

Operational Safety of Geological Repositories

Proceedings of the Joint NEA/IAEA Workshop
29 June–1 July 2016
OECD Conference Centre
Paris, France

NUCLEAR ENERGY AGENCY

Radioactive Waste Management Committee

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Foreword

In July 2016, the Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) held a joint workshop at the OECD Conference Centre in Paris to evaluate the current state of the art on operational safety of geological repositories, and to describe and discuss recent developments from the NEA Expert Group on Operational Safety (EGOS) and the IAEA's International Project on Demonstrating the Safety of Geological Disposal (GEOSAF).

Additional aims of the workshop were to:

- explore how implementers address operational safety in developing geological repositories for radioactive waste disposal;
- identify effective and practical design alternatives used to achieve operational safety in geological repositories;
- evaluate the adequacy and comprehensiveness of the existing regulatory framework guiding implementers in addressing operational safety in geological repositories;
- identify areas and topics that require further work.

This synopsis was drafted by Paul Smith (Safety Assessment Management GmbH, Switzerland) and finalised under the direction of the workshop chairs (Wilhelm Bollingerfehr, Michael Tichauer and Sylvie Voinis) and Gloria Kwong of the NEA. Jinfeng Li of the NEA and Amanda Costa reviewed and updated the synopsis. It was approved by the Programme Committee and the workshop participants.

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List of abbreviations and acronyms

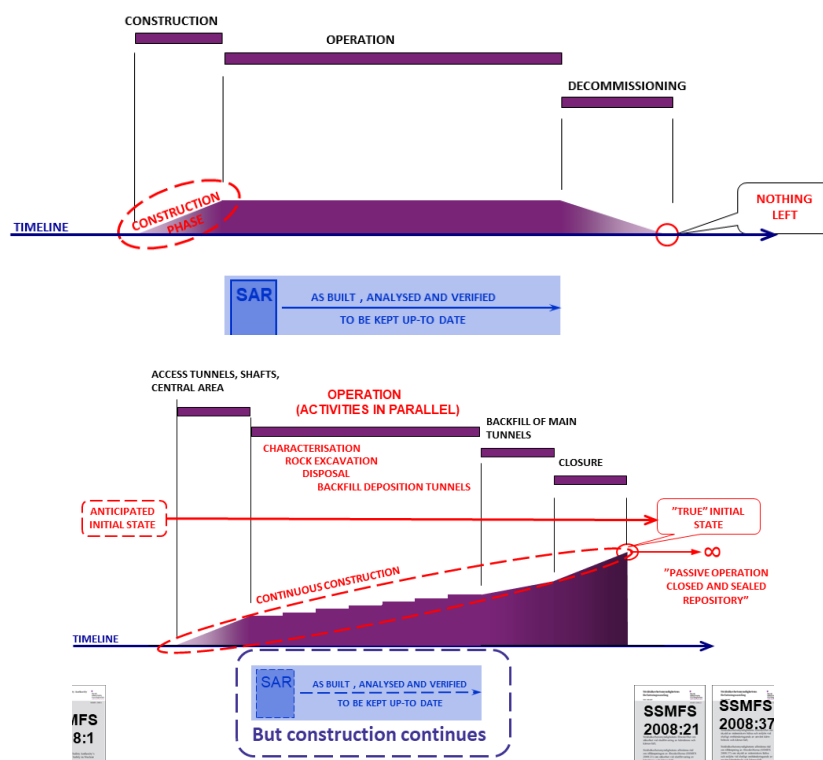
Abbreviation/acronym	Meaning
Andra	National Radioactive Waste Management Agency (France)
APM	Adaptive Phased Management
ASAM	Application of Safety Assessment Methodologies for Near Surface Waste Disposal Facilities
ASN	Autorité de sûreté nucléaire (Nuclear Safety Authority, France)
BfS	Bundesamt für Strahlenschutz (Federal Office for Radiation Protection, Germany)
DCS	Digital cellular system
DeSA	Evaluation and Demonstration of Safety for Decommissioning of Facilities Using Radioactive Material
DiP	Decision in Principle
DOE	Department of Energy (United States)
DT	Design target
EIA	Environmental impact assessment
EGOS	Expert Group on Operational Safety
EPA	Environmental Protection Agency (United States)
EU	European Union
FEP	Features, events and processes
FSAR	Final safety analysis report
GEOSAF	International Project on Demonstrating the Safety of Geological Disposal (IAEA)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Global Research for Safety, Germany)
HAZID	Hazard identification
HEPA	High-efficiency particulate arrestance
HLW	High-level waste
IAEA	International Atomic Energy Agency
IGDTP	Implementing Geological Disposal of radioactive waste Technology Platform
IGSC	Integration Group for the Safety Case (NEA)
ISAM	Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities
IRSN	Institut de radioprotection et de sûreté nucléaire (Institute for Radiation Protection and Nuclear Safety, France)
LILW	Low- and intermediate-level waste
LL-ILW	Long-lived intermediate-level waste
LLW	Low-level waste
MoDeRn	Monitoring Developments for Safe Repository Operation and Staged Closure
MOX	Mixed-oxide fuel
NAGRA	National Cooperative for the Disposal of Radioactive Waste (Switzerland)
NEA	Nuclear Energy Agency
NDA	Nuclear Decommissioning Authority (United Kingdom)
NRA	Nuclear Regulation Authority (Japan)
NUMO	Nuclear Waste Management Organization of Japan
NWMO	Nuclear Waste Management Organization (Canada)
OECD	Organisation for Economic Co-operation and Development
OLA	Operating licence application
OLC	Operational limits and conditions
ONDRAF/NIRAS	National Agency for Radioactive Waste and Enriched Fissile Materials (Belgium)
QC/QA	Quality control/quality assurance

R&D	Research and development
RD&D	Research, development and demonstration
RK&M	Preservation of Records, Knowledge & Memory Across Generations (NEA)
SADRWMS	Safety Assessment Driving Radioactive Waste Management Solutions
SAR	Safety assessment report
SE	Safety envelope
SFOE	Swiss Federal Office of Energy
SFR	Spent fuel repository
SKB	Swedish Nuclear Fuel and Waste Management Company
SSC	Systems, structures and components
SSM	Swedish Radiation Safety Authority
STUK	Radiation and Nuclear Safety Authority (Finland)
TED	Transport and emplacement device
TRU	Transuranic
TSC	Transport and storage casks
URCF	Underground rock and characterisation facility
US NRC	United States Nuclear Regulatory Commission
WAC	Waste acceptance criteria
WIPP	Waste Isolation Pilot Plant (United States)
WMO	Waste management organisation

1. Introduction

This report provides an overview of the state of the art in providing and evaluating the operational safety of geological repositories for radioactive waste. Like nuclear reactors, geological repositories are designed to operate over many decades. One of the key differences between the two, however, is that in the case of a conventional nuclear facility, operations start only once construction is completed, whereas in the case of a geological repository, construction and operation may proceed in parallel, before the facility is eventually completely filled and then closed. Figure 1.1 compares the technical life of a conventional nuclear facility with a geological repository in Sweden.

Figure 1.1: Schematic illustration of the technical life of a conventional nuclear facility (top) and of a geological repository (bottom)



SAR = Safety assessment report.

Source: Swedish Radiation Safety Authority, 2016.

Accidents may occur during the operational phase of a repository, especially considering its unusual duration. Moreover, concurrent mining/construction work underground combined with the transporting of heavy loads of radioactive material from surface facilities to the underground may bring additional risks. New information obtained during construction and

operation, including information relevant to operational safety, may motivate adjustments to the repository design or operating rules approved by the regulatory authorities at the start of operations. In any case, continuous assessment of operational and long-term safety in relation to any new scientific knowledge and design changes may be required, and changes in an already approved design may require additional authorisation procedures and resources.

For decades, geological disposal programmes have focused on long-term safety, since this is seen as the main objective of disposal. However, as programmes have matured, aspects related to engineering feasibility and operational safety have received increasing attention. It has become apparent that operating a repository safely for many decades is a challenging undertaking, as is demonstrating operational safety at a level of detail adequate to license such operations.

In view of these considerations, the NEA and the IAEA held a workshop on operational safety of geological repositories at the OECD Conference Centre in Paris from 29 June to 1 July 2016. The workshop was organised to review the recent development of the NEA Expert Group on Operational Safety (EGOS) and the IAEA's International Project on Demonstrating the Safety of Geological Disposal (GEOSAF). Additional objectives were:

- to explore how implementers address operational safety in developing geological repositories for radioactive waste disposal;
- to identify effective and practical design alternatives used to achieve operational safety in geological repositories;
- to evaluate the adequacy and comprehensiveness of the existing regulatory framework guiding implementers in addressing operational safety in geological repositories;
- to identify areas and topics that require further work.

Over 50 participants attended the workshop, representing implementing, regulatory and research bodies from 14 different countries, as well as representatives from the secretariats of the NEA and the IAEA.

Oral presentations described the work of national implementing and regulatory bodies as well as initiatives by international organisations (Appendices A and B). The workshop also included working group discussions addressing the following topics:

- challenges in addressing operational safety in a safety case (e.g. achieving an appropriate balance between operational safety and long-term safety);
- strategies in managing operational safety, feasible engineering alternatives, etc.;
- recommendations for future international collaboration projects on this subject.

The present report is based largely on the presentations and discussions at the workshop, including the working group sessions. It is structured as follows:

- Chapter 2 summarises past and ongoing work of international organisations, including the NEA and the IAEA, on topics related to operational safety.
- Chapter 3 discusses the requirements and guidance related to operational safety provided by national regulations and international bodies.
- Chapter 4 addresses the relationships between long-term safety, operational safety and repository design.
- Chapter 5 describes the process of operational safety assessment and the management of operational risks.

- Chapter 6 considers the topics of monitoring and compliance control during operations.
- Chapter 7 discusses the issue of safety culture and its relationship to operational safety.
- Chapter 8 summarises the main findings of this report and identifies future challenges.

2. Work of international organisations

Several projects undertaken by international organisations that address, or are relevant to, operational safety of geological repositories were described in presentations given at the Nuclear Energy Agency (NEA)/International Atomic Energy Agency (IAEA) workshop and are summarised in the following sections.

2.1. NEA EGOS

The Expert Group on Operational Safety (EGOS) was created in 2013, under the auspices of the NEA Integration Group for the Safety Case (IGSC). Its aims and objectives in the period 2020 to 2021 are:

- to share technical, regulatory or stakeholder-related experience in operational safety and share know-how on the practical assessment of hazards, technical solutions for risk prevention and mitigation;
- to identify potential hazards in deep geological repositories, utilising experience gained from the operation of mines (both uranium and non-nuclear), nuclear facilities and relevant engineering projects from outside the nuclear industry;
- to identify potential interactions between operational safety and long-term safety and share views on how to deal with this issue;
- to enable the IGSC to foster in-depth exchanges with other international organisations and/or projects in the field of operational safety.

As of March 2021, the EGOS consists of 22 member organisations from 14 countries, as well as the IAEA. The group has held multiple technical meetings to evaluate operational safety issues and has issued reports on:

- fire protection measures and system designs (NEA, 2015b);
- hazards in co-activities, i.e. operational hazards which may arise in underground facilities during simultaneous construction and radioactive waste emplacement activities (NEA, 2015a).

Regarding fire protection, it was observed that most programmes rely on defence in depth and that, in addition, various fire management strategies will be enacted throughout the operational phase (see Chapter 4 for specific examples).

Regarding the management of co-activities, a key aim is to prevent contamination between nuclear and non-nuclear zones, thus minimising potential radionuclide escape from the repository to the environment. The EGOS has noted that various technical options are being considered to meet this aim. It was, however, also noted that national regulatory frameworks associated with the management of co-activity risks could be improved in many countries.

The EGOS has furthermore conducted a literature review on waste acceptance criteria (WAC). It was found that WAC tend to be concept-specific and are developed alongside the waste management concept, e.g. compatible materials must be used in a repository to avoid damaging chemical reactions between waste packages, the engineered barriers and the surrounding host rock.

The current programme of work for the EGOS for the period 2020 to 2021 includes:

- *Fire assessment in deep geological repositories*: completing the draft report on development and experiences on fire assessment methodology with fire and safety experts (from within and outside the nuclear industry) in managing fire risks.
- *NEA “hazard” database*: continuing the compilation of an operational hazard list among member countries, discussing prevention and mitigation methodology for those hazards and drafting a hazard database.
- *Waste acceptance criteria (WAC)*: completing the WAC draft report addressing operational safety aspects (e.g. radiological protection and limits, waste packaging design and specifications).
- *Demonstration of safety and reliability of transport and emplacement systems*: completing the draft status report on approaches and experiences for the design, manufacture and demonstration/testing of the safety and reliability of canister transport and emplacement systems.

2.2. IAEA international harmonisation projects GEOSAF and GEOSAF II

Over the past years, the IAEA has convened a number of international intercomparison and harmonisation projects on the safety of radioactive waste management and geological repositories. The International Project on Demonstrating the Safety of Geological Disposal (GEOSAF), which ran during the period 2008-2011, was established to work towards harmonisation in approaches to demonstrating the safety of geological disposal, with a special emphasis on the expectations from the regulatory authorities engaged in the licensing process with respect to the development of the safety case (IAEA, forthcoming a)

Over the course of the project, it was noted that, after decades of work on long-term safety development, little work has been undertaken internationally to develop a common view on the safety approach related to the operational phase. Thus, as part of GEOSAF, it was decided to launch a specific programme of work on this topic.

Key achievements of the work programme included:

- a pilot study on fire risks;
- first insights on operational safety and its relationship to conventional underground risks;
- a position paper on operational safety (IAEA, forthcoming b), the conclusions of which included the identification of a set of basic principles for operational safety assessment (see Box 2.1).

One of the key findings of GEOSAF in the field of operational safety was the strong relationship between operational safety and post-closure safety and the need to integrate both operational and post-closure safety in a comprehensive safety case.

Following on from these achievements and observations, GEOSAF II was initiated with the objective to reach a joint understanding of, and work towards harmonisation of, views and expectations regarding the safety of the operational phase for geological disposal of radioactive waste and its interrelation with post-closure safety, including the integration of post-closure and operational safety into the safety case. As an outcome, a draft TECDOC has been produced on managing integration of post-closure safety and pre-closure activities

(IAEA, 2015b), as well as a progress report from the Task Group on Operational Safety (IAEA, 2015a).

An inception meeting for GEOSAF III was held one month prior to the current joint NEA/IAEA workshop. GEOSAF III will further address the interface between operational and post-closure safety and how to integrate in practice both of these in the safety case. It is expected that the outcome of the workshop will provide material that can be reflected upon when planning this project in more detail.

**Box 2.1: Basic principles in operational safety assessment
[from the conclusions given in (IAEA, forthcoming b)]**

- identification of the design, including all systems, structures and components (SSCs) and their safety functions, and of the operations and processes that will take place in the facility (and dividing the facility/and or processes into parts or phases that can be assessed);
- identification of the hazards by several possible means;
- assessment of the possible (unmitigated) consequences (all or not radiological) of the hazards;
- identification of preventive and mitigative controls;
- assessment of the acceptability of these controls;
- type of actions to take in case controls are assessed as insufficient or not acceptable;
- assessment of the consequences of the hazards, preventive and mitigative controls on long-term safety and actions to take in case the consequences are not acceptable.

2.3. NEA/IGSC Safety Case Communication Group

In 2014, IGSC formed a sub-group – the Safety Case Communication Group – to address the challenge of communicating technical information related to safety cases to less technical stakeholder audiences. A first report on safety case communication was published in 2017 (NEA, 2017). Regarding the operational phase, the sub-group has noted that the monitoring of qualitative and quantitative parameters can be an effective means to address public concerns if set up appropriately. Clear rules governing the planning and performance of monitoring, as well as sharing of results, are expected to enhance stakeholder confidence. International organisations are currently actively developing guidance that should assist in setting up such rules.

2.4. EU MoDeRn and Modern2020 projects

The EU collaborative projects MoDeRn and Modern2020 both focus on monitoring of the engineered barrier system and near-field rock during the operational period in support of post-closure safety demonstration and decision making.¹ It is, however, recognised that

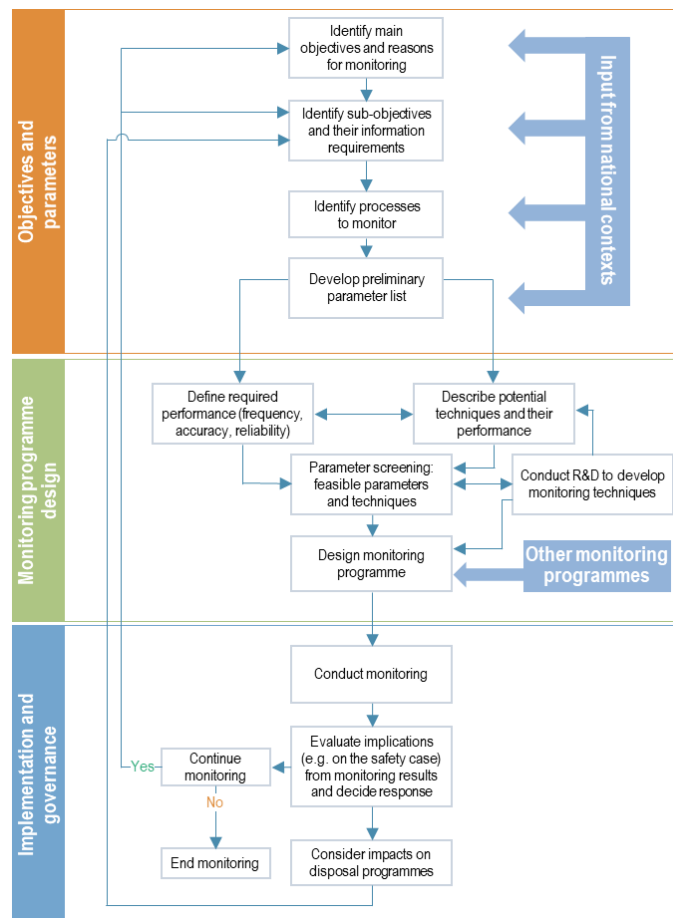
1. Published project documents are available at: IGDTP (n.d.) MoDeRn: Monitoring Developments for Safe Repository Operation and Staged Closure <https://igdtp.eu/activity/modern-monitoring-developments-for-safe-repository-operation-and-staged-closure/> (accessed on 1 July 2016)

monitoring has further important goals, including the support of operational safety, environmental protection and nuclear safeguards.

MoDeRn ran from 2009 to 2013, with 18 partner organisations from 12 countries. Key achievements were:

- development of the MoDeRn Monitoring Workflow (Figure 2.1), which provides a generic structured approach to the development and implementation of monitoring programmes, and the MoDeRn Reference Framework, which provides illustrations and examples of how monitoring can be undertaken for different contexts;
- development of an understanding of, and undertaking R&D on monitoring technologies, thereby extending the range of monitoring technologies available to repository programmes, and evaluating the range of applications for which these technologies could be used;
- describing a range of illustrative monitoring programmes that show how integrated repository monitoring programmes can be developed to address specific programme objectives;
- evaluation of stakeholders' potential role within repository monitoring programmes, and consideration of how the views of stakeholders on repository monitoring may affect the development of a national repository monitoring programme.

Figure 2.1: MoDeRn monitoring workflow



Source: Andra, 2016.

A new project on monitoring started in June 2015, called Modern2020: Development and Demonstration of Monitoring Strategies and Technologies for Geological Disposal. Based on the outcomes of MoDeRn, the overall objective of Modern2020 is to provide the means for developing and implementing an effective and efficient repository operational monitoring programme, taking into account the requirements of specific national programmes. The work addresses the following issues:

- *Strategy*: to develop a detailed methodology for screening safety cases to identify needs-driven monitoring strategies and to develop approaches for responding to monitoring information.
- *Technology*: to resolve outstanding technical issues in repository monitoring, including gaps in research in monitoring technologies (coupling of different wireless data transmission technologies, research into power supply, geophysics, reliability and qualification of components).
- *Demonstration and practical implementation*: to enhance knowledge on operational implementation, and to demonstrate performance of state-of-the-art and innovative techniques by running full-scale and in situ experimentations.
- *Societal concerns and stakeholder involvement*: to develop and evaluate ways for integrating public stakeholders concerns and societal expectations into national repository monitoring programmes.

2.5. NEA study on monitoring

The NEA project on Preservation of Records, Knowledge & Memory Across Generations (RK&M) ran from 2011-2014 and addressed regulatory, policy, managerial and technical aspects of the long-term preservation of records, knowledge and memory of deep geological disposal facilities. In this context, monitoring – by collecting, interpreting and maintaining data on a continuous basis – may be seen to serve the purpose of preserving records, knowledge and memory and continuous oversight. As part of RK&M, the NEA therefore conducted a specific study on monitoring with three objectives:

- to present in a comprehensive way general monitoring information, practices and approaches used in the various national geological disposal programmes and elaborated in a number of international projects (including MoDeRn);
- to explore the role, needs and expectations of local communities regarding monitoring and RK&M preservation of deep geological repositories;
- based on the above review, to identify lessons learnt and the rationale for monitoring geological disposal projects throughout their life cycle stages.

The results of the study were reported in NEA (2014).

3. National regulations and international guidance

Current national regulations and guidance generally do not specifically address the operational safety of geological repositories. There is, however, a range of existing regulations and guidance related to the safety of industrial workers, including radiological protection, to the operation of mines and to the operation of surface nuclear facilities that are clearly relevant to, or may be adapted to, geological repositories. The presentations at the Nuclear Energy Agency (NEA)/ International Atomic Energy Agency (IAEA) workshop included examples of fire, ventilation and other regulatory guidelines from a number of nations. These regulations and guidelines come from a range of sources, including, in the Japanese case, occupational health and safety regulations, the Mining Safety Act and a new regulatory guideline for high-level waste (HLW) storage. It was noted at the workshop that several nations are currently updating regulatory guidance to include operational safety aspects (e.g. France, Finland, Sweden).

Where relevant national regulatory guidelines do not currently exist, programmes have had to develop their own guidance. The French National Radioactive Waste Management Agency (Andra), for example, has developed guidance for fire protection, in consultation with a range of relevant experts (fire fighters, mining and nuclear experts, etc.).

A clear gap in current national regulatory guidelines seems to be the absence of any guidance addressing parallel excavation/construction and operations in a repository. An additional complication is that a range of regulatory bodies is generally responsible for overseeing the safety of construction and operations, and there appears to be a need in some programmes to clarify the roles of these various bodies, and to enhance communication between them. It was noted that, ideally, one regulator would take the lead in the course of a radioactive waste disposal project and “reach out” to the others.

There was an apparent consensus at the workshop that dedicated national regulatory frameworks for geological repositories are desirable, and that this could partly be based on existing regulations and guidelines of the types mentioned above. Such frameworks should ideally be developed early in the course of a programme, but may need to be adapted over time as the programme matures. The involvement of all stakeholders, including all relevant regulatory bodies (as noted above there may be several of these), the implementer and the general public, is to be encouraged in order to clarify expectations and to build consensus on project milestones and the level of demonstration of operational safety that is required at each of these steps.

The possibility of a degree of harmonisation between nations when developing such frameworks may be worth exploring, and the work of the GEOSAF II and III projects may be relevant here. It was described at the workshop how, given that the implications of operational safety on long-term safety are not addressed by current IAEA guidance, a specific task of GEOSAF II was to provide recommendations to the IAEA concerning the potential benefits of issuing a TECDOC on this topic (IAEA, 2015a). In addition, a broad range of existing IAEA publications was examined to explore the need for specific guidance on operational safety. A gap analysis was performed and a rationale for additional guidance was provided. A matrix was developed as a tool for performing this analysis,

which contains topics identified as important to operational safety of a geological disposal facility and the coverage of these topics in IAEA documents (IAEA, 2015a).

The analysis indicated that much information already exists on topics related to operational safety in IAEA documents. In fact, considering a comprehensive list of almost 300 topics was drawn up by reviewing relevant publications and by applying expert judgement, it was found that such topics are at least touched upon in existing IAEA documents. It was, however, noted that the level of detail with which some topics related to operational safety are covered may be too low and that further development of these topics may be warranted. Furthermore, the information on some topics is currently scattered over a number of documents. Further detailed analyses are being carried out in GEOSAF III. If these confirm the need for additional guidance (e.g. in the form of TECDOCs), this can be developed using material that can be found in existing publications as a starting point.

4. Long-term safety, operational safety and repository design

4.1. Relationship between operational safety and long-term safety

Long-term safety tends to receive the greatest attention during early programme stages because it remains the *raison d'être* of geological disposal facilities. Thus, primary design requirements related to the disposal system (including multiple, passive barriers) and the waste acceptance criteria (WAC) that are to be applied are, to a large extent, based on long-term safety needs, as identified from the results of safety assessments and, more generally, from feedback in the course of iterative safety case development. It was noted in the International Project on Demonstrating the Safety of Geological Disposal (GEOSAF), for example, that long-term safety puts constraints and requirements on the choices of materials and the techniques that can be used for construction.

It is, however, also required that the repository be constructed and operated in a safe manner. In turn, the operation of such a facility also has some impact on post-closure safety and the way it is demonstrated. In fact, the operational period can be seen as encompassing a wide range of construction and activities that aim to provide a defined state that can be considered the starting point of the post-closure period. It is therefore part of a safety demonstration to ensure that operation in general, and the following items in particular, will not have an adverse effect on post-closure safety:

- all normal operations;
- anticipated operational occurrences (postulated incidents or accidents);
- the measures (controls) put in place to ensure safe operation, as well as all monitoring systems put in place during operation and beyond.

The definition of operational limits and conditions (OLC) reflects the integration of post-closure safety as an overarching objective.

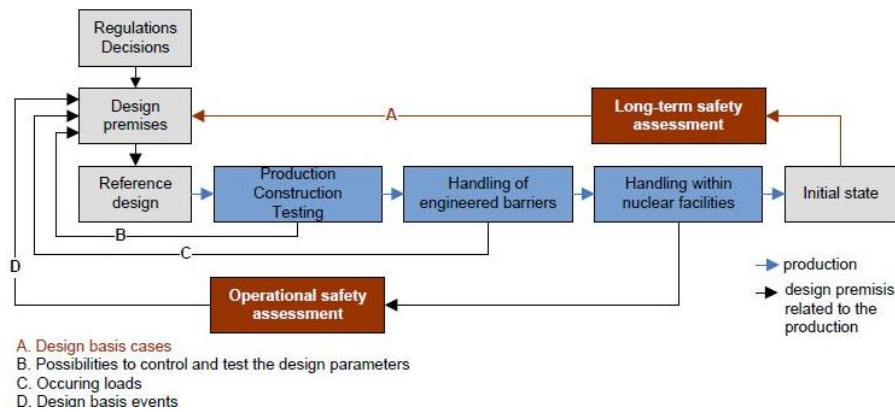
Discussions at the NEA/IAEA workshop tended to suggest that operational and long-term safety have the same overall importance (though views among participants differed), but in the event of an operational incident involving a high hazard level any urgent measures needed to restore operational safety should obviously be taken first, before necessarily considering how to restore or maintain adequate long-term safety. If, on the other hand, the immediate hazard level is lower, it may be possible to consider long-term as well as operational safety implications when deciding what measures to take to address the hazard. As highlighted by GEOSAF II, long-term safety needs to be repeatedly reassessed in light of ongoing developments (especially design changes and evolution of basic assumptions underlying the safety case, such as the inventory of waste, the state of the barriers, etc.) and incidents or accidents during the operational period. It was also suggested that the public may place more weight on operational safety and relatively “near term” long-term safety, when compared with safety in the very distant future. Many programmes are now working individually and collaboratively (e.g. via the IGSC or GEOSAF III) towards the development of safety cases that incorporate both operational and long-term safety aspects, including the impact of operational incidents and accidents on long-term safety, and where conflicts

between operational and long-term safety are explained and, as far as possible, resolved (see Section 4.4 for examples of such conflicts).

4.2. Feedback from operational and long-term safety assessments to design

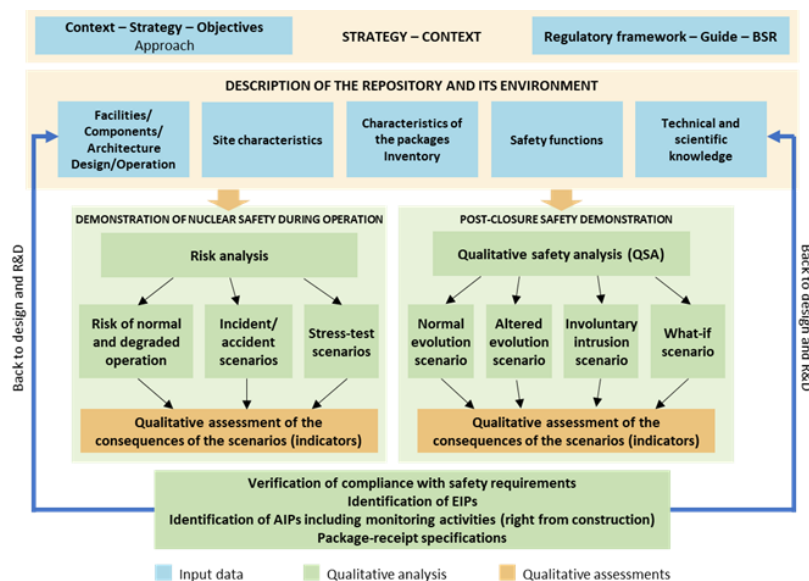
Designing a repository is an iterative process in which both operational safety assessment and long-term safety assessment play a role. The feedback from operational and long-term safety assessments to design requirements or premises, as envisioned by the Swedish Nuclear Fuel and Waste Management Company (SKB) and by Posiva, Finland, is illustrated in Figure 4.1. Similar feedback to design (and also to the R&D programme) has been described by Andra, as illustrated in Figure 4.2.

Figure 4.1: Iterative process of design development with feedback from operational and long-term safety assessments to design requirements or premises, as envisioned by SKB and Posiva



Source: Pastina (Posiva) and Skagius (SKB), 2016.

Figure 4.2: Operational and post-closure safety assessments and their feedback to design and R&D, as envisioned by Andra



Source: Voinis (Andra), 2016.

Most organisations assign long-term safety functions to the repository barriers. Some, such as Andra, have also defined operational safety functions that must be maintained during the operational period, including the containment of radioactive substances, the limitation of dose rates and the avoidance of criticality.

As underlined earlier, changes in design and to design requirements are expected to occur iteratively throughout the design and operational phases of a waste disposal programme, i.e. as understanding progresses, as design and production experience is gathered, as post-closure safety assessments and operational safety assessments are carried out in increasing detail, and as actual operational experience is gathered; any incidents, accidents or interruptions to operations during the operational phase must be assessed with respect to their impact on long-term safety. A change management process is therefore needed to ensure that the design and requirements remain consistent to safety functions, whereby the consequences to safety (operational and post-closure safety) of design changes are systematically assessed and documented before a change is implemented.

An example of design evolution given at the NEA/IAEA workshop is evolution of the layout of the Belgian geological repository to improve operational safety, where the pros and cons of a range of alternative repository architectures has been examined. A multi-criteria analysis was conducted, taking into account factors associated with operational safety (emergency exits, lengths of galleries, positions of shafts, etc.), long-term safety (e.g. radionuclide transport pathways), reversibility of operations, flexibility (e.g. the possibility to extend the repository if needed) and security. As a result, a new draft reference repository layout is currently being developed.

4.3. Prevention and mitigation of detrimental processes during operations

To meet long-term safety requirements, the barriers must withstand the loads (mechanical, chemical, etc.) to which they will be subjected during normal operations, as well as in the post-closure period. Key engineered barriers, such as canisters and other waste packages, must also be designed to be robust with respect to unanticipated or unlikely events or accidents during operation, such as dropping or fires. The equipment and controls used during construction and operation are also designed to minimise any hazards to the workforce and the general public, with the guiding principle being defence in depth.

In general, safety systems and controls can be classified as “preventers” that keep an accident from happening and “mitigators” that make the consequences of an accident less severe if it does happen. The provision of redundancy for crucial equipment can be classified as a preventer. An example of a mitigator presented at the NEA/IAEA workshop is the high-efficiency particulate arrestance (HEPA) filtration systems foreseen by several programmes that will be established where underground air exhausts to surface and would be activated in the event that radioactivity is detected in the underground ventilation air. There are also “passive controls”, or design features, and active controls, including automated equipment and administrative procedures. A view was expressed at the workshop that, where feasible, preventers should take precedence over mitigators and passive controls over active controls. On the other hand, the defence-in-depth principle indicates that no one type of safety system and control takes precedence over another. In practice, however, both preventers and mitigators are likely to be required to achieve a robust disposal system.

Fire risks appear to have received particular attention, with equipment and controls to manage these risks having been studied in some detail by several of the national programmes represented at the NEA/IAEA workshop, as well as in the IAEA’s GEOSAF project and the NEA EGOS.

Most programmes rely on layers of defence that:

- prevent fires from starting, e.g. through avoiding the use of flammable materials and avoiding ignition sources;
- rapidly detect and extinguish any fires that do occur, e.g. vehicles underground supplied with an automatic fire fighting system in the engine compartment;
- prevent fires from spreading, e.g. by the use of fire walls or doors, dampers and fire compartments;
- facilitate intervention in the event of fire (availability of fire fighters, fire suppression systems, etc.).

Figure 4.3 shows an example of a fire door at the underground rock characterisation facility (Onkalo) in Finland. The door, which includes a smaller door for pedestrian exit, closes automatically when a fire alarm is triggered.

Figure 4.3: Fire door PL3003 at the Onkalo facility in Finland



Source: Kaukonen and Sainio (Posiva), 2016.

In addition, fire management strategies will be enacted at Onkalo as it transitions into a repository and throughout the operational phase. These include:

- emergency procedures with clearly defined responsibilities assigned to operating personnel, external emergency services, etc., and the appointment of a designated emergency co-ordinator (e.g. once closed, permission to open fire doors such as that shown in Figure 4.3 can only be given by the chief fire officer);
- regular inspection and maintenance, e.g. of fire protection equipment;
- good housekeeping practices, e.g. to minimise the presence of combustible materials;
- training, including regular fire drills;
- record management, including lessons learnt from any fire incidents.

Operational safety is also enhanced by avoiding materials that may disintegrate into dangerous substances and also by providing a range of escape routes, safety containers or shelters in areas that are difficult or impossible to evacuate. Figure 4.4 shows an example of a mobile safety container at Onkalo.

Figure 4.4: Example of a mobile safety container at the Onkalo facility in Finland

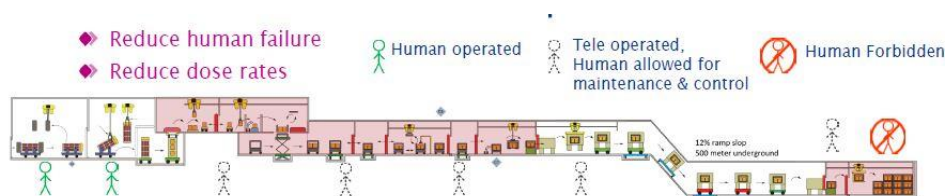


Source: Kaukonen and Sainio (Posiva), 2016.

Several workshop presentations discussed the link between ventilation systems and fire risk management and how requirements related to the need to maintain a good work setting during normal operations may to some extent compete with requirements to prevent the propagation of fire or hazardous substances that may be released in an incident situation.

Overall, operational methods relevant to fire prevention and other operational risks were noted at the workshop to vary significantly between programmes, specifically regarding the issue of transport of materials. For example, both the US Department of Energy (DOE) and Posiva use, or foresee the use of, diesel-driven trucks for their operations. Andra, on the other hand, is planning to use rail transport to minimise the risk of collisions between vehicles and to minimise the use of combustible material (tyres, thermal engines, etc.), and is also planning primarily horizontal waste package transfer processes to reduce the risk of damage due to free fall. As illustrated in Figure 4.5, Andra and some other programmes favour the extensive use of remote operations underground, partly in order to minimise risks to the workforce during normal operations, and partly to minimise the risk of human error. On the other hand, it was suggested by some workshop participants that the presence of humans underground could lead to a more rapid and effective intervention in the event of abnormal situations. Clearly, there is a need to balance the pros and cons of remote operations. In any case, there seems to be consensus that standardised and simple operational procedures (whether remotely controlled or not) are to be preferred over ad hoc or more complex ones.

Figure 4.5: Schematic illustration of Andra's concept for the transportation of waste in surface and underground facilities

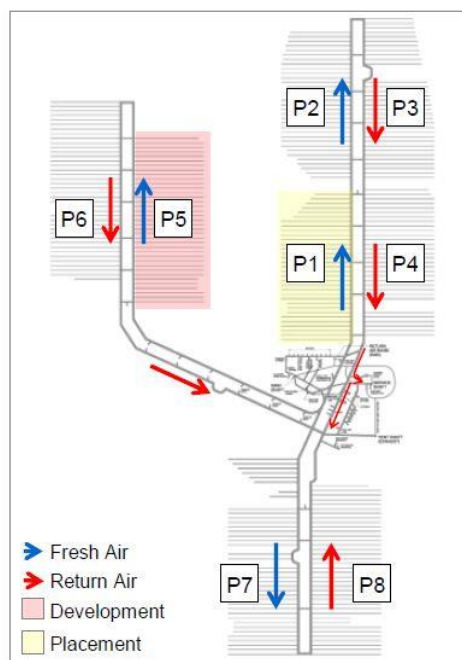


Source: Peyrolles (Andra), 2016.

Prior to the commencement of operations, equipment testing has an important role in terms of demonstrating the safety and feasibility of transport and emplacement equipment, establishing reliability and maintenance requirements for normal operations, and identifying potential operational malfunctions and planning remedial actions. In Germany, for example, 2 000 transport operations and 2 000 disposal operations for POLLUX casks were carried out to demonstrate their reliability. Although the tests performed resulted in no incidents or failure, further tests were successfully carried out to identify and remedy potential operational malfunctions.

As mentioned earlier, various technical options are being studied to prevent contamination between nuclear and non-nuclear zones during simultaneous construction and radioactive waste emplacement activities (co-activities). Examples are the physical segregation of construction and emplacement operations with distinct infrastructure and dedicated supporting systems, such as separate ventilation systems, use of mobile barriers and control procedures such as the assignment of separate routes for material and personnel transfers. The independent ventilation circuits foreseen for development and emplacement areas of the Canadian Nuclear Waste Management Organisation's (NWMO) deep geological repository are illustrated in Figure 4.6. Co-activities also require careful planning to avoid conflicts between security issues and operational safety issues.

Figure 4.6: Independent ventilation circuits foreseen for development and emplacement areas of NWMO's deep geological repository



Source: Liberda and Noronha (Nuclear Waste Management Organization), 2016.

4.4. Conflicts between operational safety requirements and long-term safety

Examples were noted at the NEA/IAEA workshop of instances where equipment and controls designed to facilitate construction, to ensure operational safety and to meet requirements for reversibility and retrievability, may potentially conflict with long-term safety requirements. Potential conflicts include:

- *Underground construction requirements vs. post-closure safety.* The use of cement, e.g. as a material for grouting fractures, is a standard practice in civil engineering projects, but cementitious materials may alter the properties (e.g. porosity and permeability) of the surrounding host rocks of a geological repository.
- *Operational safety vs. post-closure safety.* The use of rock reinforcement (rock bolts and liners) and netting for operational safety adds complexity to the predictions of the performance of the engineered barriers. As another example, the chemicals used in fire extinguishers, when used in the event of a fire, may be difficult or impossible to fully remove afterwards, and again may have detrimental effects on long-term safety barrier performance. Finally, the construction of multiple access routes may be favourable to operational safety, but may create potential pathways for flow and radionuclide transport over the long term.
- *Groundwater inflow control measures vs. post-closure safety.* Measures such as grouting may be used, e.g. to facilitate the installation of the backfill, but this may add complexity to the long-term performance predictions of the engineered barriers.
- *Requirements for retrievability vs. long-term safety.* Measures such as the use of a thick liner to facilitate retrievability may not be optimal for long-term safety.
- *Monitoring vs. long-term safety.* Certain types of monitoring during construction and operation may require cabling that passes through the long-term safety barriers and may have a detrimental effect on the long-term performance of these barriers.

Such conflicts are avoided, as far as possible, by design as part of the optimisation process. For example, the use of concrete is restricted in some programmes that rely on clay barriers, or cementitious materials are used that avoid or reduce any detrimental impact on these barriers (low pH cements). Any remaining conflicting requirements must be integrated and balanced, supported by the use of requirements management systems that deal with both operational and long-term safety issues, and the elicitation of multidisciplinary input to design optimisation.

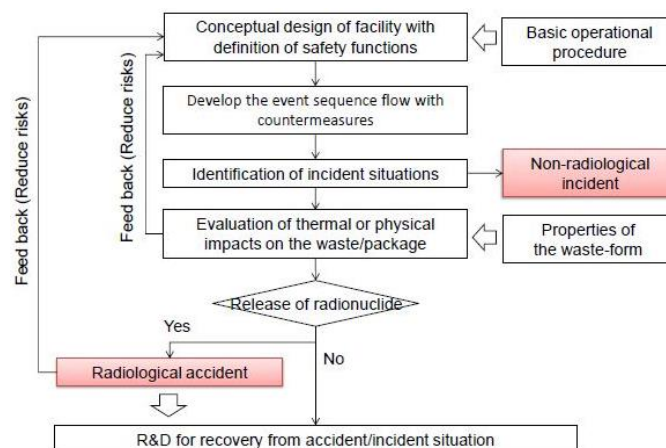
One specific proposal made at the workshop was to develop a closer link between operational safety experts and long-term safety experts. Such co-operation might resolve safety conflicts and would be beneficial to the overall development of safety cases.

5. Operational safety assessment and risk management

5.1. Overall process

Figure 5.1 shows the typical steps in an operational safety assessment and the associated feedback to design as envisaged by the Nuclear Waste Management Organisation of Japan (NUMO). The figure may be viewed as an elaboration of the feedback loop from operational safety assessment to design shown in Figure 4.1, and is consistent with the principles for operational safety assessment given in Box 2.1. Other organisations have identified similar sequences of steps, though with some variations in terminology. The overall process for identifying significant risks or hazards and then implementing suitable measures to protect against them may be termed operational risk management (or the “safety basis process” by the US DOE).

Figure 5.1: NUMO’s concept of feedback loops in operational risk management



Source: Suzuki and Kubota (Nuclear Waste Management Organization of Japan), 2016.

5.2. Identification of risks or hazards

The broad types of risks or hazards to humans and the environment from operating a geological repository comprise:

- the risk of radiological exposure to workers via radioactive dust and radioactive gases such as radon, as well as direct radiation from radioactive waste packages;
- conventional safety hazards to workers such as injury by machinery, rock fall, etc., and other non-radiological hazards such as exposure to hazardous chemicals, smoke inhalation, etc.;
- environmental hazards, including the spread of radioactive dust and gases through ventilation releases and the release of radionuclides to flowing water.

There may also be operational risks that could impact the accessibility, stability and functionality of the facility itself, including its long-term safety barriers. These risks may arise during the process of transferring waste from surface facilities to their final underground emplacement locations, and also include classical nuclear risks (fire, dispersion of radio-contaminants, etc.), which in turn have very specific features in underground spaces.

The process for identifying specific risks or hazards consists broadly of:

- understanding the facility, including its layout, the disposed wastes, the long-term behaviours of safety barriers, and the equipment used for construction and operation;
- understanding how the facility operates, including the existing or planned countermeasures that are intended to provide operational safety;
- identifying events and processes that may occur within the repository, such as the dropping of a waste container, or an underground vehicle fire, and external events, such as an aircraft crashing into the facility at the surface, that can be seen as initiators of incidental or accidental situations.

A key concern here is how to minimise the possibility of incidents and accidents and the damage that such incidents and accidents may lead to should they occur. The completeness of the incident and accident scenarios (chains of events and situations) evaluated in the safety assessment process is also a key issue. For instance, it was emphasised during the workshop that geological disposal facilities have a very particular role in the management of nuclear waste streams and that the loss of such a facility therefore has consequences for the whole industry. As a result, the identification of scenarios that can lead to the loss of part or the whole of such a facility is seen as a key activity to make sure that such chains of events and situations are prevented, detected and their consequences mitigated, in accordance with the defence-in-depth principle. These aspects are developed below.

5.3. Impact analysis

Having identified the types of incidents and accidents that are potentially of concern, it is necessary to analyse if and how these incidents or accidents may impact the workforce and the public, as well as the facility itself, including the impact on the long-term safety barriers and possible delays to the schedule for operations and closure.

Not all incidents or abnormal events need to be analysed in detail, notably:

- those with clearly low consequences;
- those that are implausible or physically impossible;
- those with a very low likelihood or frequency.

However, there are often no thresholds set in regulations for the likelihood or frequency of events that can be disregarded, and even quite unlikely events must be taken into account in the planning of countermeasures if their analyses show their consequences would otherwise be unacceptable. Furthermore, it was noted at the workshop that probabilities or frequencies assigned to internal or external events giving rise to incident situations can often be difficult to support or justify, especially given the limited experience that currently exists in operating repositories, although relevant experience from the operation of mines and surface-based nuclear facilities can be drawn upon. For this reason, impact analyses are also often deterministic rather than probabilistic in nature. As noted earlier, the importance of full-scale tests and demonstrations under realistic conditions was emphasised at the workshop to build up knowledge and experience of the likelihood, nature and consequences of abnormal

events, to develop and to justify model assumptions and to verify model calculations, as well as to enhance stakeholder confidence.

The NEA/IAEA workshop included examples of modelling carried out to analyse incident situations in support of design optimisation (in particular, the design of ventilation systems). As in long-term safety assessment, key issues include model validation and the handling of uncertainties. In general, the uncertainties inherent in such modelling are dealt with by calculating multiple cases covering a wide range of alternative scenarios and model assumptions and also through the use of model assumptions that are conservative – often highly so. Some assumptions were, however, viewed by the workshop participants as difficult to define and support, e.g. the duration of fires in so-called design basis scenarios (it was noted by NUMO that a thermal runaway reaction affecting bituminised waste could potentially occur if the assumed duration of the fire is long enough). Nonetheless, as in long-term safety assessments, all modelling assumptions need to be recorded and justified as far as possible.

As a specific example of a modelling study, the NWMO (Canada) carried out preliminary fire modelling to determine the potential for smoke back-layering (i.e. smoke propagation against the flow driven by the ventilation). The analyses showed that there were scenarios where back-layering could occur, and could be significant enough to limit underground fire fighting processes and emergency rescue, although there is no cross-contamination predicted between the ventilation circuits in different placement arms. Potential mitigation measures were identified and will be incorporated into updating the ventilation system conceptual design.

5.4. Review of countermeasures

Having identified the operational risks or hazards that could arise from incident situations, it is necessary to review and, if required, modify or extend the equipment, controls, contingency plans and other countermeasures that avoid, reduce or mitigate risks and hence protect the workers and the public. For example, the NWMO analysis of smoke back-layering referred to above identified potential in some situations to control back-layering with the airflow velocity in the ventilation system, and the ventilation system design will be updated as a result.

6. Monitoring and compliance control

6.1. Definition, objectives and scope of monitoring

Monitoring a geological repository can involve many aspects. According to the International Atomic Energy Agency (IAEA) Safety Guide SSG-14 on *Geological Disposal Facilities for Radioactive Waste* (2011):

- “Performance monitoring should be used to provide confirmation of assumptions made in the safety case.”
- “A programme of monitoring should be included as part of the safety case and should be refined with each revision of the safety case. During the operational period, the monitoring programme should be used to demonstrate compliance with the regulatory requirements and licence conditions for operation, including compliance with safety requirements for environmental and radiation protection.”

The EU MoDeRn and Modern2020 projects and the Nuclear Energy Agency (NEA) study on monitoring were discussed in Chapter 2. The NEA study identified the key objectives of monitoring as:

- to provide information for making decisions during repository development, i.e. siting, construction, operation and closure;
- to strengthen understanding of different aspects of the repository system, to support safety assessments and modelling;
- to protect workers, public and the environment during operations and to demonstrate compliance;
- to provide confidence to stakeholders, for as long as society requires, that the repository behaviour is as planned, with no undesirable impacts after closure;
- to accumulate a database of the repository for future decision making.

A wide range of parameters may be monitored, including those that are mandatory according to the national legal and regulatory framework, others that are relevant to operational safety, including classical radiological protection parameters, and those that have an impact on long-term safety. Modern2020 is developing a general framework for the identification of parameters (especially those related to long-term safety) that should be the target of monitoring.

The NEA/IAEA workshop participants noted that quality control of construction and operations may be more fruitful (and achievable) than subsequent monitoring of emplaced waste packages and the environment, although the two are complementary. There was, nonetheless, apparent consensus at the workshop that monitoring provides key input to confidence building over the operational phase and that the ongoing Modern2020 and forthcoming GEOSAF III projects are looking at these key issues from various perspectives, including:

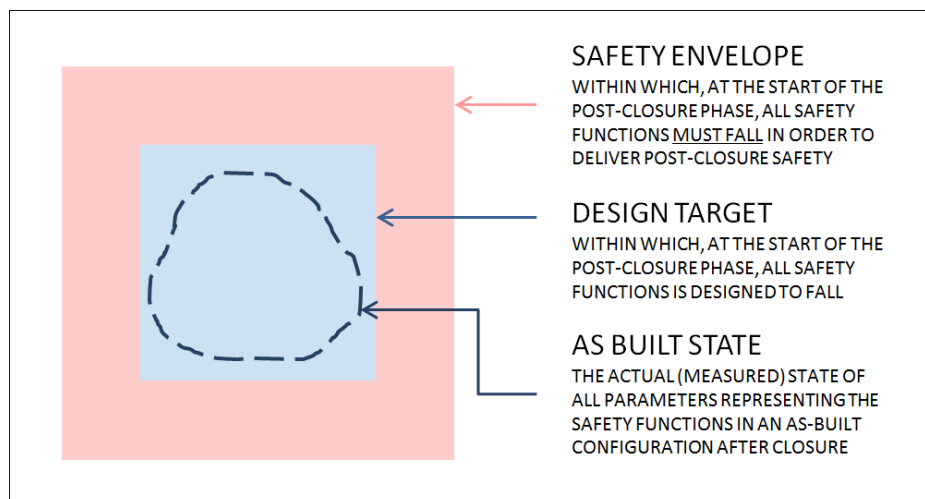
- the role of monitoring in the safety case and its links to both operational and long-term safety;
- the role of monitoring in decision making, including when a repository is to be closed;
- (as noted above) the development of a systematic methodology to identify what to monitor.

The work of these projects, and the greatest attention within national programmes, is focused on monitoring during the operational phase up to the time of closure. The continuation of monitoring thereafter will be a decision for future generations and hence it may not be useful to consider such monitoring in detail at the present time.

6.2. Design target, safety envelope and as-built state

As also noted in Chapter 2, a draft IAEA TECDOC has been produced on managing integration of post-closure safety and pre-closure activities (IAEA, 2015b). This document provides a general framework for repository monitoring and compliance control during construction and operations. In particular, the document sets out a process that an implementer can use to give assurance that construction and operation of a geological disposal facility will deliver the post-closure safety performance that is claimed within the safety case. According to the draft TECDOC, the process starts at the early design stage when the implementer (or the future operator) defines a “design target” and a “safety envelope” for the state of the disposal system at closure; these specify respectively what the disposal system is designed to achieve and what it must achieve. These concepts, together with the “as-built state” are illustrated in Figure 6.1.

Figure 6.1: Illustration of the concepts of “design target”, “safety envelope” and “as-built state”, as defined in GEOSAF II

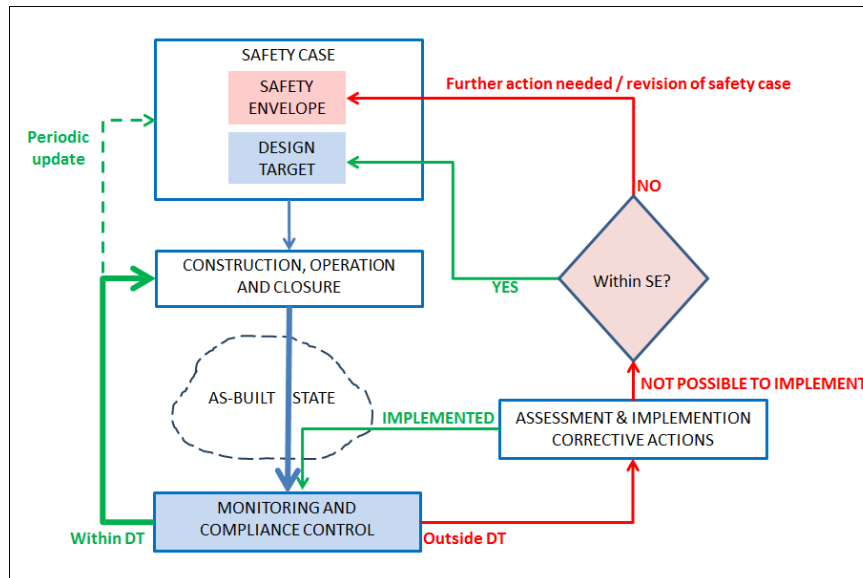


Source: Tichauer (IRSN), 2016.

The concept of design target can then be used throughout the pre-closure phase (considered to include site characterisation, construction, operations and the eventual closure period) to monitor key safety parameters and determine whether the safety case remains “on target” to achieve the performance as planned at the outset. The iterative process for tracking trends and deviations from the target is proposed (compliance control), as shown in Figure 6.2.

The IAEA TECDOC also offers guidance on the means for taking corrective actions to bring the “as-built state” of the disposal system “back on track” and/or, if appropriate, for revising the safety case.

Figure 6.2: Iterative process for assessing compatibility with the design target (DT) and for addressing possible deviations in relation to the safety case and safety envelope (SE)



Source: Tichauer (IRSN), 2016.

The forthcoming GEOSAF III project, also mentioned in Chapter 2, will address in greater detail monitoring, QA/QC and how they relate to the design targets and to the performance of repository components.

6.3. Monitoring in national programmes

Though it may be possible to devise a generic, systematic methodology to identify monitoring parameters, the details of the monitoring undertaken are affected by programme-specific decisions and constraints. For example, there is a legal requirement in France that disposal be reversible for a period of 100 years, and the engineered barriers must be monitored throughout this period to demonstrate that this requirement is satisfied. In Switzerland, the planned repositories are required to include pilot facilities in which a representative sample of the disposed waste is monitored in detail.

In general, when planning a monitoring programme, the principle of not disturbing the repository barrier system with intrusive monitoring techniques is invoked. It was, however, commented by several participants at the workshop that this principle may not be absolute. Rather, the adverse consequence of small perturbations to the barriers should be balanced against possible benefits from the additional information gained from monitoring. The workshop participants also recognised the need for broad (and early) stakeholder involvement when planning monitoring programmes.

The NEA/IAEA workshop included a presentation on monitoring requirements and activities at the Waste Isolation Pilot Plant (WIPP) in the United States. Here, the specific aims of monitoring are:

- to demonstrate compliance with public dose limits during management and storage;

- to collect data to confirm that the technical basis of the performance assessment remains valid.

Monitoring requirements at the WIPP are derived in part from the regulations of the safety authority (the US Environmental Protection Agency [EPA]).

The design, installation, testing and procedures adopted are vital elements of a monitoring programme that may be the subject of regulatory oversight, in the form of reviews of the monitoring concept and its relation to the expected performance of the repository and also reviews of the reports on the monitoring results, with a focus on their significance for repository safety. Inspections during monitoring may also be carried out to assess the quality of the measurements made, as well as the capability of the organisation to carry out the measurements and the suitability of the instruments used.

6.4. Stakeholder involvement

The question arose at the workshop as to whose responsibility it is to carry out monitoring of various types. In general, the answer appears to be that, at least during the period before expiration of a licence, monitoring is primarily the responsibility of the implementer as the licensee, but that other stakeholders can have a role, especially at later stages. For example, in the case of the WIPP, there is an independent institute that carries out monitoring just outside the site boundary during the present operational phase. Earlier in a programme it may also be possible to involve stakeholders in determining which parameters to monitor. After expiration of the licence, responsibility for any further monitoring is likely to transfer to the State. Finally, it was suggested at the workshop that local communities could also play a role in the preservation of information, including that from monitoring.

7. Safety culture

7.1. Definition and importance of safety culture

The Nuclear Energy Agency (NEA)/International Atomic Energy Agency (IAEA) workshop participants identified the maintenance of a good safety culture as a key issue in achieving operational safety. Various definitions exist, but participants agreed that they share a common notion of what safety culture is. One definition given by the IAEA is “the assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance.” (IAEA, 2006)

Discussions at the workshop focused on safety culture from the implementers’ perspective, although clearly maintaining a good safety culture is also important to regulators. In fact, the NEA has recently published a report summarising the safety culture of an effective nuclear regulatory body (NEA, 2016). Clearly, regulatory inspection of a facility is an important aspect of safety culture of direct relevance to operational safety (inspections during monitoring are mentioned in Section 6.3). In some programmes, such as that in Finland, there is a high level of trust between the implementer and the regulator, and the regulator generally gives advanced notice before inspections take place, although the regulator reserves the right to carry out inspections without prior notification.

It was suggested at the workshop that there may be a difference in safety culture between mining engineers responsible for construction of underground openings and nuclear engineers responsible for operations, with the former tending to focus e.g. on the detection and extinguishing of incidents such as fires and the latter tending to focus on prevention. Although there was some disagreement as to whether such a cultural difference is real, clearly a balance between these two aspects of risk management is needed during the simultaneous construction and operation of a repository.

A safety culture can be seen as the result of the way an organisation meets the requirements set out in its management system, including procedures, instructions and personnel training. If these elements are not into place, and are not continuously reviewed, revised as necessary and applied, safety culture is likely to be inadequate or to degrade over time. Maintaining a good safety culture requires a high level of self-assessment at all levels of an organisation, with management taking the lead, and acceptance of self-criticism. It was noted that self-criticism and openness about any failings do not have to undermine public confidence. The public may in fact be reassured to see a degree of self-criticism within an organisation.

7.2. Risks to safety culture and countermeasures

There is a danger that rigid, externally imposed schedules and cost pressures may undermine the safety culture within an organisation, and these pressures must be resisted. Experience shows that poor safety culture may lead to events that have severe consequences on the operation of a repository, and may lead to prolonged cessation of operations (see the example in Section 7.3). As stated earlier, it needs to be recognised that repositories are rare facilities of high importance to the nations that develop them, and that committing

financial and other resources to avoid accidents and mishaps may, over the long-term, save on time and costs if the delays and costs associated with the cessation of operations are taken into account.

There is also a danger that an initially good safety culture will degrade over time, especially in view of the unusually long duration of operations of a geological repository. Some countermeasures were discussed at the workshop, including:

- training;
- fostering a conducive work environment (encouragement of questioning by the workforce, etc.);
- internal and external audits;
- “lifetime learning” and knowledge transfer;
- openness to self-criticism.

It was also noted that nuclear power plants have been operating around the world for many decades and have programmes that show that a good safety culture can be maintained, sometimes learning from instances in their own or other programmes where safety culture has proved to be insufficient (see below). It was further noted that the adoption of “forgiving designs” with high safety margins on every critical component, especially when uncertainties remain relevant, can mitigate the possible degradation of safety culture over time.

Regarding “lifetime learning” and knowledge transfer, it was pointed out that human resource plans should be put in place to allow new personnel to learn from existing staff. Furthermore, plans and “as-built” designs need to be preserved, since these may be invaluable in the event of an operational accident.

As noted above, the NEA has published a report summarising the safety culture of an effective nuclear regulatory body (NEA, 2016). The IAEA has also published a safety report on how organisations can foster the development of in-house understanding of their own safety culture, and improve that safety culture as a result (IAEA, 2016).

7.3. Learning from instances where safety culture has been insufficient

Radioactive waste management programmes should, of course, always aim at achieving zero accidents. Nevertheless, when accidents do occur, these can act as a “wake-up call” to deficiencies in safety culture and thus enhance future safety. Examples presented at the workshop are two incidents that took place at the WIPP in the United States. In the first incident, which occurred on 5 February 2014, a salt haul truck caught fire due to contact between flammable liquids and hot surfaces, consuming the engine compartment and two front tyres. The specific causes have been identified as a failure to recognise and mitigate a fire hazard, to remove combustible materials and to carry out adequate preventive maintenance on equipment. In the second incident, which occurred on 14 February of the same year, a transuranic (TRU) waste drum was breached as a result of an exothermic reaction of incompatible chemical materials, leading to a release of unfiltered radioactive material into the environment. Here, highlighted causes were, among others, a failure to understand, characterise and control the radiological hazard, inadequacies in ventilation system design and operability, degradation of safety management programmes and failure to understand and effectively implement WAC. In both instances, an overarching factor contributing to these failings was a degradation of safety culture.

These incidents have resulted in a revised hazards analysis and a number of changes to the equipment and controls used at the WIPP, including e.g. modifications to vehicle fire

suppression systems, to give confidence that similar incidents will not happen in the future. Lessons learnt from the incidents have also affected other national programmes. For example, Posiva has reconsidered its own vehicle fire extinguishing systems, and has now installed automated firefighting systems in the engine compartments that operate e.g. at night when nobody is present, as well as manual firefighting equipment.

8. Summary and future challenges

The Nuclear Energy Agency (NEA)/International Atomic Energy Agency (IAEA) workshop provided insights regarding the views of implementers and regulators from a range of radioactive waste management programmes on their approaches to dealing with operational safety of geological repositories. These programmes included those at an early stage of planning, where operational considerations are rather theoretical, as well as more advanced programmes, where operational safety is an immediate and pressing concern, and practical experience on how to deal with operational hazards is now available.

Important challenges and questions remain in a number of areas, namely:

- *Regulatory environment:*
 - demonstrating compliance with a wide range of relevant regulations and co-ordinating the work of multiple regulatory bodies;
 - building and adapting a regulatory system with clear responsibilities assigned to all relevant regulatory bodies and recognising the importance of maintaining regulatory competence;
 - resolving the current lack of international guidance specifically focused on the operational safety of geological repositories and investigating the possibility of integrating harmonising national guidance;
 - preparing for emergency situations and management of post-accident situations in order to lessen both the occurrence of accidents leading to unfiltered releases to the environment and the risk of cessation of disposal activities.
- *System design and controls:*
 - managing possible conflicts in safety requirements, e.g. between fire safety requirements and provision of a good working environment during normal operations when planning ventilation systems and, more generally, between construction/operational safety and long-term safety;
 - dealing, e.g. through the development of WAC, with the often wide range of waste types that can arise over periods of decades, some of which give rise to specific safety concerns, e.g. produce gases that require venting or, as in the case of bitumenised waste, have an inherent combustion or explosion risk;
 - striking a suitable balance between prevention of incidents and accidents on the one hand and detection/mitigation/intervention on the other;
 - incorporating “robustness” and “resilience” in design, including the ability to respond and recover effectively in the event of an incident or accident;
 - implementing a change management system during the prolonged operational period of a geological repository, since changes must be properly documented for transparency and also since changes can give rise to unforeseen operational safety issues.

- *Operational safety assessment and risk management:*
 - investigating the possibility of developing standardised high-level approaches, e.g. to fire risk management;
 - better justifying certain key model assumptions, e.g. regarding the temperature and duration of fires;
 - ensuring waste retrieval operations, if needed, can be carried out safely in such a way that safeguards and security are guaranteed;
 - promoting completeness in evaluating risks or hazards and the range of potential consequences.
- *Monitoring and compliance control:*
 - clarifying regulatory expectations on monitoring at each licensing stage;
 - demonstrating and maintaining the reliability of monitoring equipment;
 - clarifying the extent to which equipment for monitoring during the operational phase needs to be removed;
 - identifying the role, nature and conditions for post-operational monitoring;
 - developing in the safety case “safety envelopes” and “design targets” that define the ranges of parameter values that are consistent with safety;
 - clarifying what contingency actions to take if parameter values that are monitored are outside their respective design targets (including circumstances in which waste packages should be retrieved) and potentially outside the safety envelope;
 - clarifying the roles of underground research laboratories and “pilot facilities” with regard to monitoring.
- *Safety culture:*
 - incorporating the notion of “robust” or “resilient” design at early phases of repository development and maintaining this approach over time;
 - maintaining safety as the main focus of the organisation over a period of many decades (continual support from management, maintaining staff competence, preserving corporate memory, etc.);
 - ensuring that schedules and cost concerns do not compromise safety;
 - resolving possible cultural differences between construction personnel (miners) and operations personnel;
 - building trust by providing options, i.e. identifying sets of possible actions that are readily available in case of an accident;
 - putting effort into identifying a comprehensive set of accident scenarios, regardless of their probability of occurrence, and establishing links between these scenarios and aspects such as detection, data and knowledge acquisition, redundancy, diversification, mitigation and possible intervention;
 - demonstrating an adequate safety culture to stakeholders.

- *Reversibility and retrievability:*
 - incorporating retrieval-friendly designs into the safety case;
 - demonstrating that retrievability of waste can be an asset for both operational and long-term safety;
 - clarifying design and operational requirements linked to retrievability and reversibility;
 - incorporating reversal of operations or retrieval of waste as possible options that are available for post-accident management.

More generally, retrievability may have advantages with regard to communication, planning and public acceptance that need to be balanced against the restrictions that it may place on the design options that are available.

A final and critical challenge is how to communicate outstanding uncertainties to the public. In spite of the best efforts of implementers and regulators, not all risks can be completely eliminated and there will be residual uncertainties concerning operational safety. While these outstanding uncertainties should not be downplayed, it must be emphasised to the public that the risks associated with the alternative of leaving the waste indefinitely on the surface can, over the long term, be much higher and does not demonstrate due responsibility to the welfare of future generations.

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Appendix A: Workshop programme

DAY 1 – Wednesday 29 June 2016

09:00 1.0 Opening Remarks

09:00 **Welcome**
Welcome remarks
Introduce co-organiser IAEA and workshop chairs
Michael SIEMANN, NEA

09:05 2.0 NEA and IAEA activities on operational safety of geological repositories *Chairs: W. Bollingerfehr/M. Tichauer/Rapporteur: Paul Smith*

09:05 a. Overview of EGOS accomplishments, current work and future activities
W. Bollingerfehr, EGOS Chair

09:30 b. Overview of GEOSAF accomplishments, current work and future activities
M. Tichauer, GEOSAF II Chair

09:55 3.0 Technical design session *Chair: W. Bollingerfehr/Rapporteur: Paul Smith*

10:00 3.1 Fire risk management and fire safety assessments

10:00 a. Fire risk management during repository construction and operation in Finland
Barbara Pastina (Posiva, Finland)

10:25 BREAK

3.1 Fire risk management and fire safety assessments (*cont.*)

10:50 b. WIPP updated DSA/TSR Revision 5: improvements and lessons learnt
Jeffrey Carswell (DOE, United States)

11:15 c. Conceptual ventilation design for a deep geologic repository
Kelly LIBERDA (NWMO, Canada)

11:40 d. Feasibility study of ventilation and fire risk assessment during operation of a geological disposal facility in Japan
Satoru Suzuki, Shigeru Kubota (NUMO, Japan)

12:05 LUNCH

13:10 3.2 On-site transportation and emplacement of radioactive waste

- a. Cigéo on-site transportation and emplacement of radioactive waste
Fabrice Peyrolles (Andra, France)
- b. Safety of underground operations in an LILW repository
Soňa Konopásková, Dmitry Lukin (SÚRAO, Czech Republic)
- c. Design, fabrication and demonstration of safety and reliability of transport and emplacement systems for an HLW repository in Germany
Wolfgang Filbert (DBE Technology, Germany)

14:25 BREAK

14:50 3.3 Small group discussions

16:50	3.4	Summary of working group discussions on technical issues
16:50	a.	Group 1 summary <i>Group 1 rapporteur</i>
17:00	b.	Group 2 summary <i>Group 2 rapporteur</i>
17:10	c.	Group 3 summary <i>Group 3 rapporteur</i>
17:20	d.	Discussion <i>All</i>
17:50	e.	Session Chair's summary (Session 3) <i>W. Bollingerfehr</i>
18:10		End of Day 1

DAY 2 – Thursday 30 June 2016

09:00	4.0	Repository regulatory framework and requirements <i>Chair: Sylvie Voinis/Rapporteur: Paul Smith</i>
09:05	4.1	Regulatory framework and conventional requirements
09:05	a.	The Swedish legal framework – allocating responsibilities for safety <i>Flavio Lanaro (SSM, Sweden)</i>
09:30	b.	Licensing and operating a geological facility in Finland <i>Ari Luukkonen, (STUK, Finland)</i>
9:55		BREAK
10:25	4.2	Monitoring requirements and capabilities during operations
10:25	a.	NEA findings on monitoring <i>Gloria Kwong (NEA)</i>
10:50	b.	Key findings of the MoDeRn project and overview of the Modern2020 project <i>Johan BERTRAND (ANDRA, France)</i>
11:15	c.	Monitoring Requirements for the Management and Storage of Transuranic Waste at the Waste Isolation Pilot Plant <i>Jonathan P. Walsh (EPA, United States)</i>
11:40	d.	IGSC Communication Group <i>Gloria Kwong (NEA)</i>
12:05		LUNCH
13:30	4.3	Small group discussions on construction and operational requirements (including monitoring), regulatory framework and communications
15:30		BREAK
16:00	4.4	Summary of working group discussions on Section 4.0
16:00	a.	Group 1 summary <i>Group 1 rapporteur</i>
16:10	b.	Group 2 summary <i>Group 2 rapporteur</i>
16:20	c.	Group 3 summary <i>Group 3 rapporteur</i>
16:30	d.	Discussion <i>All</i>
17:00	e.	Session Chair's summary (Session 4) <i>Sylvie Voinis</i>
17:10		End of Day 2

DAY 3 – Friday 1 July 2016

09:30 5.0 Radiological protection issues in DGR**Chair: M. Tichauer/Rapporteur: Paul Smith**

- 09:35 a. Operation radiological protection in deep geological repository
Edward Lazo (NEA)

10:05 5.1 Operational safety and long-term repository safety

- 10:05 a. Post-closure safety requirements and their implication on operation and operational safety
Kristina Skagius (SKB, Sweden), Barbara Pastina (Posiva, Finland)
- 10:30 b. Operational safety and long-term repository safety: Swiss programme approach
Tobias Steinbach (Nagra, Switzerland)

10:55 BREAK**11:25 5.1 Operational safety and long-term repository safety (cont.)**

- 11:25 c. Operational safety and long-term repository safety: French application to Cigéo project
Sylvie Voinis (Andra, France)
- 11:50 d. Evolution of the layout of the Belgian geological repository to improve operational safety
Christophe Depaus (ONDRAF/NIRAS, Belgium)

12:15 LUNCH**13:30 5.2 Small group discussions on operational safety and long-term safety****15:30 BREAK****16:00 5.3 Summary of working group discussions on operational safety and long-term safety**

- 16:00 a. Group 1 summary
Group 1 rapporteur
- 16:10 b. Group 2 summary
Group 2 rapporteur
- 16:20 c. Group 3 summary
Group 3 rapporteur
- 16:30 d. Discussion
All
- 17:00 e. Session Chair's summary (Session 5)
Michael Tichauer

17:10 6.0 Workshop Chairs' summary**17:30 Workshop adjournment**

Appendix B: Compilation of workshop abstracts

Overview of EGOS accomplishments, current work and future activities

Wilhelm Bollingerfehr – DBE Technology GmbH, Germany

Based on a decision of the Integration Group for the Safety Case (IGSC), the Expert Group on Operational Safety (EGOS) was founded at the IGSC annual meeting in 2013 where a discussion revealed the importance of operational safety in a safety case and the interdependencies of operational and long-term safety.

The aim of the EGOS is to identify, evaluate and help define international best practice in safely operating geological repositories for radioactive waste. The scope of issues covers all processes from construction and operation of repositories until their closure. However, the connection to long-term safety should also be addressed. Accordingly, a two-year mandate was accorded the EGOS, which was then extended for an additional two years (until December 2017). Among other requirements, the mandate stipulates the sharing of technical, regulatory or stakeholder-related experience in operational safety; identification of plausible hazards in a geological repository, utilising experience gained from the operation of mines (both uranium and conventional), nuclear facilities and relevant engineering projects from outside the nuclear industry; the sharing and improvement of know-how on the practical assessment of hazards; and the identification of potential interactions between operational safety and long-term safety and the sharing of opinions on how to balance the two. Eventually, the results of the EGOS' activities should enable the IGSC to foster in-depth exchange with other international organisations/projects in the field of operational safety

Accomplishments

The issue of fire risk management was selected as the first task of the EGOS. At several meetings the topic of which methods and techniques waste management organisations (WMOs) apply in their design and operation of repositories was discussed, and the results were summarised in an interim report available on the EGOS (password-protected) members' web page (www.oecd-nea.org/download/igsc/egos/). Another achievement, available at the same location, is the analysis report that summarises key results of a survey on hazards associated with co-activities in geological repositories. And of course the planning of the joint NEA/IAEA workshop, drafting a programme and organising the event at the OECD Conference Centre, is also an achievement.

Current work and future activities

The issue of fire risk management is ongoing and will be addressed again at additional meetings with fire and safety experts to produce a final report. Regarding ventilation systems in an underground facility and strategies to manage the operation of ventilation systems during repository operation, information exchange will be continued and finalised with a summary report as well. An NEA "hazard" database remains on the agenda for the current mandate. Thus, a database task group should be assembled and should start its activities in 2016. Another activity dealt with waste acceptance criteria (WAC). A questionnaire was

drafted and distributed. However, the evaluation of the feedback and an analysis are still pending. Very recently, a new activity was suggested examining experience in demonstrating the safety and reliability of transport and emplacement systems. The EGOS agreed to further study safety and reliability issues of on-site transportation, including all activities at both surface and underground facilities focusing on essential safe transport requirements for waste handling/emplacement. A first meeting was held in February 2016 where seven presentations from six member states were given showing the individual status of their designs and in a few cases the status of large-scale demonstration tests.

International Atomic Energy Agency harmonisation projects GEOSAF, GEOSAF II and GEOSAF III

Michael Tichauer – IRSN, France

Following numerous international projects based on the safety case core concept (ISAM, ASAM, DeSA, SADRWMS...), the International Project on Demonstrating the Safety of Geological Disposal (GEOSAF) was established in 2008 with the aim to work towards harmonisation in approaches to demonstrating the safety of geological disposal. GEOSAF focused on the safety case concept, especially on post-closure safety of geological disposal facilities. As existing guidance on production of safety cases for geological disposal had then been concentrating on the safety case for the post-closure period, a need was identified during the course of GEOSAF for more guidance on issues related to pre-closure safety (covering pre-operational and operational periods), in particular how pre-closure activities should be planned, designed and executed to deliver the “initial state” required for a successful demonstration of post-closure safety. This formed the rationale for the inception of the GEOSAF II project (2012-2015). In 2016, IAEA member states established the first terms of reference of a follow-up project called GEOSAF III, which intends to dig deeper into practical implementation of concepts from the outcomes of GEOSAF II. This document outlines the outcomes of the IAEA international harmonisation projects GEOSAF I and II and the perspectives captured within the scope of GEOSAF III.

GEOSAF

GEOSAF members focused on the development of the safety case for geological disposal, through a review of the European Pilot Study, a review of the Draft Safety Guide on the Safety Case and Safety Assessment for Radioactive Waste Disposal which eventually became IAEA SSG-23, and designed a questionnaire on long-term safety. A dedicated group was also formed to produce a companion report on operational safety, including a case study on fire risks. At the end of GEOSAF, it was found relevant to keep working on safety case development for geological disposal facilities, focusing more deeply on the relationships between pre-closure activities and post-closure safety and on the development and review of an overall safety case that integrates both pre- and post-closure aspects.

GEOSAF II

The GEOSAF II project was established with the aim to define a structure and methodology for a geological disposal safety case, integrating both operational and post-closure phases and proposing a framework for demonstrating safety as the facility moves from operations to post-closure. During the course of the project, an IAEA TECDOC as well as a specific report presenting a methodology to identify gaps within the existing guidance documentation on operational safety of geological disposal facilities were compiled. GEOSAF II underlined the need for an integrated safety case with a practical use of basic concepts such as the “as-built state”, “design target” and “safety envelope”, throughout the stepwise evolution of

the safety case. Additional attention was paid to managing deviations during the operational phase to allow post-closure safety functions to still be delivered at the time of closure.

GEOSAF III

Detailing the main aspects developed in GEOSAF II, GEOSAF III (2016-) proposes to expand the practical use of the safety envelope (SE), the design target (DT) and the operational limits and controls (OLCs) for the operational phase, QC/QA and monitoring, uncertainty management with respect DT, SE, OLCs, management of deviations from the DT and the SE, requirements management and decision on corrective actions. The aim of such a project is to harmonise practical implementation methods of these concepts into the integrated safety case outlined in previous projects.

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Fire risk management during repository construction and operation in Finland

Kari Kaukonen, Lauri Sainio – Posiva Oy, Finland

Fire safety during repository construction

Fire safety during construction of a geologic repository is challenging due to the complexity of extinguishing, evacuating and rescuing operations in case of a fire in an underground facility. Underground rescue operations set specific requirements not only on the fire extinguishing methods but also on the protection of the fire rescue team. If the fire has developed extensively, it could be even impossible to extinguish without endangering the rescuers' safety. The focus of fire protection is first and foremost individuals' location and evacuation.

Management of fire risk

The natural underground rock environment does not itself present any fire risk, but risk is induced by the materials, equipment, vehicles and working methods used underground. Fire risks are minimised by allowing underground only controlled materials that have been

accepted for use, by regularly checking the conditions of the equipment and vehicles through a preventive maintenance programme and by managing different hot-work activities through a specific hot-work licensing system.

Fire containment and smoke removal are key in evacuation and fire extinguishing operations. To this end, the access tunnel is divided into two parts by a fire door, which closes automatically upon fire detection. When closed, the door reduces the ventilated volume area thereby containing the fire and smoke. The door can be opened only by special command from the chief fire officer to allow smoke removal by gravity.

Minimisation of risk to individuals

The general principle is to always minimise the number of individuals working underground at the same time. Before going underground, individuals are informed about fire warning systems, such as sirens and other signals. In case of fire, the individuals receive an alarm message through their digital cellular system (DCS) phones concerning the location of the fire in order for them to assess the evacuation possibilities. DCS phones are connected to the internal phone network through several base transceiver stations.

In case of fire, the access ramp is the primary evacuation route. At least one suitable evacuation vehicle must always be available. If evacuation via a rescue vehicle is not possible, individuals are transferred to shelters or to mobile safety containers.

Four shelters are located at the underground junction with the incoming air shaft providing protection in case of a fire. The shelters are always overpressurised with respect to the incoming air shaft, which also improves safety and removes the immediate need for evacuation. The individuals in the shelter can be transferred to the surface through a special rescue basket installed in the incoming air shaft (emergency rescue route). Mobile safety containers are also planned for fire protection. Safety containers are moved as the construction proceeds and in case of need, to adapt the evacuation strategy to ongoing working activities.

Fire safety during disposal operations

During construction and operation, underground openings, repository components, technical systems and equipment have to be protected from fires to prevent them from becoming a fire safety hazard. The fire risk during operations is assessed against internal and external hazards in the technical contingency plan.

In addition to operating instructions and working methods for fire protection management, fire safety concepts for the surface encapsulation facility and for the underground repository are compiled. As construction work proceeds and premises are finalised, fire partitioning, fire detectors and alarms as well as local fire suppression systems are added to improve the initial fire extinguishing readiness.

Fire safety management will become particularly challenging at the beginning of the actual repository operations, in the year 2024, when the repository areas will be constructed at the same time as the spent nuclear fuel canisters will be installed. In addition to securing individuals and property, new safety, security and safeguards restrictions will be introduced in order to ensure nuclear safety, corporate security and nuclear material surveillance. Since fire escape routes are also potential sources of external threats, access from unsupervised construction areas to nuclear facility area will also be prohibited during rescue operations. In practice, this means that independent access and evacuation routes will be set up in the construction and deposition areas. According to Posiva's stepwise construction concept, disposal and excavation operations are carried out in sufficiently distant locations, access

and evacuation routes are separated and operations are staged so that construction work does not induce risks to nuclear operation and vice versa.

WIPP updated DSA/TSR Revision 5: improvements and lessons learnt

Jeffrey Carswell – DOE, United States

This abstract was unavailable at the time of publication.

Conceptual ventilation design for a deep geologic repository

Kelly Liberda – NWMO, Canada

The Nuclear Waste Management Organization (NWMO) is responsible for implementation of Adaptive Phased Management (APM), the federally approved plan for safe, long-term management of Canada's used nuclear fuel. Under the APM plan, used nuclear fuel will ultimately be placed within a deep geological repository in a suitable rock formation.

The conceptual ventilation system design for the repository is based around three vertical shafts, which will be used to intake and exhaust the air from the surface through the underground facility and back to surface. A series of surface fans and underground booster fans will be required to achieve the design flow distribution in the underground repository.

The ventilation conceptual design was analysed for the impact of a fire to understand if any design changes needed to be made. Possible worst case fires during construction and operations were reviewed to understand the issues of smoke dissipation and fire spread, and the ability for workers to reach refuge stations. As a result, some ventilation design changes are being proposed.

Feasibility study of ventilation and fire risk assessment during operation of a geological disposal facility in Japan

Satoru Suzuki, Shigeru Kubota – NUMO, Japan

Background

The target radioactive wastes of geological disposal of Japan are vitrified waste arising as a result of the reprocessing of spent fuel (HLW, hereafter) and low-level waste arising as result of reprocessing and MOX fuel fabrication, which is solidified with mortar or bitumen and contains transuranic nuclides and radioisotopes of iodine and carbon (TRU waste, hereafter). The ongoing update of the safety case for co-disposal of HLW and TRU waste in Japan will include a more extensive assessment of operational safety than has been carried out in the past. The pre-closure safety case aims to assure both radiological and non-radiological protection of the public and workers. The ventilation and fire hazards assessment are key issues of operational safety in the underground facility.

The major host rocks which are expected in the siting process of Japan are plutonic rocks, Neogene sedimentary rocks and pre-Neogene sedimentary rocks, which cover an area of land that is 16-25%, 10-15% and 33-45%, respectively (variations are due to differences in depth between the surface and 1 000 m). The rest are volcanic rocks and unconsolidated Quaternary sediments which are unfavourable for geological disposal. The characteristics of each host rock are taken into consideration for operational safety issues, for example, the production of gas or the amount of water inflow to tunnels.

The radioactive wastes are sealed into carbon steel packages (“overpack” for HLW and the “waste emplacement package” for TRU waste, hereafter). The heat, mechanical and chemical properties of these wastes are taken into consideration for operational safety.

The layout of the disposal tunnels is also a key issue for operational safety. The underground facility consists of disposal tunnels lined in parallel, connecting tunnels, an access ramp and shafts. Both the panel and fishbone style layouts are examined in the safety case and in addition, the ease of ventilation is compared between these design options.

Operational activities in an underground facility include: transportation of packaged HLW and TRU waste by access ramp, machine emplacement, backfill of disposal tunnels and plug sealing of the ends of disposal tunnels. Fire risks are considered for all of these operational procedures.

Ventilation study in the underground facility

For non-radiological protection, the working environment will be maintained to ensure worker comfort and safety during normal operations. In many cases, requirements are set out in regulatory guidelines, e.g. for the ventilation system. Further, underground tunnels and ventilation shafts should be laid out to facilitate ventilation pathways, taking transport routes for excavated rock and waste into consideration and required active/inactive zoning.

To understand the factors influencing the ventilation system, the wind velocity along the ventilation pathways was evaluated for the repository design. The major factors are methane or hydrogen gas production and heat emitted by the different types of host rock and radioactive waste. Methane gas production is characteristic in certain Neogene sedimentary rock formations and hydrogen gas production might occur due to the radiolysis of water contained in the mortar filler of the TRU waste package. The tunnel layout and tunnel curvature are also key factors. The wind velocity in tunnels was below the criterion 7.5 m/s and the temperature of the work area can be maintained below the 37°C criterion.

Based on the results, the pros and cons of the repository design are now being discussed qualitatively. The ventilation pathways are more complicated in the case of the panel style layout relative to the fishbone style because it must be determined to fulfil the requirements of the excavation and transport routes simultaneously. If the curvature of a tunnel is small, as often occurs in the panel style layout, an undesired loss of air pressure can occur and therefore the fishbone style layout is preferable to the panel style layout. If the Neogene sedimentary rock is selected as the host rock, the dilution of methane gas (below explosion limit) by ventilation is an additional requirement. Because the amount of hydrogen gas production by radiolysis of water contained in the TRU waste packages is poorly known, further studies are required, such as the production rate under irradiation, in order to design countermeasures.

Fire incident assessment

The potential vulnerabilities of operational processes have been considered; most of these would pose little risk to the public, but the complexity of recovery operations and risks to workers could be significant. Fire incidents were identified using an event tree method and possible, cost-effective countermeasures identified that would reduce their likelihood or mitigate their impact. Fire incidents may occur if there is an accident with a transporter vehicle or an emplacement machine (ignition of light oil or lubricant oil) or self-ignition of an electric cell used as a power source.

Evacuation routes for fire incidents should be organised in the fresh air side of fire locations (opposite direction of air flow), the elevator for worker transportation should be provided

in the fresh air intake shaft and emergency shelters provided at appropriate locations. To minimise the radiological contamination of tunnels, the operational area where overpacks or waste emplacement packages are emplaced should be isolated from the construction area. Because of the short duration of a fire (of the order of 1 minute), the increase in temperature of the waste form is not significant for HLW, while it is up to 90°C for the bituminised TRU waste. In the latter case, the auto-ignition temperature of bitumen is ca. 350°C. Thus, the thermal robustness of radioactive waste assures no release of radionuclides as a result of fire incidents in the underground facility.

Cigéo on-site transportation and emplacement of radioactive waste

Fabrice Peyrolles, Jean-Michel Bosgiraud – Andra, France

Cigéo is the French acronym used to describe a deep geological repository for long-lived high- and intermediate-level radioactive waste that is being currently designed in France. Cigéo entered in industrial design development as of 2011, is set to be commissioned around 2030 and will be in operation for +100 years. Among other technical and safety challenges, handling and transferring irradiating waste disposal packages along significant distances underground is a particular operating activity that shall comply with strict operational safety requirements. As a result, since they have to be safe, reliable and flexible over time, handling and transportation operations are one of the key issues of the Cigéo design.

During the initial stages of the project, Andra had selected and subsequently studied a wide range of technological options, equipment and processes to receive and control the primary waste package, to condition it in disposal package, then to handle and transfer the disposal waste package in the underground facility. Technical choices were made taking into account that operational safety requirements are hardly negotiable, while technologies can be improved and optimised.

Due to the vast variety of equipment involved in a dynamic process, specific interface defect risks are to be analysed in addition to the usual safety risks (equipment or human failure, component malfunction, etc.). Furthermore, blockage risks have to be evaluated at all stages of the process, from the point of view of both potential operational safety issues and impact on performances (and operability rates).

According to the defence-in-depth principle, the approach that has been adopted by Andra seeks reduction of handling elevations and human interventions as much as possible, keeping in mind that a single failure must not lead to a serious accident with significant releases. As consequence, Andra preferred to have a funicular system for the transfer of the disposal packages from surface to the underground level and a “stacker-crane” for the positioning of LL-ILW packages layer by layer in the disposal vaults.

Therefore, the overall waste transfer process is based on the use of overhead cranes, rail trolleys, a funicular system installed in the ramp tunnel and other specially designed equipment which fulfil the safety requirements.

Today, most of the technical options have been characterised in terms of operational safety risks and technical performances. Tomorrow, at the completion of the detailed design, these solutions will be refined and elaborated in order to prepare the licensing documents for the construction of Cigéo.

Safety of underground operations in an LILW repository

Soňa Konopásková, Dmitry Lukin – SÚRAO, Czech Republic

LILW repositories for institutional waste are sited in abandoned mines in limestone and granite rocks. This leads to the need to manage not only radiation, but also the mines' safety.

Operational limits and conditions, QA programme, emergency plans and monitoring programme are directive documents approved by the regulatory body which have to be implemented during operations.

Radiation protection of repositories during the operational period is controlled by the State Office for Nuclear Safety, a regulatory body based on the Atomic Act. Mining safety is regulated by the Regional Mining Authority. Both radiation and mining safety are assured during regular operation and during emergencies. Emergency situations are described by emergency plans, dealing with their consequences. Identified incidents are the following: caving, fire in underground, final waste form destruction, contamination within handling, ventilation interruption and inadvertent intrusion. All emergency situations are estimated to be of first or second order. This means that there is indicated no possible situation of the third order, that could lead to environmental impact or to impact on population.

During the operational period, an accent is put on radiation and mine safety of workers as well as on security. Effective doses of workers are subject to the waste composition and activity, but in substantial measure, radon inhalation provides a contribution to the professional dose. Radon concentrations in underground are minimised using ventilation systems: optimisation of the concentration of radon products and related internal dose is a base of radiological protection requirements in underground.

The security system is ensured by physical protection in nuclear installations and by guarding in other facilities.

In addition, operational issues related to safety comprise events and processes that could affect post-closure safety coming from activities performed during the operational period. Present and future near-field processes have been included in scenarios describing final waste form and barrier performance as well as the source term quantification. From this point of view, the solidification process of the final waste form and the extent and quality of stabilisation and/or filling barriers, including the means of their application, are determining inputs to post-closure safety assessment.

An emphasis on barrier quality is stated in the quality assurance programme. The schedules of evidence, controls and the extent of possible interventions are set by operational directives including the monitoring programme. Sensitivity, probability and uncertainty analyses evaluate the extent of the effect of FEP on post-closure safety.

Monitoring and controls cover security system, emergency preparedness activities, radiological protection related parameters, final waste form parameters, stabilisation barriers data, and system of evidence safety-related data in the form of database.

Design, fabrication and demonstration of safety and reliability of transport and emplacement systems for a HLW repository in Germany

Wolfgang Filbert, Wilhelm Bollingerfehr – DBE Technology GmbH, Germany

Three different disposal options for spent fuel and high-level radioactive waste have been considered in Germany. In the 1980s and 1990s a large-scale RD&D project was carried out to develop the technology needed to license and eventually operate a repository. One

major part of these efforts was the development of all technologies required to operate a repository that were not state of the art and their full-scale testing. Since the early 1960s, the preferred host rock for a repository in Germany has been rock salt. Thus, rock salt was the basis when developing the transport and emplacement technology. A current assessment shows that – with minor changes – this technology could also be applied in clay or granite.

First disposal option: Disposal of spent fuel rods or radioactive waste canisters in self-shielding carbon steel POLLUX® casks (max. weight 65 t) in horizontal drifts

In the late 1980s, heavy-duty hoisting facilities operated in mines with a technological limit of around 40 t payloads, with the loads being conveyed from underground to the surface. However, this first disposal concept required hoisting of about 85 t payload (cask and transport cart) from the surface to the underground. It could be demonstrated that with some technical changes and new developments, the new hoisting equipment could meet the state of the art in science and technology. Upon reaching the underground shaft landing station, the loaded carts are removed from the shaft and conveyed by train to the disposal drift. There, an emplacement device unloads the carts and places the casks on the floor. The safety and reliability of this transport and emplacement technology has been demonstrated in full-scale tests.

Second disposal option: Disposal of spent fuel rods or radioactive waste in unshielded canisters in vertical boreholes drilled 300 m deep from the emplacement level

The transport system consists of a transfer cask (weight 51 t max.) to provide shielding for the transport of the canister to the underground. The hoisting system developed for the transport of the POLLUX® casks will be used as well. Upon reaching the underground shaft landing station, the loaded carts are removed from the shaft and conveyed to the drift for borehole disposal. An emplacement device designed to accept and handle the transfer cask is already placed on top of the borehole. There, it takes the transfer cask from the cart, turns it into an upright position, picks up the canister, and emplaces it into the borehole. The safety and reliability of this transport and emplacement technology has been demonstrated in full-scale tests.

Third disposal option: Disposal of spent fuel or radioactive waste canisters in transport and storage casks (TSC) in short horizontal boreholes

Due to the fact that the TSC weighs around 160 t, the hoisting equipment again needed technical modifications. A conceptual design shows that such a system is technically feasible. Upon reaching the underground shaft landing station, the transport cart is removed from the shaft and the TSCs are reloaded onto the underground transport and emplacement device (TED). The TED is conveyed by two locomotives to the disposal drift and placed in front of the horizontal borehole. The TED then pushes the TSC into the borehole. For this option, full-scale tests to demonstrate safety and reliability of the system are pending.

The Swedish legal framework – allocating responsibilities for safety

Flavio Lanaro – SSM, Sweden

In Sweden, the establishment of a geological disposal facility for radioactive waste is subject to licensing, with the licensing authority being the government. Licensing includes parallel processes under the Environmental Code, on the one hand, with the Environmental Court submitting a statement to the government on permissibility, and under the Act on Nuclear Activities on the other hand, with the Swedish Radiation Safety Authority (SSM) submitting a statement on nuclear safety and radiological protection to the government. Stakeholders

are involved in the process through public consultations during the preparation of the licence application and during the licence review process, and are invited to provide comments on siting, completeness, scientific soundness and fulfilment of safety requirements. The local municipalities hosting the candidate sites for the geological disposal facility have the right of veto on governmental decisions.

SSM is endorsed the right of issuing detailed regulations on the matter of nuclear safety and radiological protection. Enforcement actions are contemplated in case of violation of fulfilment of the requirements. Presently, there are general regulations concerning the safety of nuclear facilities during construction, operation and decommissioning, and specific safety regulations for geological disposal facilities concerning radioactive waste after permanent closure. Swedish regulations for nuclear activities are largely formulated to be generally applicable to any nuclear facility; therefore, there are some non-trivial aspects of their implementation. For implementation of geological disposal facilities the main issues are the need to fulfil requirements related to post-closure safety as early as the construction of the facilities, and the potential challenges of having rock excavations ongoing in parallel with waste disposal operations. Swedish regulations do not explicitly take into consideration these cases, but they are designed to facilitate their application to geological disposal facilities when combined with facility-specific licence conditions issued before and during the phases of construction, trial operation, routine operation and closure of a disposal facility. Conflicting requirements from nuclear activity regulations and conventional regulations are solved by the authorities on a case-to-case basis, where the licensees always retain responsibility over the nuclear safety and radiological protection of their facilities.

Swedish regulations do not envisage requirements on the siting of a geological disposal facility. However, to prepare the environmental impact assessment (EIA), the applicant is required to conduct a public consultation process involving concerned stakeholders, i.e. members of the public, local and regional representatives, competent authorities and non-governmental organisations. Similarly, Swedish regulations require geological disposals to be based on a system of passive barriers that by definition should not need performance monitoring and environmental control after closure. This is also one of the prerequisites for the termination of a license for a geological disposal, where the Swedish state releases the licensee of further responsibilities on the basis of demonstration of post-closure safety commensurate to the radiological hazard of the waste.

Management and disposal of nuclear waste from operation and decommission of nuclear reactors and other nuclear facilities, as well as of institutional waste, is a long-term commitment that involves several generations. In this context, Sweden set up a national framework in the mid-80s for which the cornerstones are RD&D on geological disposal facilities and financing arrangements to cover all the waste management costs. The Swedish legal framework provides preconditions to ensure that the regulatory authority has the human and financial resources necessary to fulfil its obligations. The legal framework also requires licensees to provide for and maintain adequate financial and human resources to fulfil their obligations, subject to review by the regulatory authority.

Licensing and operating a geological facility in Finland

Ari Luukkonen – STUK, Finland

The Finnish government set a time schedule for spent nuclear fuel disposal with a policy decision in 1983. From 1983 to 2000 geological investigations were undertaken to find and select suitable disposal site. Based on Decision in Principle (DiP) applications and EIAs, the government made DiPs in 2001 and 2002 on a spent fuel repository (SFR) to be built in Olkiluoto. The first DiP covered the spent nuclear fuel inventory originating from the

operating four nuclear power plant units and a licence to construct an underground rock and characterisation facility (URCF). The latter was an extension to include the Olkiluoto 3 Nuclear Power Plant. Before the governmental DiP Eurajoki municipality accepted the project. The DiP's were ratified by Parliament in 2001 and 2002.

The Radiation and Nuclear Safety Authority (STUK) published its first detailed safety regulations regarding a SFR in 2001. For Posiva (the licensee) the forthcoming 15 years were intensive, confirming site investigations (including underground investigations). STUK oversight covered among other things site investigations, concept development work and construction of the URCF. In accordance with government policy, Posiva applied for a construction licence for the SFR at the end of 2012, and the license was granted by the Finnish government in 2015.

STUK's role in nuclear facility licensing is strictly related to nuclear safety, security and safeguards. Other important authorities include the Ministry of Employment and Economy (licensing preparations), the Ministry of the Interior (security, rescue), the Ministry of the Environment (conventional construction regulations), the Ministry for Foreign Affairs (nuclear non-proliferation) and Eurajoki municipality (non-nuclear planning, construction).

Posiva is currently preparing to start the SFR construction activities. At the same time STUK is drafting a new regulatory guide for SFR oversight. Both of these undertakings are scheduled for the end of 2016.

In accordance with government policy, Posiva aims to file its operating licence application (OLA) for the SFR by the end of 2020. However, according to Posiva's current plans the licence application will be updated with supplements which should be finalised by 2022. In the OLA phase, STUK's main tasks will be reviews of Posiva's final safety analysis report (FSAR) and post-closure safety case, and on giving its safety evaluation report on the OLA. Subsequently, it is also highly likely that STUK will update regulatory guides regarding the SFR operational activities.

Monitoring of deep geological repositories

Gloria Kwong – NEA

Monitoring of geological repositories in most NEA member countries is planned for the pre-operational, operational and post-closure phases. In most cases, monitoring is carried out for the following purposes:

- to better understand how the repository will evolve and to confirm that the repository is performing as expected;
- to verify that the repository is capable of safely managing the emplaced radioactive waste over its long design lifetime, i.e. to demonstrate compliance with regulatory requirements;
- to assist in the decision-making process by presenting the necessary site-relevant information to various stakeholders.

An NEA report titled *Preservation of Records, Knowledge and Memory Across Generations: Monitoring of Geological Disposal Facilities – Technical and Societal Aspects* (NEA, 2014) presented the technical aspects of monitoring and explored the needs and expectations of local communities with respect to monitoring. This report summarises the current status of monitoring as follows:

- Certain monitoring activities shall begin at the early stage of site investigation to obtain a good understanding of the natural, undisturbed environment for establishing the baseline of the disposal system.
- Long-term monitoring of a geological repository faces various technical problems and uncertainties, although monitoring techniques and equipment currently exist; continuous R&D efforts (particularly long-term full-scale demonstrations) remain necessary.
- An effective monitoring programme for geological repositories shall ensure a safe working environment during the construction, operation and pre-closure periods.
- Post-closure monitoring is still being discussed in many member countries as most programmes are designing their disposal systems to retain their passive safety functions without reliance on monitoring.
- During the post-closure phase, some forms of oversight will be required, e.g. in maintaining records and memory of the site. The concept of oversight was outlined in ICRP 122, which addresses both long-term monitoring and preservation of records, knowledge and memory.
- Oversight can be exercised not only through technical parameters and administrative provisions but also through monitoring agreements made with the local hosts and other stakeholders.

Reference

NEA (2014), *Preservation of Records, Knowledge and Memory Across Generations: Monitoring of Geological Disposal Facilities – Technical and Societal Aspects*, NEA/RWM/R(2014)2, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19442.

Key findings of the MoDeRn project and overview of the Modern2020 project

Johan Bertrand – Andra, France

This paper provides an overview of the MoDeRn project's main goals and results and introduces the Modern2020 European project, which continues the work on monitoring aspects for geological repositories.

MoDeRn has progressed on both the associated process issues – why to monitor, how to develop a programme and how to use monitoring results – and technology issues – technical requirements and constraints, technology state of the art, and focused R&D and *in situ* demonstrators. To achieve progress on process issues, the basis for a structured development of monitoring programmes was established, focused on justifying and proposing key objectives, how to attain them and how to use monitoring results to assist decisions of disposal process management. Their application was tested through developments of case studies in various host rocks. Furthermore, the results of a focused sociological study provide a basis for associated stakeholder engagement activities as well as a better understanding of whether and how monitoring will contribute to enhancing confidence in and acceptance of the disposal process.

Initiated in June 2015, the Modern2020 project aims at providing the means for developing and implementing an effective and efficient repository operational monitoring programme, taking into account the requirements of specific national programmes. The work allows advanced national radioactive waste disposal programmes to design monitoring systems

suitable for deployment when repositories start operating in the next decade and supports less developed programmes and other stakeholders by illustrating how the national context can be taken into account in designing dedicated monitoring programmes tailored to their national needs. The work is established to understand what should be monitored within the frame of the wider safety cases and to provide methodology on how monitoring information can be used to support decision making and to plan for responding to monitoring results. R&D aims to improve and develop innovative repository monitoring techniques (wireless data transmission, alternative power supply sources, new sensors, geophysical methods) from the proof of feasibility stage to the technology development and demonstration phase. Innovative technical solutions facilitate the integration and flexibility of required monitoring components to ease the final implementation and adaptation of the monitoring system. Full-scale *in situ* demonstrations of innovative monitoring techniques will further enhance knowledge on the operational implementation of specific disposal monitoring and will demonstrate the performance of the state of the art, innovative techniques and their comparison with conventional ones.

Finally, Modern2020 has the ambition to effectively engage local citizen stakeholders in the R&D monitoring activity by involving them at an early stage in a repository development programme so as to integrate their concerns and expectations into monitoring programmes.

Monitoring requirements for the management and storage of transuranic waste at the Waste Isolation Pilot Plant

Jonathan P. Walsh – US EPA

The Waste Isolation Pilot Plant (WIPP) is a deep geologic repository located in New Mexico for disposal of defence-related transuranic waste. It is operated by the US Department of Energy (DOE) and its contractors. The US Environmental Protection Agency (EPA) regulates radionuclide emissions from the facility both during management and storage activities (the operational phase of the repository) and disposal (after the shafts are sealed). During the operational phase, the EPA requires monitoring activities for two purposes: to demonstrate compliance with applicable public dose limits, and to collect data to confirm that the technical basis of the performance assessment remains valid. For the purpose of demonstrating compliance with the public dose limits during operation, the DOE must sample radioactive emissions from the facility and model potential public dose. Sample collection, radiochemical analysis and modelling are performed using EPA-approved methods. All facility air emission points are sampled continuously, and environmental air, soil, water and biota are sampled as a confirmatory measure. Additionally, the EPA certifies the ability of the WIPP to meet long-term performance requirements after closure, based on performance assessment modelling. As part of the certification process, the DOE and the EPA agreed to disposal system parameters that are relevant to the facility's performance, to be monitored both during and after facility operation. This monitoring programme includes measuring parameters related to the underground excavations' geomechanical behaviour, the chemistry and flow of the overlying aquifer, and subsidence of the ground surface, and using databases to precisely record regional well-drilling activities and the components of the waste that has been emplaced in the repository. The results of all monitoring programmes are reported to the EPA, which inspects their implementation annually. Because the EPA's disposal regulations prioritise waste containment, direct monitoring of the underground will not take place after the WIPP is closed and the shafts sealed. Surface-based monitoring will continue until the DOE has demonstrated to the EPA that the system is stable and there is no benefit from further monitoring activities.

Safety case communication

Gloria Kwong – NEA

A safety case for a deep geological repository presents the scientific evidence and analyses to demonstrate the safety of a repository. The compilation of a safety case is a highly technical undertaking involving a number of scientific disciplines and analyses that could be unintelligible to a typical “stakeholder”. Yet it is the stakeholders and public that will be asked to accept that a proposed repository will be safe during their lifetimes and long after. Recognising the fact that many NEA member countries are facing the challenge of communicating scientific results with non-technical stakeholders, the NEA Integration Group for the Safety Case (IGSC) formed a working group in 2014 to address the challenge of communicating highly technical information to less technical stakeholders. A report collating the lessons learnt and insights gained to date from existing experience was published in 2017 to guide ongoing stakeholder communications efforts by implementers and regulators.

In discussing technical issues with public stakeholders, the report suggests beginning with an explanation of the national regulatory framework for ensuring safety, including defence in depth and emergency preparedness, to demonstrate the completeness of the regulatory process and to build public confidence in the regulator’s competency. Presentation materials should be tailored to engage the audience considering their education levels, interests, risk perceptions and preferred methods of reviewing information. Tools such as photos, diagrams and animations are effective in illustrating the complex, long-term process of repository evolution. In dealing with critical observations, it is important to understand the emotion behind the issue(s) and recognise that stakeholders may have a different concept or definition of risk than technical experts or regulators. Then when communicating about risk, being honest about the inherent uncertainties and presenting information in an uncomplicated and open manner can help build the public’s trust as well as increase receptivity to understanding and discussing issues constructively. Communication is an interactive process and can be a complex and challenging task. Both implementers and regulators therefore ought to be involved in stakeholder outreach and dialogue. When conveying complicated or technical information to the public, clear, accurate and accessible information without minimising or exaggerating issues is considered necessary and practical.

In illustrating how to communicate measures used to support repository safety in a safety case, the report discusses the use of indicators and repository monitoring in communicating a safety case. Monitoring may consist of qualitative and quantitative parameters and can be an effective means of addressing public concerns. Clear rules governing the planning and performing of monitoring, as well as results sharing, will limit potential distrust of information. Indicators can provide additional assurances of repository performance. Engaging the public in developing the use of indicators or assisting non-technical audiences to understand the applications/interpretations of different indicators and monitoring results could enable local communities to better appreciate the functions of the engineered barriers and the repository system.

The report concluded that for effective communication among stakeholders, there are clear benefits for technical experts to hone their communication skills and communication experts to be integrated into the repository development process. As all effective communication requires trust, building trust with stakeholders is a key requisite for effective communication with the public.

Reference

NEA (2017), *Communication on the Safety Case for a Deep Geological Repository*, NEA No. 7336, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_15032.

Post-closure safety requirements and their implication on operation and operational safety

Kristina Skagius – SKB, Sweden; Barbara Pastina – Posiva Oy, Finland

Both Posiva in Finland and SKB in Sweden are planning to build a repository for spent fuel according to the KBS-3 method. Spent fuel will be encapsulated in copper canisters and then disposed of at depth in the bedrock. The engineered barriers are the canister itself, the bentonite buffer surrounding the canister, the deposition tunnel backfill and closure structures.

As other nuclear engineering projects, a geologic repository for spent nuclear fuel is managed through different types of requirements, e.g. radiation safety, nuclear safety, safeguards, as well as a special category of requirements related to post-closure safety. Post-closure safety requirements apply to the long-term performance of the geologic repository and, in some cases, they could be in conflict with operation and operational safety requirements. For example, the use of cement is standard practice in most engineering projects but cementitious materials can have a negative impact on the clay components of a KBS-3 geologic repository, hence its use is limited. Another example of a conflicting requirement is the use of rock reinforcement for operational safety, which adds complexity to the predictions of the performance of the engineered barriers.

The different types of requirements need to be managed through a requirements management system, which records the origin of each requirement (e.g. post-closure safety vs. operational safety), its justification and links the requirement at hand to the requirements (or the constraints) set to different components. Requirements need to be organised in a hierarchical and structured fashion illustrating the requirements verification process and to provide transparency and traceability. Requirements verification is particularly challenging for post-closure safety due to the long time periods considered. Verification of post-closure safety requirements thus relies heavily on design requirements that can be verified during repository construction and operation.

The implementation of a requirements management system is particularly important as the implementation phase approaches; this is when both the designs and the requirements need to be optimised for sustainable implementation. To manage design or requirements changes, a robust change management process is also needed to ensure that the system fulfils the different safety requirements at any given time.

Different types of requirements, including post-closure safety requirements, should be prioritised and balanced to avoid jeopardising post-closure safety in favour of facilitating the construction and operation of the repository and vice versa. Different optimisation possibilities should be assessed through a risk/cost assessment addressing the entire operational period of the repository (which can span 100 years or more) and the impact on the fulfilment of the different types of requirements.

Operational safety and long-term repository safety: Swiss programme approach

Tobias Steinbach, Jürg Schneider, Piet Zuidema – NAGRA, Switzerland

A number of important steps have been taken in Switzerland to ensure the safe management of radioactive waste and to implement the necessary disposal facilities. The feasibility of

safe long-term disposal of all wastes arising in Switzerland in deep geological repositories has been demonstrated in so-called *Entsorgungsnachweis* projects and was confirmed by the federal government. Over the past several years, the main activities in the Swiss programme have been focused on site selection. The process of site selection is set out in the conceptual part of the Sectoral Plan for Deep Geological Repositories [available in English from the Swiss Federal Office of Energy (SFOE)], which specifies that the selection of sites for geological repositories in Switzerland is to be conducted in three stages.

The Swiss waste management concept assumes two deep geological repositories, one for low- and intermediate-level waste and one for spent fuel, vitrified high-level waste and long-lived intermediate-level waste with the option to dispose all types of waste in one repository, the so-called “combined” repository. The proposed design concepts are based on the requirements in the nuclear energy legislation that long-term safety is to be assured by a system of multiple passive safety barriers. The barriers are the waste matrix, the disposal container, the backfilling of the underground disposal rooms, the backfilling and sealing of the underground structures, the host rock with its confining units and the overall stable geological situation. The barriers ensure physical separation of the waste from the human environment, long-term stability, containment of the radionuclides, delayed release of nuclides and nuclide retention in the near-field and the geosphere, thus ensuring low release rates and low doses.

Although the start of the operation of the repository is still far away, there is a need to provide qualitative and quantitative analyses with respect to operational safety, already in the phase of site selection. The applied methodology to assess risk and safety starts with the analysis of initiating events. The so-called resulting hazards can lead to specific hazard states that potentially can cause specific consequences for the different types of damage. The types of damage considered are nuclear safety (operational phase), conventional health and safety as well as impact on environment. Measures to prevent and/or mitigate undesirable effects are identified on different levels (i.e. for initiating events, hazard states, damage states and consequences). For example, nuclear safety is ensured by the selection of an adequate site (e.g. to exclude/minimise external events), the design of the facilities (e.g. limitation of drop heights, fire protection), safety barriers (e.g. robust disposal canister and transport casks), operation procedures (e.g. temporal separation of “simple” procedures) and suitable waste properties (e.g. ensured by waste acceptance process and WAC).

Operational safety and long-term repository safety: French application to the Cigéo project

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Cigéo is the French acronym used to describe a deep geological repository for long-lived high- and intermediate-level radioactive waste that is being currently designed in France. The geological disposal facility project for HLW and LL-ILW complies with Article L542-1 of the French Environment Code, which stipulates that “research into, and implementation of the required means for the safe disposal of radioactive waste must be undertaken (...) with a view to precluding or limiting the burden placed on future generations.”

Passive post-closure safety is a specific Cigéo project feature that reflects this requirement. Implementation of these passive measures relies heavily on the favourable properties of the Callovo-Oxfordian (“clay rock”), which have been studied for a number of years, particularly by the Meuse/Haute-Marne Centre.

Research undertaken since 1991 on disposal in deep geological formations aims to achieve the objective of “precluding or limiting the burden placed on future generations.” Safety iterations were implemented as of this date, based on the acquisition of phenomenological

knowledge, the development of methods appropriate to deep geological disposal, and R&D on technological solutions. Cigéo entered in industrial design development as of 2011, is set to be commissioned around 2030 and will be operated for +100 years.

The design of Cigéo fulfils both operational safety functions (contain radioactive substances, limit dose rate, avoid criticality, avoid heat accumulation, ...) and post-closure safety functions (limit the transfer into the biosphere of the radioactive substances and toxic elements in the waste by preventing the circulation of water; restricting the release and immobilising of radionuclides and toxic elements and delaying and reducing migration). In that context, a requirements management tool integrating operational and post-closure functions and related requirements has been developed and will help to follow the compliance of design to the requirements.

At the assessment stage, the aim is to demonstrate that the design options satisfy the safety functions, by means of the safety analysis relative to facility operating, based on a risk analysis and, where appropriate, the implementation of the prevention and protection measures required to reduce the risks identified. The post-closure safety analysis, based on an analysis of post-closure uncertainties by means of qualitative safety analysis which identifies and assesses, for each individual component, the uncertainties regarding the evolution of repository behaviour to ensure that they are covered by design options or in the scenarios (normal evolution, altered and what-if scenarios considering the potential dysfunction of disposal system components).

At the end, based on the safety assessment, both the most important components and related characteristics are identified in accordance with post-closure and operational phase during the design of Cigéo. A key part is the identification of the post-closure most important component in view of putting relevant efforts on them at the subsequent stage of the development of the project as well as identifying the control/monitoring activities to be conducted during construction and operation in line with post-closure safety functions and requirements. These important components depend on the site context. For instance, in the case of Cigéo, due to its intrinsic geometric and physicochemical characteristics (more than 300 m deep, more than 130 m thick, low permeability, high retention capacity, low diffusion coefficients, etc.), the Callovo-Oxfordian formation in which Cigéo will be built is the chief component that will ensure post-closure passive safety and for a very long time after. The adopted design measures, in particular in terms of Cigéo's general architecture, leverage the favourable characteristics of the Callovo-Oxfordian formation as for instance its dead-end architecture that restricts flows within the repository by preferably utilising the low flows in the Callovo-Oxfordian formation. Due to their specific position at the repository outlet, the seals on the surface-bottom connection structures play, along with the Callovo-Oxfordian formation, the most important role in the long-term post-closure safety of the repository.

Evolution of the layout of the Belgian geological repository to improve the operational safety

William Wacquier, Didier Raymaekers, Christophe Depaus – ONDRAF/NIRAS, Belgium

In Belgium, the legislature entrusted the management of radioactive waste to a public institution with legal status: the National Agency for Radioactive Waste and Enriched Fissile Materials, known by the French/Dutch acronym ONDRAF/NIRAS.

No institutional policy has yet been formally approved in Belgium for the long-term management of existing and planned Category B and C waste.

Nevertheless, in accordance with the legal framework, ONDRAF/NIRAS has taken the initiative to develop solutions for a geological repository in poorly indurated clay and to demonstrate the feasibility of this repository.

Several studies have been performed in order to increase the level of details in the planned construction and operation of the repository and to solve or minimise open issues with regard to the feasibility to construct, operate and close the facility in a safe manner and within budget commensurate with the nature of the task.

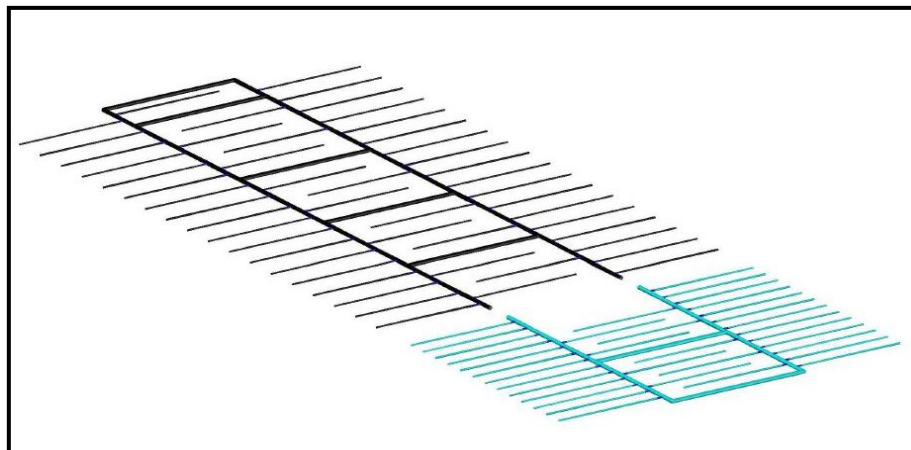
Recently remarks have arisen at ONDRAF/NIRAS regarding how operational safety requirements or future regulatory requirements might demand changes to the reference layout of the repository. Most of these remarks were formulated by an independent peer review of the design (SYNATOM, 2012) and during a hazard identification (HAZID) study on the repository construction (Tractebel and Andra, 2016).

Consequently, ONDRAF/NIRAS took the decision to launch an underground layout optimisation study with the aim to evaluate all potentially suitable layout options in regard to operational safety and their ability to adapt to possible future regulatory requirements.

A new layout, with a U-shaped access gallery connected to intermediate crossing passages, centralised shafts and disposal galleries limited to 400 meters, had emerged from this study (Figure A.1) (ONDRAF/NIRAS, 2016).

The next step, planned for 2016, is to finalise and fix this new layout (position of the shaft, space needed for the equipment, final diameter of the galleries, possibility to install seals, ...).

Figure A.1: New reference layout for the Belgian geological repository



Source: Depaus (ONDRAF/NIRAS), 2016.

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