workshop on Repository Monitoring:

- S4P1: Jorge Villagran (NWMO, Canada), presented work conducted to develop a repository monitoring programme within the framework of Adaptive Phased Management in Canada.

- S4P2: Richard Guppy (NDA, UK), on behalf of James McKinney, presented integrated guidance on controlling storage conditions and monitoring higher-activity waste packages during interim storage.

- S4P3: Mansueto Morosini (SKB, Sweden) provided an overview of the hydrogeological monitoring programme carried out at the Äspö Hard Rock Laboratory in Sweden.
- S4P4: Susanna Andrén (SKB, Sweden) presented the groundwater monitoring programme at the Forsmark site in Sweden, performed to establish the baseline (undisturbed) conditions of the site.

- S4P5: Susanna Aro (Posiva Oy, Finland) presented results from the Finnish programme to monitor the hydrogeological effects of construction of the ONKALO URL in Finland.

- S4P13: Jiro Eto (RWMC, Japan) described the requirements on a wireless monitoring system for application during the stepwise backfilling and sealing of a geological repository.

- S4P14: Hiromi Tanabe (RWMD, Japan) discussed the basic requirements on monitoring activities in geological disposal, and the role of wireless data transmission in supporting the delivery of these requirements.

- S4P21: Matthew White (Galson Sciences Ltd, UK) described the monitoring plan for the new low-level waste facilities at Dounreay in the UK, and implementation of the associated groundwater monitoring programme.

The points below record the key areas of discussion following oral presentations under this theme.

**Impact of National Context on Development of a Monitoring Programme**

The scope of a monitoring programme developed for a particular repository will be affected by a range of factors that are specific to the disposal programme in question. For example, the disposal concept design and safety functions associated with different parts of the disposal system could have a significant impact on monitoring objectives and decisions on where and how to monitor. There may also be national policies, such as a requirement for retrievability, and/or regulatory requirements to monitor a particular process, or to carry out monitoring in a particular part of the repository, that influence the choice of monitoring parameters. In addition, the feasibility of successfully employing certain monitoring and wireless data transmission techniques is strongly dependent on the thickness and composition of engineered barriers such as the backfill, and plugs and seals, and on the characteristics of the local host rock. For example, clay rocks typically impede magneto-induced wireless data transmission to a greater extent than evaporites and crystalline rocks, and this effect is particularly significant when signals are transmitted over long ranges using low frequencies. The water-filled porosity of rocks also has a significant effect on the potential transmission distance. For similar reasons, micro-seismic monitoring tends to yield better results in crystalline rocks, compared to clay rocks.

Collectively, the considerations that are relevant for a particular repository development programme can be referred to as the national context for monitoring. This term has been widely used in the MoDeRn Project (which included a task to collate national contexts for partner countries) and also in previous collaborative studies on repository monitoring.

The implication of variations in the national contexts for monitoring is that there will be significant differences from country to country in the specific objectives for monitoring, the desired timescales for monitoring, and how monitoring is targeted at different components of the disposal system and the surrounding environment (and hence, in the characteristics of the associated monitoring programmes). Clear communication of the reasons for these differences to stakeholders might be important to allow stakeholders to understand why there are differences between monitoring programmes in different national programmes.
Monitoring Objectives from the Implementers’ Perspective
A key objective for monitoring in many national programmes is to confirm\(^1\) acceptable performance of components of the disposal system, particularly those providing key safety functions. At least theoretically, performance of such components could either be monitored directly, for example through the use of sensors attached to dummy waste packages, or indirectly, for example through the measurement of any radionuclide contamination in the groundwater around a repository. However, there is some evidence that public stakeholders would be typically more interested in monitoring conditions in their local environment, to ensure that there is no direct impact on them.

Direct monitoring of barrier performance may require the use of instrumented example (demonstrator) units or sacrificial components of the disposal system, possibly located within a pilot facility. This could be facilitated by a plan for retrieval and re-packaging/re-emplacement of a small quantity of waste at some point, once sufficient monitoring has been carried out. Information on the performance of disposal system components is also derived from the wider science programme, including experiments conducted within URLs and surface laboratories, and through modelling.

Drivers for Post-closure Monitoring
International guidance on repository monitoring recognises that monitoring and surveillance could be maintained for as long as society considers it beneficial \([1]\). However, it is a principle of geological disposal that assurance of safety does not require post-closure monitoring. Any post-closure monitoring undertaken by future generations should be designed in such way that no negative impacts on the performance of the containment barriers and therefore on the long-term safety of the repository would occur. Implicit in this principle is that the safety case has to provide sufficient confidence that a repository is safe and performing as expected before permission is granted to close the facility.

However, in some countries, notably Germany and France, national legislation and/or regulations either explicitly or implicitly require some form of post-closure monitoring or surveillance to be carried out. For example, in Germany\(^2\), safety requirements governing the final disposal of heat-generating radioactive waste require the establishment of a monitoring system “during emplacement operations, decommissioning, and for a limited period following decommissioning, in order to verify that the input data, assumptions and statements of the safety analyses and safety cases performed for this phase have been observed” \([3]\). This contrasts with the situation in some other countries (for example in Sweden and Switzerland), where the responsibility of the implementer ends when the repository is closed, such that the implementer would not be responsible for any post-closure monitoring carried out.

It is recognised that even in countries where there is no requirement for post-closure monitoring associated with confirming the continued acceptable performance of the repository, there may still be other reasons for undertaking some form of post-closure monitoring. Key among these is the use of post-closure monitoring to provide confidence to local communities that a repository is safe.

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\(^1\) Note that the perception and interpretation of terminology such as ‘confirmation’, when used in the context of describing monitoring objectives, was the subject of repeated discussion during the International Conference and Workshop on Repository Monitoring, as reflected in Sections 2.4 and 3.2.

\(^2\) In Germany, the implementer is required to provide a comprehensive monitoring concept. However, German regulations state that the authorities are free to decide who will be responsible for conducting monitoring. This means that monitoring could be performed by an independent institution, rather than the implementer. This point has relevance for discussion of the independence of repository monitoring captured within Sections 2.4, 3.2 and 4.4.
The way in which post-closure monitoring is implemented will be strongly dependent on why it is being carried out. It is therefore crucial to understand the drivers for post-closure monitoring, in order to evaluate the potential benefits it offers, and to plan an appropriate programme of monitoring activities.

It was noted during the conference discussions that the public has a relatively high degree of confidence in the implementers in Finland and Sweden – countries that do not expect to carry out post-closure monitoring. A participant suggested that there may be a connection between these two points, based on the observation that post-closure monitoring is often driven by lay stakeholders not trusting an implementing body, and wanting reassurance that a repository continues to perform safely.

Balancing Technical Feasibility against Timescales for Post-emplacement / Post-closure Monitoring

If desired, monitoring could be employed during all phases of repository implementation, from monitoring the baseline (undisturbed) conditions of a repository site, through repository construction, operation, closure and post-closure. Applicable techniques and timescales for monitoring vary depending on the phase in question.

During the operational period, there is an opportunity to monitor the engineered barrier system following emplacement of the waste, buffer, backfill and initial plugs and seals. There are several challenges associated with monitoring repository evolution after waste emplacement, and, in particular, with extending such monitoring into the post-closure period. Barrier functions will typically be provided over many hundreds or thousands of years (or longer), and many processes in a repository are expected to occur very slowly. In many cases, it will not be feasible to monitor such processes over relevant timescales using either currently available technology, or even taking account of anticipated future advances. It is therefore important to define realistic objectives for post-emplacement and/or post-closure monitoring, and to link these objectives to sensible monitoring timescales.

In addition to timescale issues, there are specific technical issues associated with monitoring following emplacement. For sensors emplaced in the engineered barrier system, these include the capabilities for wireless data transfer and in situ power supplies, and the possible impact of the sensors on the performance of the barriers. For non-intrusive monitoring, technical issues are associated with the resolution of monitoring data, translating measured parameters to information on repository evolution, and recovery and backfilling of measurement equipment (e.g. geophones placed in boreholes). It is important to communicate the technical limitations of monitoring to stakeholders, and to avoid “promising too much”, which could undermine confidence in future. One possible objective for post-closure monitoring could be to carry out post-closure monitoring to support a potential decision to remove institutional controls from a closed repository. This would then focus such monitoring on surface activities such as human actions rather than on detailed monitoring of the engineered barrier system.

Successful implementation of a pre-defined post-emplacement monitoring programme over a realistic timescale could be used to demonstrate, to a variety of stakeholders, an implementer’s capability to emplace the engineered barrier system as specified in the design. This could help to build trust in the implementer’s subsequent activities and in the long-term safety of the disposal system.

Once realistic timescales for monitoring have been identified, these can be used as the basis for targeting future RTD on monitoring technologies to meet specific needs.
Future generations will be responsible for taking decisions on whether to continue to monitor a repository after closure. However, it was recognised that there is a need to plan ahead so that post-closure monitoring could be undertaken, if it appears that this may be a requirement in the future.

Dealing with Unexpected Results and Building Stakeholder Confidence

There is a clear requirement to demonstrate that a repository will be safe before implementation, which is achieved through development of the safety case. Once construction and operation have begun, integrating the results of an ongoing monitoring programme into the long-term safety case could increase confidence in it.

However, results from a monitoring programme may not be consistent with the assumptions or arguments within a safety case. These would be classified as unexpected results. A monitoring programme should specify trigger values, based on the characteristics of a particular disposal system, which, when exceeded, call for an action in response to the monitoring results. Different scales of response can be implemented, depending on the extent of implications for safety. The significance of unexpected results to the safety case could be considered by re-running performance assessment calculations and by carrying out a range of sensitivity studies. Other possible responses to unexpected results include engineering intervention and retrieval of waste.

The potential for obtaining unexpected results with implications for performance of the disposal system (particularly to the point where retrieval of waste packages might be considered to be necessary) will be mitigated through implementation of a comprehensive safety strategy in development of the safety case and through the design and planning of repository implementation. Nevertheless, putting plans in place to respond to unexpected monitoring results is considered to be important in giving stakeholders confidence that appropriate contingency measures exist if a repository does not perform as expected.

Development of European Standard on Geotechnical Monitoring

The European Standards Organisation is in the process of drafting a standard for geotechnical monitoring. The monitoring requirements associated with this new standard, once published, should be considered within all national disposal programmes.

3.2 Theme 2: Monitoring – The Wider Perspective: Regulatory and Stakeholder Viewpoints

The following oral presentations were delivered under this theme during Sessions S3 and S5 of the International Conference and Workshop on Repository Monitoring:

- S3O1: Anne Bergmans (University of Antwerp, Belgium) presented different views on monitoring and governance of repository development and staged closure based on engagement with expert and lay stakeholders.

- S3O2: Herman Sannen, (STORA, Belgium) presented a stakeholder viewpoint of monitoring for geological disposal.

- S3O3: Punam Thakur (Carlsbad Environmental Monitoring and Research Center, USA) described the environmental monitoring programme of the Waste Isolation Pilot Plant (WIPP) in the US, including presentation of recent results.
• S3O4: Morgan Meyer (CNRS, France) presented a theoretical and sociological analysis of monitoring and demonstration.

• S3O5: Claudio Pescatore (NEA) discussed preliminary findings from the Records, Knowledge and Memory Across Generations (RK&M) Project, currently being undertaken under the auspices of the NEA. The project is considering the role of “oversight” and the role of monitoring in the development of geological repositories.

• S5O1: Kai Moeller (IAEA) presented the status, structure and content of the IAEA draft safety guide on monitoring and surveillance of disposal facilities.

• S5O2: Jussi Heinonen (STUK, Finland) described the regulatory view on monitoring of spent fuel geological disposal in Finland.

• S5O3: Ann-Kathrin Leuz (ENSI, Switzerland) set out monitoring requirements in the context of the Swiss regulatory framework.

The points below record the key areas of discussion following the presentations under this theme.

Lay Stakeholder Perspectives on Monitoring Objectives
Lay stakeholders are typically of the view that the details of how a repository monitoring programme should be undertaken should be specified by the responsible implementing organisation, with input from the relevant regulators and government.

At the conference, it was suggested that where stakeholders do suggest specific monitoring activities, there is typically a greater degree of interest in environmental monitoring (as discussed under Theme 1), with the objective of ensuring that there are no detrimental impacts of a repository on the area stakeholders are living in, than on monitoring parameters more directly linked to performance of the disposal system, such as package corrosion and seal integrity. This is reflected in the creation of organisations such as the Carlsbad Environmental Monitoring and Research Center (CEMRC), which was set up primarily to undertake environmental monitoring of the WIPP site and the surrounding area.

For monitoring that is associated with an objective to confirm barrier performance, it was noted that from a lay stakeholder perspective, it is considered difficult to demonstrate the safety of a repository purely using laboratory experiments. This implies that some form of monitoring of the underground environment is called for by some lay stakeholders (e.g. monitoring of disposed waste packages and/or the surrounding engineered barriers or monitoring within a pilot facility).

A related point is the perception by some lay stakeholders that the typical implementer focus on confirmation, rather than on checking, of expected behaviour comes across as arrogant. The implementers’ perspective arises because of the requirement to develop a robust safety case before any disposal activities take place. However, the basis for this perspective needs to be successfully communicated, to avoid a perception of over-confidence and dismissal by implementers of the important role that monitoring can play in checking successful implementation of geological disposal.

Use of Monitoring to Build Public Confidence
For confidence building, there needs to be a clear demonstration that the choice of parameters to monitor is developed, at least in part, through dialogue, engagement and participation with
stakeholders. Some monitoring may be undertaken largely (or even purely) to address stakeholder concerns. An example proposed at the conference was monitoring of seismic activity in the area around a proposed repository, even when expert analysis suggests that this will not be a significant factor affecting repository performance.

A key requirement for building local stakeholder confidence appears to be the continual collection of data on the properties of the repository system, so that any changes in behaviour can be identified. This includes a significant period collecting information on the properties of the system before any waste is emplaced. This desire is already recognised within international guidance on repository monitoring as the requirement for the collection of monitoring data on baseline conditions at proposed repository sites [1,2]. Baseline environmental monitoring was undertaken by the CEMRC in the vicinity of the WIPP, including air quality sampling before the facility began to receive waste, and is also being undertaken at proposed repository sites by other national waste management organisations, for example in Sweden and in Finland.

An associated point is a preference expressed by some stakeholders that all monitoring data should be made publicly available, to avoid any perception that only selected results are being communicated to the public. Whilst such an approach increases the openness and transparency of a monitoring programme, it is recognised that raw data may not always provide meaningful information to local communities. To address this point, the CEMRC publishes the results of specific monitoring activities in newsletters and in local newspapers, and includes guidance on the interpretation of data and its perceived significance within these publications. This is done in conjunction with making all monitoring data available on the internet, once it has be checked internally for quality assurance purposes.

At the conference, participants noted that stakeholders expect implementers to develop expectations for what will be observed through monitoring, and how monitoring results may change over time. Bearing in mind the duration of a repository implementation programme (likely to be in excess of a hundred years), as well as the long timescales over which some processes in the repository will occur, there is an expectation that implementers will periodically re-evaluate their understanding of system performance as the implementation programme progresses, taking account of new data as they become available, and considering any associated changes in requirements for monitoring. Developments in the implementer’s understanding also need to be discussed with stakeholders in a transparent and accessible way.

The level of public interest in repository activities in general, and monitoring in particular, is expected to be relatively low in situations where a significant level of stakeholder confidence in disposal system performance has been established, i.e. if no releases to the accessible environment have been measured from the onset of monitoring. During such periods, the very existence of an on-going monitoring programme can contribute to public confidence. Interest in, and scrutiny of, monitoring programmes may increase if concerns arise over system performance. This might result from factors that are specific to the repository in question, such as small increases in the measured radioactivity in the environment. However, it might also arise as a result of external factors, for example if there were any increased concerns over nuclear safety on a global basis in the future. An increased interest in the CEMRC’s monitoring activities was observed following the Fukushima Daiichi disaster.

Lay stakeholders often express a preference for repository monitoring to be carried out by an independent organisation not associated with the implementer, regulators or government. This is particularly the case in countries where, due to the national context of the repository development
programme, there is limited confidence in the actions of the implementing organisation, and/or limited confidence in the ability of the nuclear regulators to provide independent scrutiny of a repository development programme on behalf of the public. As an example, it was noted that environmental monitoring around the WIPP facility is carried out by both the CEMRC and the Department of Energy (DOE). However, there is generally a greater degree of public trust in the results of monitoring carried out by the CEMRC, due to the perceived independence of this organisation. Some participants commented that in cases where the funding for independent monitoring organisations originates from the implementing organisation (as is the case for the CEMRC), this could undermine confidence in the independence of the monitoring organisation. This point was discussed further in Workshop 2, Track 1 (see Section 4.4).

Role of Informed Lay Stakeholders and Approach to Stakeholder Engagement
Public stakeholder groups, particularly in the vicinity of an existing nuclear site, often include individuals with expert knowledge in highly relevant fields. Examples noted at the conference included structural engineers with expertise on the performance of concrete in civil construction, and former/current site workers with knowledge of nuclear safety and plant operation. Such groups are also likely to include individuals without relevant expertise and with only limited understanding of key issues for radioactive waste management and disposal. Depending on the extent of previous engagement and outreach activities, and the involvement of individuals within a group in such activities, there is also likely to be a varying degree of understanding of key issues such as:

- An appreciation of the technical limitations of monitoring.
- The requirement that monitoring does not adversely affect the passive safety provided by the repository.
- Recognition that it may be difficult to monitor safety relevant parameters directly, or over meaningful timescales.

This raises the question of what constitutes a “lay” and an “expert” stakeholder, and indicates that the distinction between the two types of stakeholder may not be straightforward. It also has important implications for approaches used to engage with public stakeholders in the development and implementation of monitoring programmes.

Lay stakeholders with specialist expertise may play an important role during engagement activities with an implementing organisation, acting on behalf of a wider public group. For example, they may be comfortable challenging detailed aspects of information presented by implementers. They may also be able to assist in explaining the significance of technical information and technically complex ideas (e.g. probabilistic safety assessment) to less informed members of a public group, although conversely, they may deliberately choose not to do so, if they regard this to be an important responsibility of the implementers themselves.

Sociological analysis of monitoring and demonstration has identified key considerations to be taken into account when planning and conducting the involvement of lay stakeholders in the development and implementation of monitoring programmes. In particular, there is a need for implementers to appreciate that the public are already involved in monitoring, through taking an interest in, and commenting on, repository programmes, and that lay stakeholder perspectives need to be considered, and where feasible, integrated into development of a monitoring programme, even if the implementing organisation does not agree with these perspectives. It was suggested that the philosophy of an implementing organisation in engaging with local stakeholders will have profound
implications for the success of a repository development programme, particularly where local communities have a role in decision-making associated with repository siting. In order to be successful, the implementing organisation needs to wish to engage, and to hope to gain something through doing so. There is an associated need to appreciate that engagement activities are not just about communicating technical information; the act of stakeholder engagement and involvement is one of reassurance, particularly where this is done in a continuous, repeated or ongoing manner.

Monitoring versus “Oversight”
The concept of oversight of a repository was discussed. Oversight is a general term for “watchful care” and refers to society “keeping an eye” on a technical system and the actual implementation of associated plans and decisions. In the context of radioactive waste disposal, oversight and safety assurance are considered in terms of the active institutional control of a repository, including factors such as a dedicated monitoring programme, knowledge management and long-term records management, as well as passive control of the facility, for example through built-in design features and safety functions provided by components of the disposal system. Passive controls could also include indirect monitoring of factors affected by repository performance. A gradual transition from active controls requiring human intervention, to passive controls that do not require intervention is expected to occur as a repository implementation programme progresses. Requirements for active controls, such as long-term records management may be strongly linked to the timescales for monitoring, particularly post-closure monitoring.

The International Commission on Radiological Protection (ICRP) is currently developing guidance on the concept of oversight and associated recommendations for international and national policy and guidance. A draft of this guidance has been released for consultation, and has been reviewed by the NEA and various radioactive waste management organisations [4]. The guidance is expected to be published shortly.

Oversight can also be used as a term to indicate that something has been overlooked and missed. Careful communication of the context for using this term is therefore important.

Monitoring Hazardous Waste Disposal
Transferable experience may be available from approaches to monitor the disposal of stable hazardous (non-radioactive) wastes such as wastes contaminated with heavy metals, although the regulatory basis for disposal of such wastes is quite different from that for radioactive waste disposal. Radioactive waste management organisations have been involved in reviewing the outputs from EC projects considering this topic, and there may also be valuable experience to feed back into development of monitoring programmes for geological disposal of radioactive waste.

Regulators’ Perspectives on Monitoring
Regulatory requirements relating to monitoring tend to focus on demonstration of the assumptions and arguments in the safety case provided as a basis for licensing, and typically place a lower emphasis on aspects of trust and confidence in the implementer than perspectives expressed by lay stakeholders.

Where monitoring is used in order to demonstrate repository performance, there is a requirement that this monitoring is representative of behaviour in the repository itself, especially if monitoring is undertaken on a limited part of the repository or in a separate area such as a pilot facility. At the same time, a key principle within regulations for geological disposal is the requirement that monitoring must not undermine the safety provided by the multi-barrier system of the geological disposal system. For example, UK guidance on requirements for authorisation of geological
disposal state that monitoring should not compromise the environmental safety case for a disposal facility, for example, by providing routes through which significant amounts of radioactivity might reach people [5]. Similarly, Swiss regulations require monitoring to be carried out in a pilot facility where conditions are representative of those in the repository itself, but which is spatially and hydraulically isolated from the repository, such that activities in the pilot facility do not adversely impact on the conditions in the repository.

Regulatory requirements on monitoring timescales differ from country to country. However, the challenge of monitoring slow processes occurring over long timescales in a repository is widely acknowledged. One possible approach to mitigate against this is to concentrate on monitoring processes during a transient phase of evolution, early on in the lifetime of a repository, for example, during the resaturation of disposal areas following their closure. Some regulators consider that there may be benefits, for ease of management, in amalgamating site characterisation, site investigation, monitoring and surveillance of a repository into one overarching programme. However, it is also recognised that these activities vary in their objectives and scope, and that it might therefore be more appropriate to consider them separately.

In some national programmes, regulators are significantly involved in working with implementing organisations to design and develop an appropriate repository monitoring programme. However, even in such cases, there is a distinction in responsibilities: the implementer will have responsibility for conducting monitoring and using it to demonstrate safety, whereas the regulator will be responsible for evaluating whether the monitoring system fulfils its objectives and is being implemented appropriately.

Clear use of terminology is important in the regulation of repository monitoring. The International Standards Organisation (ISO) and European Standards Organisation recommend a strict four-level hierarchy of terminology, as follows (in decreasing strength of emphasis):

- A requirement, which indicates that something shall be done.
- Guidance, which indicates that something should be done.
- Permission, which indicates that something may be done.
- A possibility, which indicates that something can be done.

This terminology is applied in the hierarchy of safety standard documentation that has been produced by the IAEA.

### 3.3 Theme 3: Monitoring Technologies: Feasibility and Limitations

The following oral presentations were delivered under this theme during Sessions S6D (focusing on monitoring barrier and repository component demonstrators) and S6T (focusing on monitoring technologies) of the International Conference and Workshop on Repository Monitoring:

- S6O1: José-Luis García-Siñeriz (Aitemin, Spain) summarised the review of the current state-of-the-art in monitoring technologies that was carried out under the MoDeRn Project, focusing on experience drawn from long-duration experiments and demonstrators carried out in European URLs.
• S6DO1: Stephane Buschaert (Andra, France) described the design and development of a large-scale in situ monitoring test section in the Meuse/Haute-Marne URL.

• S6DO2: Tobias Vogt (Nagra, Switzerland) described experiences monitoring thermo-hydro-mechanical effects in a full-scale emplacement experiment at the Mont Terri URL.

• S6DO3: Joachim Stahlmann (Technische Universität Braunschweig, Germany) discussed experiences from monitoring a test set-up for a sealing dam installed at the Morsleben repository in Germany.

• S6TO1: Hansruedi Maurer (ETH Zurich, Switzerland) described recent experiments and advances in techniques to monitor components of geological repositories using non-intrusive seismic methods.

• S6TO2: Thomas J. Schröder (NRG, The Netherlands) described investigations of wireless data transmission from the HADES URL to the surface that were carried out under the MoDeRn Project.

• S6TO3: Ignacio Bárcena (Aitemin, Spain) described a new wireless data transmission system based on high-frequency radio communication that has been developed under the MoDeRn Project.

• S6TO4: Friedemann Grafe (IBeWa-Ingenieurpartnerschaft, Germany) discussed experiences of wireless data transfer through salt host rock.

• S6TO7: Lou Areias (ESV EURIDICE, Belgium) set out plans to incorporate a new corrosion sensor within upcoming reduced-scale tests of the Belgian supercontainer.

• S6TO6: Norman Wagner (Institute of Material Research and Testing, Germany) discussed the technology, feasibility and limitations of using spatial time domain reflectometry for moisture monitoring in geological repositories.

The following poster presentations were delivered during Session S4 of the International Conference and Workshop on Repository Monitoring:

• S4P8: David Jaeggi (Swisstopo, Switzerland) described testing of a fibre optic system for long-term monitoring applications under in situ conditions in the Opalinus Clay of the Mont Terri URL.

• S4P9: Fidel Grandia (Amphos 21, Spain) discussed monitoring of radon gas emission distribution as a technique used to characterise gaseous releases from CO₂ storage sites, a technique that could be transferable to monitoring of a repository for radioactive waste.

• S4P10: Thomas Spillman (Nagra, Switzerland) presented the approach to, and results from, geophysical monitoring of a gas permeable seal experiment undertaken at the Grimsel Test Site in Switzerland.

• S4P11: Oliver Czaikowski (GRS, Germany) discussed and compared different methods for monitoring pore water pressure and pressure variations.
• S4P12: Kei Suzuki (RWMC, Japan) described the development of a wireless data transmission system employing low-frequency electromagnetic radiation, and utilising miniaturised wireless transmitters and borehole type receivers.

• S4P15: Lou Areias (ESV EURIDICE, Belgium) discussed the application of Digital Image Correlation to detect the potential onset of micro-cracking in the concrete buffer of the supercontainer.

• S4P18: Reza Goudarzi (Clay Technology, Sweden) summarised measurements carried out as part of the prototype repository test at the Äspö Hard Rock Laboratory in Sweden.

• S4P19: Nicolas Linze (Université de Mons, Belgium) presented work to develop optical fibre vibration sensors based on light polarisation properties.

• S4P20: Alexey Faustov (SCK.CEN, Belgium) described the results of a distributed temperature measurement experiment employing fibre optic sensors, performed in a low-dose radiation environment of the sub-pile room under the material testing reactor BR2 vessel in Belgium.

The points below record the key areas of discussion following oral presentations under this theme.

General Points of Clarification from Technical Presentations

Regarding in situ monitoring sensors (discussed in Paper S6O1), it was noted that modern sensors typically employ improved mechanisms and materials that are expected to prolong the sensor lifetime under repository conditions compared to older designs. Older sensors used in experiments in URLs have already performed well for periods of over 15 years. Modern sensors would be expected to last for longer periods, although this remains to be demonstrated through long-running experiments.

The state-of-the-art concerning non-intrusive seismic tomography as a monitoring technique (discussed in Paper S6TO1) currently focuses on examining the elastic properties of pressure waves, and does not include consideration of shear waves. Analysis of shear waves could be considered in future developments of this technique, potentially as part of using seismic tomography to examine the anisotropic properties of a disposal system.

Regarding wireless through-the-Earth (TTE) data transmission from a repository to the surface (discussed in Paper S6TO2), it was noted that excavated spaces within the repository could be employed to maximise the size of the antenna used for data transmission. However the geometry of such excavations would affect the efficiency of signal transmission; use of a rectangular antenna rather than a circular antenna of comparable size would potentially reduce efficiency by up to ~20%. Key influences on the feasibility of wireless TTE data transmission include the electrical conductivity of the overlying rock and levels of noise/interference at the surface in the vicinity of a repository (e.g. from power lines, cars and local weather).

Corrosion sensors developed in Belgium (discussed in Paper S6TO7) for application in monitoring corrosion of the supercontainer overpack will be used during supercontainer half-scale demonstrator tests, with the objective of confirming that the supercontainer design will fulfil performance requirements. It is not currently planned to install corrosion sensors in situ within supercontainers emplaced within a Belgian geological repository. The corrosion rate of the carbon steel overpack
within the supercontainer is expected to be very slow, and corrosion products are not expected to significantly affect the integrity of the supercontainer buffer. The long-term integrity of the overpack is intended to ensure that there are no radionuclide releases from the supercontainer into the surrounding near field during the thermal phase of the contained waste.

Approaches to calibrate measurements from spatial time domain reflectometry for moisture monitoring (see Paper S6TO6) were discussed. It would be desirable to calibrate this technique in order to convert readings obtained into physically meaningful quantities such as the water content of the disposal system component being monitored. However, it is currently only possible to calibrate this technique indirectly, for example in a laboratory, by examining the frequency dependent properties of different components of the disposal system as a function of conditions such as water content and temperature. The combination of various components exhibiting different electromagnetic properties in the disposal system itself, such as the host rock, porewater and overlying soil makes it difficult to convert readings from spatial time domain reflectometry into absolute physical quantities. This technique is therefore considered to be primarily useful to monitor for changes in the behaviour of a disposal system, such as progressive saturation of a repository near field, rather than to determine absolute values of, for example, pore water pressure.

**Implications of Technical Presentations for Building Public Confidence**

It was observed that aspects of the oral presentations given under Theme 3 and subsequent discussions were found to be complex by some of the audience at the conference. It was also observed that the manner in which messages from some of the presentations were presented, could have a negative effect on public confidence, if similar messages were presented during specific engagement events. Such aspects included:

- The presentation of technically detailed materials, which would be impenetrable to a lay audience. Use of such information to explain the objectives and outcomes from monitoring programmes is expected to be of limited value to building lay stakeholder confidence, and may even reduce confidence in the work of an implementing organisation. Lay stakeholders may find it difficult to understand the key implications of an overly detailed presentation, and, in situations where there is not a high level of trust in the implementer, may consider that important points are being either inadvertently or deliberately masked in technical details. Experts therefore need to be able to clearly explain what they are doing and why, and to target their discussions to a particular audience.

- The presentation of uncertainty inherent in the development of approaches and techniques for monitoring. From a scientist’s perspective, initial uncertainties are a natural step in planning research, since they provide the basis for developing hypotheses to be tested. However, perceptions of uncertainty can vary, and therefore such uncertainties need to be carefully communicated (and put into context), particularly as a disposal programme develops in maturity and moves closer to implementation.

- Questioning and criticism of experts’ work by each other. As with the last point, review and challenge of new research outcomes are considered to be key aspects of a rigorous scientific approach. However, such activities might undermine lay stakeholder trust in technical work, if it leads to an enduring perception that such work is often flawed.

The International Conference and Workshop on Repository Monitoring brought together a large and diverse audience, and presentations in the technical sessions were mainly aimed at a technical audience, rather than at a wider group of stakeholders, some with a less technical background.
Therefore, it is not surprising that some issues of this nature were recognised at the conference. The comments and queries raised may also reflect the relatively novel nature of many of the techniques and approaches presented at the International Conference and Workshop on Repository Monitoring, which are at the forefront of technological developments relating to repository monitoring and reflect the current state-of-the-art, as well as participants’ initially low level of familiarity with these novel developments.

Discussion of the feasibility and limitations of monitoring technologies is considered an integral component of advancing understanding of repository monitoring techniques through dissemination of work and is therefore central to the scope of the conference. Nevertheless, these observations provide useful insight to the perception of technically detailed material by a lay audience, and, given the importance of monitoring as a tool to build confidence, they would need to be considered as part of any plans to discuss similar material at a meeting or event targeted specifically at a lay audience.

Discussion during this technical theme highlighted that there tends to be a greater degree of confidence, amongst both lay and expert stakeholders, in the performance of purpose-built repositories for radioactive waste, compared to confidence in the performance of pre-existing facilities, such as mines, that have been modified for use as repositories. This is largely because the facilities have not been specifically designed for use as repositories, and the need to modify the facility designs to allow for safe waste disposal introduces an element of doubt in the mind of stakeholders.
4. Record of Workshop Discussions

This section provides a factual record of comments and opinions expressed during each of the six workshops held on 20-21 March. For each workshop, the discussion records:

- Key points from group discussion, based on notes taken during this discussion and feedback to plenary provided by the workshop chair.
- Points raised in the associated plenary discussion.

Each of the workshops involved a different group of participants. As such, there are some examples where differing opinions were provided in different workshops.

4.1 Workshop 1, Track 1: How to monitor?

Elizabeth Harvey (Galson Sciences Ltd), Jose-Luis Fuentes-Cantillana (Aitemin)

Discussion focused on the technical feasibility and limitations of monitoring technologies, based on the current state-of-the-art in each of the following areas:

- Wireless data transmission, including short-range and long-range transmission using radio frequency electromagnetic radiation, as well as alternative transmission systems not based on the use of radio waves.
- Options for long-term power supply to underground monitoring equipment.
- Durability of monitoring components, including susceptibility of in situ monitoring equipment to failure under the environmental conditions expected within the repository.
- Geophysical methods for monitoring, including consideration of monitoring equipment installed within the near field of a repository, as well as in the far field, e.g. in boreholes, at the surface, or from the air.

Wireless data transmission

The application of wireless techniques for data transmission within a repository could facilitate direct monitoring of the engineered barrier system whilst removing the need for cables or wires to pass through engineered and natural barriers. Cables and wires could provide a pathway for radionuclide migration and impact the long-term environmental safety case.

Short-range data transmission (e.g. across a plug or seal) could utilise high-frequency radio waves, whereas long-range data transmission (e.g. TTE) would typically need to utilise lower frequency radio waves. Both long-range and short-range data transmission systems need to be configured according to the repository design and layout.

The distance of rock through which data can be transmitted using high-frequency radio waves is of the order of a few metres. It could be possible to transmit data using high-frequency radio waves over greater distances by using intermediate relays. However, to ensure regulatory compliance, it would be important not to undermine the isolation function provided by the rock overlying a repository. One possibility might be to emplace intermediate wireless receivers/transmitters within a repository shaft or drift during the sealing and closure process.
Feasible distances for long-range TTE data transmission using radio waves depend on the electrical conductivity of the transmission medium, i.e. the host rock and overlying strata, including the nature of the pore water within the rock. In general, long-range data transmission using electromagnetic radiation is considered to have better prospects for successful application in hard, dry rocks, due to the tendency for signal attenuation in soft rocks with higher pore water content, although work within the MoDeRn Project has demonstrated the feasibility of low-frequency data transmission across 225 m of poorly indurated clay and overlying sandy aquifers.

There was more limited experience within the workshop of other wireless data transmission techniques besides those using radio waves, such as those using vibration (sound) waves. In general such techniques were expected to have higher power demands than available radio frequency systems. They were also not considered to be feasible in some geological environments, such as poorly-indurated clays.

Research into high-frequency and low-frequency wireless data transmission has focused on different phases of repository implementation. High-frequency techniques could be used following closure of individual disposal tunnels or disposal boreholes, by installing receiver equipment in the adjacent access tunnel. They are therefore primarily applicable during the post-emplacement period, but prior to complete repository closure. In contrast, low-frequency wireless data transmission would primarily be of benefit during the post-closure period, once there is no direct access to any part of the repository.

The expectation that wireless data transmission would typically not be required until fairly late-on in a repository implementation programme, potentially decades, or even centuries into the future (particularly for long-range techniques), led some workshop participants to question the need for extensive research on these techniques at this time. They argued that it would be preferable to postpone further work in this area until a point in time closer to when such techniques were actually applied, by which time, the state-of-the-art of relevant technologies may have advanced significantly. On the other hand, if an implementing organisation wishes to employ in situ monitoring during the post-emplacement and/or post-closure period as part of a wider monitoring programme, then it would have to demonstrate, at a relatively early stage in the licensing process, that it would be feasible to carry out the required monitoring, and design of the associated data transmission systems would need to be incorporated into the overall repository design. Further research in this area was therefore considered to be beneficial to confirm the feasibility of such approaches, as well as to ensure continued advancement of the state-of-the-art. Target areas for improvement include feasible distances for data transmission, improved transmission across difficult media, and improved approaches to manage signal interference and noise levels.

Current state-of-the-art wireless monitoring techniques are considered to be largely sufficient for application in a repository pilot facility, where data transmission over 5-10 m is likely to be required. However, there was uncertainty in the workshop over whether it would actually be necessary to employ wireless techniques within a pilot facility, or whether more conventional techniques employing wires/cables would be acceptable here.

Long-term non-intrusive power supply
A factor limiting the lifetime of in situ monitoring equipment (e.g. sensors and data transmission components) and hence, the feasible timescales for post-emplacement and post-closure monitoring, is the availability of a reliable long-term power supply.
Electrical batteries are widely available in a variety of forms. There is relatively limited experience on their long-term behaviour, and the maximum lifetime of existing batteries is currently expected to be a few decades. It was the view of workshop participants that advances in battery technologies between now and when they would be required to power remote wireless monitoring equipment in a repository (decades or centuries in the future) are expected to improve the battery lifetimes in the future. It was also recognised by the workshop that other, currently unforeseen power sources, suitable for long-term remote applications, may emerge during this period.

Generation of electrical power based on thermal gradients within the repository was considered by workshop participants to be a promising technology worth investigating further. The radioactive waste inventory to be disposed of within a repository offers an extensive source of potentially suitable radioactive decay, particularly in terms of high heat-generating inventory components such as spent fuel or HLW, and specific radionuclides such as strontium-90, which have already been used in thermoelectric generation for other applications such as satellites, space probes and unmanned remote facilities, and which are abundant in some radioactive waste streams. The thermal gradient accessible for energy harvesting is an important factor affecting the feasibility and efficiency of thermoelectric generation.

Realising thermoelectric generation from the waste in a repository could require adaptations to the design and layout of the repository, for example, changes in the waste packaging approach and/or changes in the distribution of different waste streams across a disposal area. Further research is required to improve understanding of how to apply this technique within a repository environment. Any required design adaptations would still need to comply with regulations applicable to radioactive waste disposal, and should not undermine the safety case for geological disposal.

Miniaturised nuclear reactors installed within a repository were also proposed by workshop participants as another option for a long-term power supply to monitoring equipment. This technology has been proposed as a small-scale generation route that could be applicable to supply power to e.g. individual towns and space stations. The implications of installing such devices on the safety case for a repository would need to be evaluated, but it was felt by some participants that this option would merit further investigation.

**Durability of monitoring components**

Sensor lifetime was a key area of discussion during the workshop. Experience of long-term sensor performance is available from the last 30 to 40 years during which sensors have been extensively developed and employed in a variety of industries. However, the timescales over which monitoring sensors in a repository are required to perform could potentially be longer than this. Moreover, the conditions in a repository for radioactive waste will be relatively aggressive (this could include, for example, high temperatures, an alkaline chemical environment and a high radiation field), which could reduce the lifetime of sensors compared to that observed in other applications. There is limited experience of the behaviour of relevant sensors under such harsh conditions, and this was identified as a key area requiring further investigation. It was also felt that tests which deliberately accelerate the degradation of wireless monitoring equipment could be used to identify weak points in designs, for improvement in the future.

There is limited experience of long-term electronic component performance in relevant environments. Electrical systems employed on the Voyager space probes have continued to function for over 30 years, despite the extremes of temperature and relatively high radiation environment they are exposed to. However, some degradation of thermocouples and other electrical components has occurred over this period, which has reduced the efficiency of the power
supply to the probe below anticipated levels based purely on radioactive decay of the power source. This is recognised as an area of rapidly-advancing technology; the durability of new sensor types will therefore need to be tested as they emerge.

Glass fibre optic sensors have a relatively high chemical durability, although the polymer coatings surrounding some fibres are typically much less durable. The glass fibres themselves are susceptible to signal attenuation arising from irradiation, as well as hydrogen diffusion into the fibres, although some workshop participants observed that hydrogen diffusion could actually improve the resistance of glass fibres to further radiation damage.

Fibre optic sensors are a relatively recently-developed sensor technology, and experience of their application is therefore limited. Nevertheless, some relevant experience of the long-term performance of fibre optic sensors is available from their application in other industries, for example monitoring dam integrity in the vicinity of man-made reservoirs, although the transferability of this specific experience may be limited, given the different environmental conditions compared to those present in a repository.

Improved collaboration between research groups working on related projects could benefit further development of fibre optic monitoring systems. An example proposed in the workshop discussions was continued collaboration between the Belgian and French research groups that have been developing fibre optic monitoring sensors and monitoring systems during the MoDeRn Project.

Considerable transferable experience of the performance of relevant sensors and other monitoring equipment is thought to be available within the oil and gas industries, particularly in terms of employing monitoring systems in aggressive (i.e. corrosive and hot) underground systems.

Geophysical methods for monitoring
A variety of geophysical techniques are available to address a range of monitoring requirements. These can be employed with different levels of proximity to the repository itself, for example:

- Equipment installed in the repository itself, or in the surrounding near field.
- Techniques in the far field, for example in boreholes drilled from underground excavations, or based at the surface.
- Airborne techniques.

The resolution of data from geophysical monitoring equipment installed in a repository near field, for example, the results from cross-hole seismic tomography monitoring, depends on the frequency of the seismic source used, the distance between the monitoring boreholes, and the velocity structure of the near-field rock and engineered barriers being monitored. In general, increasing the resolution requires the monitoring boreholes (for sensor and receiver equipment) to be placed closer to the near-field rock and engineered barriers being monitored. This has obvious implications in terms of whether such monitoring techniques can be regarded as being truly non-intrusive, which is key to their potential application. Near-field geophysical monitoring techniques are therefore considered to be primarily useful for monitoring relatively large changes in repository characteristics, such as widespread saturation characteristics, rather than highly localised processes, such as the saturation of a small component of the engineered barrier system.
There are also similar inherent physical limits associated with the spatial resolution of monitoring results obtained from geophysical equipment installed on the surface overlying a repository. Workshop participants considered that it would be possible to monitoring large-scale processes, such as preferential flow paths, but that more localised processes would be difficult to observe using current state-of-the-art techniques. Some improvements in resolution could be achieved using sensors or sources installed in monitoring boreholes, provided this did not affect the isolation function of the rock.

Airborne and satellite-based geophysical techniques such as synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR) facilitate precise detection of ground movements at the Earth’s surface. This has potential applications for safeguards monitoring (e.g. to detect unauthorised activities), as well as for monitoring large-scale processes such as thermal uplift. Such techniques have been employed to measure uplift associated with underground carbon dioxide sequestration tests.

As discussed previously, the feasibility of applying geophysical monitoring techniques tends to be strongly dependent on the characteristics of the host rock and overlying strata, with the exception of airborne techniques that monitor changes at the surface.

4.2 Workshop 1, Track 2: Why monitor?

Matthew White (Galson Sciences Ltd), Nicolas Solente (Aitemin)

International guidance on repository monitoring recognises that monitoring is undertaken to provide support to the post-closure safety case, to support operational safety, to ensure environmental protection and as part of safeguards. The workshop session on why to monitor therefore focused on the expected benefits that would be realised from repository monitoring.

Influence of Costs on Repository Monitoring
Considering why monitoring is undertaken may provide a basis for considering how much effort is required to deliver the monitoring programme, and how much money should be spent on monitoring. From the implementers’ perspective, a regulatory requirement to undertake specific monitoring programmes must be addressed and it would not be appropriate for the requirements for specific monitoring activities to be challenged. However, society including the public may question the need for expensive monitoring programmes.

Alternatively, monitoring could be considered as part of the optimisation of the repository system and may support decisions to use more cost-effective approaches to disposal of radioactive waste, or support decisions to close a facility earlier than planned, leading to cost savings. In terms of stakeholder engagement, the use of monitoring in optimising the disposal process may be a good message to communicate.

Therefore, optimisation of implementation and support for cost-effective delivery of the repository programme may be seen as reasons for undertaking repository monitoring.

Monitoring, Knowledge Management and Post-closure Monitoring
One of the objectives of a monitoring programme could be to provide an information source to future generations. It is expected that information collected at an early stage in the programme will be of use to future generations. This will require the strategies for monitoring and knowledge management to be integrated and to work together. In order to provide meaningful data to future
generations it will be necessary to record the decisions made in developing the monitoring programme.

These decisions may be different when different phases of the monitoring programme and the influence of the national context are considered.

The role of various involved parties, or “actors” (see Section 4.5 for further discussion of this term) can differ between different national programmes. This includes different responsibilities being assigned to implementers, regulators, and contractors working for both the implementers and the regulators. The social organisation of a country will also influence responsibilities, for example the division of roles between the state and industry.

It was proposed that the driver for undertaking post-closure would be to address any health concerns held by members of the public, and that this could be addressed by monitoring of the groundwater. The context for monitoring groundwater quality has to be considered, and some participants felt that groundwater standards could change in the future. The participants felt that, for some programmes, it would not be feasible however to monitor for the failure scenarios considered in the safety case. For example, failure scenarios considered in safety assessments undertaken by SKB consider processes and events that could occur in association with the next ice age, which is expected to occur in 20,000 years from now.

Baseline and Pre-closure Monitoring
Participants at the workshop recognised that commencing monitoring early was important. This would provide a baseline for understanding the significance of any data collected following emplacement of waste. The importance of monitoring prior to closure was stressed by one participant who felt that there would be no significant processes or events to monitor following closure.

Reasons why monitoring could be undertaken prior to closure mentioned by workshop participants included:

- To provide information to update the safety case – in this context, it was noted that the repository will probably be classified as an operational nuclear facility and will therefore have to provide an updated safety case every ten years. The updated safety case will need to be supported by data from monitoring.

- Demonstration of the safe operation of the repository.

- To learn as much about the disposal system as possible.

- To support decisions related to retrievability where retrievability is required in national regulations.

- To ensure the safety of workers and the public, especially to protect against health effects if there was a major accident by providing early notification of such an event.

Monitoring for Public Acceptance
One participant noted that new innovative visualisation tools were being developed to support communication to the public. Provision of data to populate such communication tools could be a reason for undertaking monitoring.
Another participant noted that, in some fields, there had recently been a shift from the concept of social acceptability to the paradigm of social responsibility. Adoption of this paradigm could imply that a reason for monitoring was the implementer decide that the public should be provided with additional data over and above that which the implementer themselves considered necessary or valuable. Alternatively, this could be interpreted as a responsibility not to undertake monitoring if it was of no value.

Workshop participants proposed that, in addition to understanding why monitoring should be undertaken, it was important for monitoring programme development to consider reasons why a proposed monitoring parameter should not be monitored, and to record these reasons as justifications in instances where such consideration led to the rejection of a monitoring parameter. In particular, it was proposed that monitoring that responded to “irrational fears” should not be undertaken, as this may only serve to provide tacit support to the fear. However, an alternative view expressed was that monitoring only the minimum necessary could appear arrogant to stakeholders.

**Importance of Defining Why Monitoring is Undertaken**

In conclusion, it was stressed that a clear definition of why monitoring was being undertaken was necessary for a successful monitoring programme to be undertaken. The reasons for monitoring should provide the basis for a robust selection of monitoring methods and locations. This would allow the data collected to be compared to the specific objectives defined and provide a context against which significance could be judged. In support of this argument, it was noted that there is a widely-held view that a large monitoring programme had been established in the local area following the Fukushima disaster but not all of this monitoring was of value to robust decision making. However, it was difficult to find a reason to stop monitoring a particular parameter once monitoring had started unless it was associated with a specific objective.

The discussion on why monitoring should be undertaken highlighted that the answer to this question may be different for different phases of repository. There appeared to be consensus about the drivers for monitoring during the early stages of repository implementation, but less consensus about the drivers later in the programme. Optimisation and cost-effectiveness were good reasons for undertaking monitoring. Monitoring could be used to support stakeholder engagement (including visualisation of the repository evolution) and stakeholders could potentially provide good advice on the development of the monitoring programme. However, as with all monitoring issues there would be different answers to the why question for different national programmes.

**4.3 Workshop 1, Track 3: When and how long to monitor?**

*Peter Simmons (UEA), Jaap Hart (NRG)*

This workshop was concerned with the timing of monitoring, with when, during the life of a repository, monitoring should be carried out and for how long it should be continued. The workshop chairman opened by noting that the questions of ‘when’ and ‘how long’ could not be decoupled from the questions ‘why’, ‘how’, ‘what’ and ‘where’ to monitor. He situated the questions in the context of a step-wise decision process by displaying a figure that summarised the phases of repository implementation and gave examples of major decision points (Fig. 4.1).
To stimulate discussion the chairman presented a series of quotations, taken from papers presented at the conference, from reports produced by international agencies and research groups, and from reports of the MoDeRn project itself, which offered a range of responses to the questions of ‘when’ and ‘how long’ to monitor. Associated questions suggested by the chairman included:

- What are the views of:
  - Regulators?
  - Experts?
  - Citizens and stakeholders?

- If demanded, how long is post-closure monitoring possible?
  - What are the implications of the technological state of the art (e.g. advances in wireless techniques in MoDeRn) for post-closure monitoring?
  - How long can monitoring programmes, or “oversight”, be expected to be sustained, either technologically or institutionally?

The discussion ranged across a number of issues raised for participants by the question of when and for how long monitoring should be carried out.

For some stakeholders the questions of when and how long linked inevitably to the uncertainties and challenges associated with the very long time scales over which waste remained hazardous and the repository would evolve.

When to begin monitoring
One point upon which there was general agreement was that monitoring should begin as early as possible in order to establish baseline data and subsequently to provide as much information as possible about wasteform and repository evolution. It was also emphasised that monitoring had a role through all of the phases of repository development and implementation. There was also, however, some related discussion about where monitoring was to be conducted, with some participants distinguishing between monitoring within and outside a facility, and noting the different time scales over which, for technical and safety reasons, monitoring might feasibly be carried out at different distances from the waste once it is emplaced.

Continued monitoring to provide societal oversight
Although there was general recognition of the role that monitoring would play during the operational phase of a repository, discussion returned several times to the rationale for continuing
monitoring in the post-closure phase. Following presentations earlier in the day, there was discussion of the notion of ‘oversight’ and of its relationship to monitoring. Some participants were concerned to define these terms clearly in order to avoid any confusion between monitoring, understood as involving measurement and data collection, and oversight, understood as the continuous and extended involvement of society beyond repository closure. The notion of oversight was justified by reference to the continuing hazard presented by the waste, despite it being contained within a repository system several hundred metres below the surface, and the potential loss of regulatory credibility that would be associated with ‘walking away’ from a licenced facility after closure.

The call by some stakeholder participants for continued surveillance of a repository reflected concerns that there might be unexpected processes or events which could compromise safety. It was pointed out that no very long term management option is risk free. In response to this it was argued that consideration of all conceivable scenarios would ensure that these were addressed by the design concept but some stakeholders nevertheless expressed a clear wish for extended monitoring to provide ‘early warning’ of any adverse developments in the repository system. Although there was no agreement among participants on the necessity of post-closure monitoring or about its precise nature, with some referring to both repository and environmental monitoring in this context, it was agreed that if society demanded it and resources could be directed to developing the necessary technical means to do so, there was no reason why it should not within safety constraints.

For several participants the question of post-closure monitoring or of some form of oversight and continued institutional control raised the issue of preserving data records and of ensuring that future generations would be able to interpret them and understand their meaning. This would require the design of institutional arrangements capable of maintaining the societal capacities and competences necessary to do so. Against this call for continued institutional oversight and providing for the information needs of a future society, other participants argued that we are unable to envisage the future configuration and needs of society. It was pointed out that enormous transformations in the organisation of society have taken place over the past 300-400 years - and for some countries (e.g. Germany) even recent decades have seen dramatic change. It was argued that the lesson to be drawn from history is that societal futures are not predictable, suggesting that the maintenance of human institutions to provide oversight would be very uncertain over the extended timescales being discussed.

When to stop monitoring?
The discussion of how long to monitor also raised the question of when to stop. It was pointed out that a primary purpose of monitoring was to provide information to support decision making and that monitoring would therefore need to continue for as long as there were decisions still to be made. A slightly different view, expressed in relation to monitoring for the very specific purpose of providing early warning of unforeseen problems, was that such monitoring should be maintained only as long as there was the possibility of responding in some way, after which there was no longer any point continuing with it. A more general point made was that wider societal acceptance of repository safety and of the eventual cessation of monitoring was more likely if citizens better understood radiation and the measures for the containment of radioactive waste. It was suggested that a technical repository programme would need to be accompanied by a programme of continued education and engagement.

Technical challenges of long-term monitoring
A final strand of discussion when considering how long to monitor concerned the technical capacity to monitor over the long term. Several participants were sceptical about the durability of
monitoring sensors, pointing to the eventual failure of any instruments. It was suggested that, for this reason, no manufacturer would guarantee performance of their instruments over the periods of time for which it would be required in a repository. This led one participant to argue that sensors should only be placed where they could be physically checked and replaced, in order to be able to distinguish anomalous readings due to instrument failure from any genuinely unexpected evolution of the repository system. Nevertheless, others voiced the expectation that there would continue to be new developments in knowledge and in instrumentation that would extend current capabilities for monitoring. The timescale over which repositories would be implemented provided opportunities for continued research and development. It was also proposed that working collaboratively with other industries could foster creative approaches to the problem, which might produce technical innovations that would make continued oversight possible. The nuclear batteries used in space craft were suggested as an example of an existing technology that might be explored, although it was also pointed out that the implications of any new technology for the safety case would also need to be considered.

4.4 Workshop 2, Track 1: How to use monitoring results?

Elizabeth Harvey (Galson Sciences Ltd), Brendan Breen (NDA)

This workshop considered what arrangements need to be in place for effective governance of a repository monitoring programme, and how monitoring results should be used. Associated questions raised by the workshop chairman to initiate discussion included:

- What is governance?
- Who needs to be involved in monitoring and who should be responsible? This topic was covered in more detail under Workshop 2, Track 2. Therefore, discussion during this workshop focused on who should be involved in governance arrangements, and how those responsible for governance may change over time.
- How can monitoring be carried out independently (if required)?
- How should the results from a monitoring programme be made publicly available and what associated requirements are there for processing and interpretation of monitoring data?
- How should monitoring feed into decision-making, particularly decisions on when to stop monitoring?
- What measures are required to respond to unexpected results?

Discussion during this workshop focused on the role of monitoring in providing stakeholder reassurance. The discussion therefore focuses on how repository governance, particularly in terms of managing an effective monitoring programme, can be used to build and maintain stakeholder confidence.

What is governance?
Governance implies on-going control, regulation and oversight of repository operation, waste disposal and associated monitoring activities. In this respect, there are notable synergies between the discussion during this workshop and the work of the NEA relating to oversight of a geological repository (see Paper S3O5 and Section 3.2 of these proceedings). Governance can be applied both
as part of the activities of the implementer (e.g. through good management and quality control practices), and also through external oversight activities, potentially at different hierarchical levels (e.g. by national regulators/government, through the EU, and/or through the NEA and/or IAEA). A key concept contributing to effective governance is that stepwise licensing of a repository can be used as a means of ensuring periodic review and on-going control of disposal activities.

The licence to construct, operate, and eventually to close a repository is awarded by government, or by the relevant nuclear regulators. However, its award is likely to require the buy-in of the local community. In order to build the trust of these stakeholders, it will therefore be important for long-term governance arrangements to be in place before the disposal implementer applies for a licence.

Effective governance of a monitoring programme requires the application of an objective and impartial viewpoint, without preconceptions of the outcomes of the programme. Governance mechanisms need to be stable to changes in political decision-making, including changes in local and national government, in order to maintain continuity over the long timescales of repository implementation.

Who needs to be involved, including the impact of monitoring phases and timescales
In the context of governance, it is important for each involved organisation to have a pre-defined set of responsibilities, prior to initiating activities at a disposal site. However, the scope and distribution of responsibilities will depend on a country’s national context for monitoring, and are therefore difficult to define generically. There is also a need for flexibility to allow appropriate changes to governance practices as a repository implementation programme progresses. For example, it might be appropriate for there to be a gradual evolution in the responsibilities for records keeping and knowledge management, from the implementing organisation in the first instance, towards higher-level national or international organisations. Workshop participants proposed that the United Nations Educational, Scientific and Cultural Organisation (UNESCO), who are charged with the custody of aspects of human heritage, could be an appropriate international organisation to which responsibility for records keeping and knowledge management could be transferred.

It is important to ensure that knowledge and understanding is sustained and transferred across generations, particularly given the long-running nature of a repository programme. This includes communication of the historical motivation for undertaking specific monitoring activities, particularly if there is a desire for some form of post-closure monitoring to be undertaken, so that stakeholders in the future can make informed decisions as to whether such monitoring is still necessary.

Long-term engagement with stakeholders on the topic of repository monitoring may require an additional skill set focused on placing repository monitoring programme into context, and sustaining this knowledge and ability to explain the significance of results over the long term. Communication and education approaches should be designed to embed the concept of repository safety within individuals and into society for the future, recognising that institutions are unlikely to prevail over the timescales of interest. The workshop recognised that a challenge in achieving this was the potential for a loss of interest in a repository monitoring programme over time, particularly if there are no observable changes or unexpected results arising from the monitoring programme.

Pluralism, specifically the parallel interpretation of monitoring results by different organisations, groups or individuals was felt to be an important principle in support of confidence building.
Parallel monitoring of the WIPP by the CEMRC and by groups within the DOE were cited as examples of good practice in this respect.

**How to ensure independence?**
Assigning responsibility for repository monitoring to an independent organisation was initially felt by the workshop to be a key aspect of using monitoring for reassurance and confidence building. It was recognised that all organisations or groups with a stake in geological disposal would have their own perspective on safety, which might skew their approach to gathering and interpreting monitoring data. To counteract this, a body with no pre-existing stake in the geological disposal process could be needed, either to oversee monitoring activities, or to undertake them on behalf of other stakeholders.

The possibility of having a truly independent monitoring organisation or group was questioned. In particular, it was recognised that even if such a group were set up, with a wholly independent remit, the funding to enable it to operate would typically be routed via the implementing organisation (as is the case for DOE funding of the CEMRC) or via waste producers. This could undermine the perception of its independence in some countries. Independence from political processes, particularly changes in local and national governing bodies, was also felt to be crucial for ensuring continuity in measurement approaches, given the potentially long-running nature of a repository monitoring programme.

What was felt to be more important than the true independence of a monitoring organisation, was the ability for stakeholders to trust that a nominated organisation responsible for monitoring would carry out monitoring objectively, without bias, and provide open, honest reporting of results.

The choice of organisation responsible for monitoring, and the mechanisms used to ensure satisfactory independence in its approach, will therefore depend on the national context of the country in question. Depending on the particular situation, the most appropriate group to carry out monitoring might be the nuclear regulators (or associated supporting organisations), the repository implementers (if there is sufficient trust in their behaviour) or a completely separate organisation, possibly funded via a route that does not undermine confidence in their independence.

**How to use results**
A key requirement proposed by workshop participants for building confidence is that all of the raw results obtained from a monitoring programme should be made publicly available, preferably without any form of pre-processing or filtering of data. Such an approach could be seen to maximise the transparency of the monitoring programme, and might facilitate independent analysis of monitoring by groups or individuals not affiliated to a repository implementation programme. Workshop participants felt there might be benefit if stakeholders could make their own interpretations of monitoring data, which could either confirm the interpretations made by the organisation responsible for monitoring, or offer a different interpretation for discussion. This approach recognises that the interpretation of raw data is sometimes rather subjective (workshop participants remarked that in some cases, subject experts could offer different interpretations of a data set), and acknowledges the value of alternative views.

At the same time, it was felt that guidance should be offered on the possible interpretation of monitoring data. Processing and interpretation of the meaning of monitoring data should be carried out by experts, and their interpretation of the significance of the data should also be made publicly available, accompanied by clear explanations of the assumptions made in interpreting the data, and the rationale for the conclusions drawn.
Combining these two approaches demonstrates a willingness to communicate monitoring results and their interpretation to interested stakeholders so that it can be understood by all parties, but also offers the opportunity for independent scrutiny of the interpretations made.

**Deciding when to stop monitoring**

Consistent with a step-wise process for licensing repository activities (as mentioned above), it is generally acknowledged that closure of a repository would not be approved until there was confidence that the disposal system was performing largely as expected, and that it would continue to ensure safety through passive measures over the long term. It therefore follows that after closure there would be no technical basis for carrying out any further monitoring, and that any monitoring beyond this point would be undertaken purely to address societal requirements. This philosophy reflects the principle of not placing a burden for waste management onto future generations.

The implicit associated change in the main objectives for monitoring that would occur following closure, could have the effect of changing the location of monitoring activities, for example, from non-intrusive monitoring of barrier performance in the near field, to monitoring for public reassurance (e.g. safeguards monitoring or environmental monitoring) at the surface. In particular, it is anticipated that environmental monitoring (e.g. of groundwater or aerial discharges) may continue when other forms of monitoring have stopped, probably as part of existing national monitoring programmes.

Regulators or government would be responsible for deciding when to approve repository closure and hence, when to stop monitoring to support the long-term safety case. However, it is expected that the opinions of local stakeholders would be sought as part of this decision-making process.

After closure, local communities could have a continuing, and potentially more significant role in directing a monitoring programme if they felt that continued monitoring was important for their reassurance. Such monitoring could potentially continue for many years, until local communities had sufficient confidence in the long-term safety of the repository. Local communities are therefore expected to take the final decision on when to stop monitoring. This does not indicate a burden placed on future generations, since they would only be undertaking monitoring at this stage voluntarily, for their own reassurance.

**Responding to unexpected results**

Various principles were suggested for responding to unexpected monitoring results, which were considered to be part of ensuring good governance of a monitoring programme and wider repository implementation activities. These included:

- Recognising that results that could affect the assumptions and arguments in the safety case could occur, and clearly setting out the range of reasons why they may occur.

- Putting in place contingency planning for responding to unexpected monitoring results. This should include a sliding scale of responses, depending on the implications of the results for the safety case.

- Communicating contingency plans to stakeholders.

- Setting trigger values or early warning systems to enable rapid identification of unexpected results and appropriate response before there is a significant issue.
• Responding quickly to unexpected results to avoid any escalation in the potential impact of any detrimental processes that might be occurring.

• Clear communication of unexpected results to stakeholders.

• Clearly explaining the significance of unexpected results and involving stakeholders in discussing appropriate response measures. It was suggested that obtaining monitoring results that are outside expected ranges (e.g. outside pre-defined bounding values) might trigger an increase in the frequency of stakeholder engagement and communication activities.

A key challenge for governance is to formulate effective responses to monitoring results that are completely unexpected and cannot reasonably be foreseen. Some flexibility in the approach to respond to unexpected results is therefore needed. It was also noted that options for responding to unexpected results will evolve, and become more limited as the repository implementation process progresses, and particularly, as repository operation moves towards closure.

4.5 Workshop 2, Track 2: Who should be involved in monitoring?

Matthew White (Galson Sciences Ltd), Anne Bergmans (UA)

The discussion in this workshop session focused on the roles and responsibilities, and issues associated with the different actors involved in monitoring. The discussion considered three different groups of actors:

• Implementers and regulators.

• Advisory bodies.

• Public stakeholders.

Implementers and regulators

In general, it is expected that the implementer will undertake monitoring and evaluate the results and that the regulator will perform checks on the monitoring undertaken by the implementer and the use of the monitoring results in decision making.

The workshop recognised that there is concern on an international basis on the availability of competent scientists to act as advisors to regulators. The EU Sustainable network of Independent Technical EXpertise for radioactive waste Disposal (SITE) Project was mentioned. This project is aiming to establish the competence for supporting regulatory reviews of safety cases. The work of the SITE Project will include definition of the competence required to support such reviews, and will then provide recommendations on how to develop and maintain it. Existence of such expertise would be valuable in the future when regulators are seeking to review implementer’s monitoring programmes.

The independence of implementers and regulators was discussed. It was agreed that it was acceptable for implementers and regulators to undertake joint research activities, but that decision-making processes should be strictly separated. This issue is captured in the EC Directive on the disposal of radioactive waste. It was also agreed that no one group has the right to ownership of
basic scientific understanding, and, therefore, it was appropriate for implementers and regulators to work together on some specific issues, for example development of processes and features affecting repository evolution. Therefore, there may be areas of repository monitoring research where implementers and regulators could work together, such as research on monitoring technologies.

The workshop session discussed whether there was any need for independent monitoring to be undertaken in addition to the monitoring undertaken by the implementer. There was no consensus on this. However, it was recognised that environmental monitoring around a GDF could, and perhaps should, be undertaken by national monitoring organisations, i.e. organisations responsible for monitoring groundwater quality or food standards. Such environmental monitoring could also be undertaken by new, specialist monitoring organisations such as the CEMRC.

Advisory bodies
Advisory bodies were considered to be a good organisation for providing independent expert guidance to a repository programme. An advisory body could play a role in monitoring by undertaking periodic reviews of the programme (rather than being involved on a regular basis).

However, the independence of advisory bodies was questioned during the workshop discussion. The members of advisory bodies are likely to be of similar backgrounds to individuals in implementer and regulator organisations. Advisory bodies are likely to discuss repository programmes with, and provide advice to, government. Therefore, there is a potential for local stakeholders to lack confidence in advisory bodies. The example of the Committee on Radioactive Waste Management (CoRWM) - an advisory body in the UK - was raised. Some stakeholders in the UK have raised questions about members of CoRWM, although the structure of the organisation itself has been broadly accepted.

There is a requirement for balance in the membership of advisory bodies. During its existence, the membership of CoRWM has changed from members with general expertise to specific knowledge of scientific issues. This reflects the progression of the repository implementation programme in the UK. It means that members of advisory bodies would have to have appropriate knowledge of monitoring to be able to advise on monitoring issues.

The independence of advisory bodies was discussed. It has been observed in several programmes that there is no possibility of having a totally independent view, as all individuals will be affected by their history and current circumstances.

Public stakeholders
The discussion of the SITEX Project recognised that public stakeholders may also want access to independent advisory groups. A workshop on the requirements from stakeholders is planned for the SITEX Project.

In terms of public involvement in monitoring, it was noted that local public stakeholders would rather have trust and confidence in implementers and regulators than have to be involved actively. In particular, local stakeholders are volunteers and do not have a professional involvement in repository programmes; they want to maintain a balance between involvement in the repository programme and other activities.

Associated with the issue of the extent of involvement, the workshop recognised that the representativeness of local stakeholder groups is variable. Typically, stakeholder groups consist of older men, and it is difficult to involve younger people and women. However, for long-term
projects, it would be desirable to involve individuals over long periods, meaning that it would be beneficial to have public stakeholders involved from a young age.

An example of the type of involvement that public stakeholders may value was provided based on experience in Belgium. A licence application for disposal of LLW in a near-surface facility was submitted in January 2013. The implementer is undertaking extensive consultation with the local public through a partnership forum. Each month the implementer presents one section of the licence application to the forum and answers questions. A similar type of involvement of local stakeholders in monitoring programmes could be envisaged. The local public were aware that holding these workshops represented a significant investment of time and money from the implementer. The local public were also aware that there were on-going discussions between the implementer and the regulator, and were supportive of this.

It was noted that, in Switzerland, engagement with public stakeholders had begun at the earliest stages of site selection. This experience implies that local stakeholders could be involved, perhaps through exchange fora, at the earliest stages of development of monitoring programmes, i.e. during development of plans for baseline monitoring.

The extent to which local stakeholders may input to the development and review of monitoring programmes is likely to depend on the nature of engagement on the overall repository programme. As an example, it was considered that the decision to use a pilot facility in the Swiss programme was a message that Nagra were open to inputs and proposals on monitoring.

Summary
The key conclusions from the workshop discussion were as follows:

- The implementer, regulator and others all have a role in monitoring: the implementer does the monitoring, the regulator checks the approach and the results, and other stakeholders input opinions and provide further oversight.

- Monitoring is part of the wider safety case; identifying who would be involved depends on wider groupings developed within the safety case framework, as it is difficult to concentrate on monitoring alone.

- SITEX is an example of an international regulator initiative to develop independent groups capable of reviewing safety cases, and, by extension, could be used in reviewing monitoring programmes.

- If the regulator and implementer are undertaking similar work, there is a need to communicate the ways in which they can work together and where separation would be ensured, e.g. research versus assessment/evaluation.

- The nature of, and representation on, advisory bodies depends on who is driving programme - the programme may be government-led or implementer-led.

- It should be recognised that true independence may be difficult to achieve, and it may be better to recognise that all actors have an agenda.

- Efforts should be made to broaden the representativeness of advisory bodies and public stakeholder groups.
• Active processes of transparency are important.

• Environmental monitoring is done now and will continue to be done by environmental monitoring organisations in the future – so national monitoring organisations have a role in repository monitoring but this is not currently integrated into monitoring programmes. This also means that active roles in repository monitoring is not just about involving local stakeholders.

• Involving local stakeholders in monitoring is a challenge as it requires effective communication and explanation from the developers.

• There is a range of examples from existing nuclear and non-nuclear programmes, for who can be involved in monitoring programmes and these examples provide a useful resource for national programmes to consider.

4.6 Workshop 2, Track 3: What to monitor and where?

Alastair Clark (NDA), Michael Jobmann (DBE-TEC)

The aim of this workshop session was to stimulate general discussion rather than identify a list of monitoring parameters, and the following questions were posed (the first three concern ‘what to monitor’, whilst the fourth and fifth questions concern ‘where to monitor’):

• Should we monitor all parameters that can technically be monitored to get as much information as possible?

• Should monitoring be constrained to processes that are described in a site-specific features, events and processes (FEPs) catalogue and identified as significant in the safety case, or should monitoring be more comprehensive and include site evolution in general?

• Should implementers only monitor processes that can be related to safety functions?

• Should monitoring be carried out across the whole of a repository, in order to ensure that all processes occurring can be monitored, or should monitoring only be carried out in a limited area of the repository, or in a pilot facility, on the assumption that this is representative of all other disposal areas.

• Which engineered barriers need to be monitored, to confirm that they continue to function appropriately, and where should the equipment for monitoring these engineered barriers be installed?

Parameter choice through modelling

Modelling during the development of a safety case can help to identify key monitoring parameters by providing information on the scale of physical and chemical phenomena that may occur during the evolution of the repository. For example, key monitoring parameters have been identified for the German salt environment through consideration of 30 years of modelling results. The spatial and temporal resolution limitations associated with modelling must be accounted for when determining what parameters could be included within a monitoring programme, i.e. the robustness of parameter choice is dependent on the scope of modelling. Confidence in parameter choice will
be limited where natural processes are relatively complex or there is a lack of available data which results in relatively high uncertainty. Monitoring cannot be expected to provide a definitive representation of sub-surface processes; it is a representation with residual inaccuracy.

It was agreed that URLs can be used to provide evidence about natural processes. For example, evidence of the rate and extent of concrete crack propagation gathered at the Mol URL, has been applied wider in the Belgian programme.

Most programmes are at the research and development stage so the extent of experience from actual repository sites is currently limited, and, for some programmes, non-existent. Monitoring programmes will only be optimised following site characterisation and during construction to ensure that monitoring is based on the fullest possible understanding of site characteristics. Nonetheless, the development of monitoring programmes during research and development should define key parameters to monitor during operational and pre-operational phases.

The cost of monitoring should be proportionate to the programme cost. Therefore, monitoring should concentrate on parameters that are going to provide most benefit for decision making and other programme goals. A comparison was made by workshop participants, who noted that waste acceptance criteria are typically based on a relatively narrow range of parameters.

Where to monitor?
Monitoring of the near field and far field may be undertaken following closure for public acceptance and confidence reasons. It was suggested that given the current technical limitations of monitoring it is perhaps easier to monitor in the region close to the near field, which was defined in the workshop as the ‘middle field’. However, some participants felt that there were good prospects for monitoring the near-field, citing recent advances in non-intrusive geophysical techniques.

Repository monitoring will be undertaken over long periods, and this requires the monitoring programme to evolve in response to development of knowledge on the repository evolution and also in response to developments in repository monitoring technologies. There is good precedent of monitoring supporting the development of knowledge. For example, Nagra and Andra have witnessed examples of self-sealing of clay host rocks in the excavated damaged zone around underground tunnels in URLs.

To stimulate more specific discussion, an example of engineered barrier system parameters that could potentially be monitored after emplacement was presented (Fig. 4.2). It was noted that methods for monitoring the proposed parameters were well-known and had been applied for 20-30 years. Therefore, there is good experience on which to develop engineered barrier monitoring systems.

The proposed monitoring system illustrated in Fig. 4.2 includes measurements in a dummy canister to determine pressure and pore pressure increase, and measurements above and below the borehole plug to check for its tightness.

Regarding the possibility of monitoring radionuclide migration following closure, workshop participants noted that, if such monitoring was to take place, it should focus on the radionuclides of most concern to the safety case.
Figure 4.2: Parameters that could be monitored in a disposal borehole in the German disposal concept for geological disposal of HLW and spent fuel.

Workshop participants suggested that post-closure monitoring could be used to verify that repository-derived radionuclides do not enter the food chain/biosphere. However, other workshop participants argued that the engineered barrier system would provide better performance than assumed by those proposing monitoring of radionuclide migration, and therefore suggested that such monitoring was not necessary or worthwhile.

The workshop participants agreed that a set of baseline monitoring parameters should be established by each national programme and that these parameters should be monitored until the end of institutional control. A period of 200 years for such monitoring was proposed. It was suggested that a list of possible monitoring parameters could be proposed on an international basis, and that each country could use this list as a starting point for developing national parameter lists focusing on the national context of their own programme. It was noted that the national context would affect the selection of monitoring parameters in each national programme.

One of the workshop participants suggested that implementers should start with a site-specific parameter list and that over time some parameters may be phased out while some will become more prominent depending on specific information requirements. Flexibility in the parameters monitored is needed over a repository lifecycle; e.g. parameters associated with the performance of the sealing system will be most important in the period after their emplacement when the most significant transient processes are occurring.

It was noted that the MoDeRn Project is producing a reference monitoring framework. This framework was based on the philosophy that monitoring programmes should be sufficiently flexible to incorporate learning and continued development of technology.
The philosophy behind the proposed use of a pilot facility in the Swiss national programme was discussed. The approach to be adopted with the pilot facility was to concentrate on representative boundary conditions and processes but that this does not mean Nagra would not also eventually monitor in the main repository too. Monitoring in the pilot facility and emplacement of waste in the main repository would be conducted in parallel.

Aspects of Why to Monitor?
One of the possible drivers for developing a monitoring programme discussed in the workshop was to support decision to reverse the disposal process or to continue with it. The workshop participants commented that both the French and Swiss national programmes are designing the repository with the possibility of retrievability in mind. It was commented that the response to retrieve waste or leave it in should be based on risk assessment (i.e. the potential consequences). The retrieval of toxic waste from disposal sites near Basel, Switzerland was cited as an example of the use of monitoring to support decisions on reversibility of a disposal process.

Other workshop participants stated that the monitoring was undertaken to support optimisation of operational practices and repository design. In this respect, monitoring would be regarded primarily as a tool for confidence building rather a tool for mitigating failures. It was proposed that implementers should look to other industries (e.g. the oil and gas industry and the chemical processing industry) and learn lessons from monitoring case studies.

It was also recommended that implementers should adopt a complimentary, concentrated approach to monitor to understand both localised processes and regional (e.g. network of seismic system sensors) processes.

A key reason for monitoring in the view of participants at the workshop was to ensure that the repository performance lies within the range of conditions assumed in the safety case. Therefore, a response plan was required should the monitoring programme demonstrate behaviour outside of the range assumed. The workshop discussed ICRP principles associated with radiological exposure (Table 4.1), noting that one principle is to move materials or people in the event of ‘exposure situations’ [6].

Table 4.1: Examples of radiological exposure as a function of disposal facility evolution [6]

| Radiological exposure situations as a function of disposal facility evolution and presence and type of oversight |
|---|---|---|
| Disposal facility status | Type of oversight | |
| | Direct oversight | Indirect oversight | No oversight |
| Design-basis evolution | Planned exposure situation | Planned exposure situation | Planning exposure situation |
| Non-design basis evolution involving significant exposures to people and the environment | Emergency exposure situation at the time of exposure, followed by an Existing Exposure situation | Emergency exposure situation at the time of exposure, followed by an Existing Exposure Situation | Emergency and/or Existing Exposure Situation |
| Inadvertent human intrusion | Not relevant | Not relevant | Emergency and/or Existing Exposure Situation |
5. References


Appendix A. Detailed Conference Programme
## Day 1
**19 March, 2013**

### Welcome & Introduction

#### KEYNOTE ADDRESS AND OVERVIEW OF THE MoDeRn PROJECT
Session 1, co-chaired by the European Commission and Andra

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
<th>Speaker</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:10</td>
<td>Keynote: Monitoring and long term safety</td>
<td>P. Zuidema</td>
<td>Nagra, Switzerland</td>
<td>S101</td>
</tr>
<tr>
<td>13:40</td>
<td>Overview of the MoDeRn project: A reference framework for developing a monitoring programme -Presentation of the three themes</td>
<td>N. Solente</td>
<td>Andra, France</td>
<td>S102</td>
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### THEME 1 - IMPLEMENTERS PERSPECTIVE: PROGRAMMES AND CASE STUDIES ON MONITORING
Session S2, chaired by Nagra

<table>
<thead>
<tr>
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<th>Title</th>
<th>Speaker</th>
<th>Location</th>
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<tbody>
<tr>
<td>14:00</td>
<td>MoDeRn – A Case Studies</td>
<td>M. Jobmann</td>
<td>DBE Technology GmbH, Germany</td>
<td>S201</td>
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<tr>
<td>14:20</td>
<td>Confirmation Monitoring of Repositories in the United States</td>
<td>S. W. Wagner</td>
<td>Sandia National Laboratories, USA</td>
<td>S202</td>
</tr>
<tr>
<td>14:40</td>
<td>Monitoring strategy of Cigéo reversible disposal</td>
<td>S. Buschaert</td>
<td>Andra, France</td>
<td>S203</td>
</tr>
<tr>
<td>15:00</td>
<td>Monitoring of the planned repository for spent nuclear fuel in Sweden</td>
<td>J. Andersson</td>
<td>SKB, Sweden</td>
<td>S204</td>
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<tr>
<td>15:20</td>
<td>Development of the UK’s Geological Disposal Facility Monitoring Programme</td>
<td>B. Breen</td>
<td>NDA, United Kingdom</td>
<td>S205</td>
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#### Discussion

**Coffee Break**

### THEME 2 - MONITORING: THE WIDER PERSPECTIVE, THE REGULATORY AND STAKEHOLDERS VIEW POINT
Session S3, chaired by University of East Anglia

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<tbody>
<tr>
<td>16:30</td>
<td>Different views on monitoring and the governance of repository development and staged closure</td>
<td>A. Bergmans</td>
<td>UA, Belgium</td>
<td>S301</td>
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<tr>
<td>16:30</td>
<td>Monitoring for Geological Disposal: A stakeholder’s viewpoint</td>
<td>G. Lauwen H Sannen</td>
<td>STORA, Belgium</td>
<td>S302</td>
</tr>
<tr>
<td>17:10</td>
<td>Environmental Monitoring of the WIPP-A Deep Geological Repository for Transuranic Waste</td>
<td>P. Thakur</td>
<td>Carlsbad Environmental Monitoring &amp; Research Center, USA</td>
<td>S303</td>
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<tr>
<td>17:30</td>
<td>Monitoring and science programmes as “demonstrators” of safety</td>
<td>M. Meyer</td>
<td>CNRS, France</td>
<td>S304</td>
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<tr>
<td>17:50</td>
<td>Oversight of a Deep Geological Repository and the Role of Monitoring – Some preliminary findings by the RK&amp;M Project of the NEA</td>
<td>C. Pescatore</td>
<td>NEA/FSC</td>
<td>S305</td>
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#### Discussion

#### Session S4: Poster Session & Cocktails

**Jean Monnet building, 1st floor**
### Day 2 am
20 March, 2013

#### THEME 2 - MONITORING: THE WIDER PERSPECTIVE, THE REGULATORY AND STAKEHOLDERS VIEW POINT

**Session S5, chaired by Enresa**

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<tr>
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<th>Room</th>
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<tr>
<td>8:40</td>
<td>MoDeRn – Regulatory view View on Monitoring of spent Fuel Geothermal Disposal in Finland</td>
<td>J. Heinonen</td>
<td>STUK, Finland</td>
<td>S502</td>
</tr>
<tr>
<td>8:55</td>
<td>Monitoring requirements in the Swiss regulatory framework</td>
<td>A.-K. Leuz</td>
<td>ENSI, Switzerland</td>
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#### Discussion

#### THEME 3 - MONITORING TECHNOLOGIES: FEASIBILITY AND LIMITATIONS- TECHNOLOGY

**Session S6 & S6 Demo, focus on components & barriers, chaired by NDA**

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<tr>
<td>9:25</td>
<td>State of art of monitoring technology for repositories: instrumentation performance obtained from long duration experiments</td>
<td>J.L. García-Silleriz</td>
<td>AITEMIN, Spain</td>
<td>S601</td>
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<tr>
<td>9:45</td>
<td>Design and development of large scale in situ monitoring section test in the French URL at the CMHM</td>
<td>R. Farhoud</td>
<td>Andra, France</td>
<td>S602</td>
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<tr>
<td>10:00</td>
<td>Monitoring THM effects in a full scale EBS/host rock system – first experiences of the FE-Experiment in the Mont Terri URL during construction and ventilation phase</td>
<td>T. Vogt</td>
<td>Nagra, Switzerland</td>
<td>S603</td>
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<tr>
<td>10:15</td>
<td>Monitoring of Sealing Dams – Experiences from a Test Set-up at the Repository ERAM, Germany</td>
<td>J. Stahlmann</td>
<td>Technische Universität Braunschweig, Germany</td>
<td>S603</td>
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#### Discussion

**Coffee Break**

#### Session S6-Tech, focus on technology, chaired by Aitemin

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<th>Speaker</th>
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<tr>
<td>11:10</td>
<td>Monitoring High-Level Radioactive Waste Repositories with Non-intrusive Seismic Methods</td>
<td>H. Maurer</td>
<td>ETH Zurich, Switzerland</td>
<td>S6TO1</td>
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<tr>
<td>11:25</td>
<td>MoDeRn: Wireless Transmission of Data from the HADES Underground Laboratory to the Surface</td>
<td>T. Schröder</td>
<td>Nuclear Research and consultancy Group (NRG), Netherlands</td>
<td>S6TO2</td>
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<tr>
<td>11:40</td>
<td>New wireless data transmission system based on high frequency radio communication: design, development and testing results under repository conditions</td>
<td>I. Bárceca</td>
<td>AITEMIN, Spain</td>
<td>S6TO3</td>
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<tr>
<td>11:55</td>
<td>Wireless data transfer in salt rock</td>
<td>F. Grafe</td>
<td>BeWe-Ingenieurpartnerschaft, Germany</td>
<td>S6TO4</td>
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<tr>
<td>12:10</td>
<td>Reduced scale tests to assess corrosion of a steel overpack in the Belgian Supercontainer</td>
<td>L. Areias</td>
<td>Euridice, Belgium</td>
<td>S6TO7</td>
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<tr>
<td>12:25</td>
<td>Spatial Time Domain Reflectometry (Spatial TDR) for Moisture Monitoring in Geological Repositories – Technology, Feasibility, and Limitations</td>
<td>N. Wagner</td>
<td>Institute of Material Research and Testing (MFPA) at the Bauhaus-University Weimar, Germany</td>
<td>S6TO6</td>
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#### Discussion

**Closure of plenary sessions and Introduction to workshops**

**Lunch**
## Workshops

### Day 2 pm
20 March, 2011

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<th>Session wp1-2</th>
<th>Session wp1-3</th>
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<tr>
<td>15:00</td>
<td>How to monitor? Feasibility &amp; limitations</td>
<td>Why Monitor? Driving force? Do we need it?</td>
<td>When &amp; How long to monitor?</td>
</tr>
<tr>
<td>Chairs</td>
<td>Jose-Luis Fuentes (Aitein)</td>
<td>Nicolas Solente (Andra)</td>
<td>Jaap Hart (NRG)</td>
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<tr>
<td>17:00</td>
<td>Liz Harvey (GSL)</td>
<td>Matt White (GSL)</td>
<td>Peter Simmons (UEA)</td>
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### Day 3
21 March, 2011

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<tr>
<th>Time</th>
<th>Session wp2-1</th>
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<th>Session wp2-3</th>
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<tr>
<td>09:00</td>
<td>How to use results Monitoring &amp; governance</td>
<td>Who is involved? Roles &amp; responsibilities</td>
<td>What &amp; where to monitor? Parameters, spatial distribution &amp; justification</td>
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<tr>
<td>Chairs</td>
<td>B. Breen (NDA)</td>
<td>Anne Bergmans (UA)</td>
<td>Michael Jobmann (DBTech)</td>
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<tr>
<td>11:00</td>
<td>Liz Harvey (GSL)</td>
<td>Matt White (GSL)</td>
<td>Alastair Clark (NDA)</td>
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<td>11:00</td>
<td>Coffee break</td>
<td>A, B, C Sessions reporting (Chairs)</td>
<td>Conference room M6</td>
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<tr>
<td>11:30</td>
<td>Discussions</td>
<td>D, E, F Sessions reporting (Chairs)</td>
<td>Discussions</td>
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<tr>
<td>12:00</td>
<td>General conference conclusion</td>
<td>Alan Hooper, General Rapporteur</td>
<td>General conference conclusion</td>
</tr>
<tr>
<td>12:40</td>
<td>Closure &amp; adjourn</td>
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# Appendix B. List of Participants

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