3. ENGINEERED BARRIER SYSTEMS; THEME OVERVIEW

Develop an engineered barrier system, tailored to the characteristics of the waste and compatible with the natural (geological) barrier, that performs its desired functions for the long-term disposal of radioactive waste.

Deep geological repositories for the disposal of radioactive waste generally rely on a multi-barrier system to isolate the waste from the biosphere. This multi-barrier system typically comprises the natural geological barrier provided by the repository host rock and its surroundings and an engineered barrier system (EBS). This multi-barrier principle creates an overall robustness of the system that enhances confidence that the waste will be successfully contained, as the natural barrier provides a stable environment that allows the EBS to function for hundreds to many thousands of years, depending on the disposal concept. The EBS is defined as a system of man-made components including the the waste canisters, the disposal containers, the buffer, the backfill, the repository seals and other engineered features. Some waste form itself can be regarded as a part of the EBS when the waste material has been specifically conditioned for disposal (e.g., by incorporating it in a cement matrix). Other waste forms cannot be significantly processed or conditioned for disposal (e.g., direct disposal of spent fuel or non-conditioned bulky items) and are thus not regarded as part of the EBS. Although their properties (e.g., corrosion resistance) could contribute significantly to overall safety, although no safety function can be specified for them.

For a given national programme, and depending on national policy, there will be a number of different waste forms considered for disposal, including vitrified high-level waste and spent fuel, intermediate level reprocessing, operation and decommissioning waste, low level waste of different types, legacy waste and more. Waste may be immobilized in a glass, cement or bitumen matrix. The waste or waste form may be pre-packaged in concrete, steel or bituminized waste packages. A given national programme may also select host rocks of different characteristics for the repository. Since the EBS should be tailored to the characteristics of the waste and be compatible with the natural (geological) barrier, there will be a significant number of different options and combinations of engineered barriers selected for use in disposal facilities in each country.

Typical barrier types are:

- Waste forms;
- Waste form package materials;
- Containers, canisters, overpacks (e.g. metal, concrete, ceramic);
- Buffers, backfills and seals (e.g. bentonite, cementitious-based materials, crushed rock);
- Vaults, liners and other structures and ‘simple’ barriers (e.g., concrete, grouts, gravel).

The selection of barriers results in an optimisation process including (See, also Concept Selection):

- The quantity, type and condition of waste – radiotoxicity, quantities and volumes, chemical and physical characteristics, and thermal load.
- The geological setting and type of host rock – available rock volume, hydrogeological and chemical environment, thermo-hydro-mechanical stability, and mechanisms for fluid and solute transport properties (hydrogeological).

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- The safety concept defining the long-term safety functions attributed or derived – the ways in which the multiple barriers can help prevent or limit the release of radionuclides and their migration to the surface environment.
- Compatibility of barriers – potential detrimental impacts of one barrier on another are minimised, including the impact of the EBS and its evolution on the properties of the host rock.
- Operational feasibility and safety requirements – working with reliable and tested technologies or new technologies based on qualification tests.

The overall safety objective of a geological repository is the protection of human health and protection of the environment. The various components of a multi-barrier system contribute to fulfilling this high-level safety objective in different ways and over different timescales. Each of the engineered barriers possesses a set of safety functions, which set out what the barrier component should achieve to ensure safety. Safety functions are associated for a specific period of time and are translated into performance targets and design requirements. Examples of barrier safety functions expressed in required properties and/or parameters that contribute to (generic) safety functions are:

- CONTAINMENT – complete containment for a given time. Provided by metal containers and can be expressed in terms of corrosion and mechanical properties (See, 3.2.1 High level waste and spent fuel disposal containers).
- CONTAINMENT – hydraulic barriers, limiting advective transport (diffusion control). Provided by clay barriers and to some respect concrete barriers under some circumstances. Can be expressed in terms of hydraulic conductivity and self-sealing ability.
- RETENTION AND RETARDATION – low diffusivity barriers. Provided by concrete barriers and to some respect clay barriers. Can be expressed in terms of diffusivity.
- STABILITY – the disposal system is robust to possible disturbances and perturbations, e.g., limiting microbial activity in the repository. Provided by clay and concrete barriers and can be expressed in terms of dry density/swelling pressure or pH control respectively.
- STABILITY – mechanical barriers, that gives mechanical support to other barriers (typically the host rock). Provided by clay and concrete barriers (and crushed rock backfill, if it has a stability role) and can be expressed in terms of swelling pressure or strength.
- CONTAINMENT, RETENTION AND RETARDATION – chemical barriers that limit the corrosion of containers and waste forms and enhances sorption of radionuclides. Provided by concrete barriers and can be expressed in terms of pH-control.
- CONTAINMENT – hydraulic cage barriers, which diverts the groundwater from the waste vault. Provided by gravel or other permeable materials. Can be expressed in terms of (high) permeability.
- IMMOBILISATION – waste forms like glass or spent fuel with radionuclides embedded in a sparingly soluble solid matrix showing only very slow dissolution rates in case of groundwater/pore water access, immobilising a large part of its radionuclide inventories for many tens of thousands to millions of years.

Based on the desired safety functions appropriate engineered barriers can be selected for a given waste form and a given host rock. It should be noted that many safety functions are common between repositories, even if the host rock or the waste form may differ. The emphasis and requirements on the safety function may however be different.

KEYWORDS: Disposal System, Waste Packaging, Disposal Container, Canister, Insert, Source Term, Wasteform, Encapsulant, Buffer, Backfill, Plug, Seal, Liner, Near-field, Containment System, Cement, Concrete, Bentonite, Organic Polymeric, Bitumen, Ceramic, Coating.

KEY ACRONYMS: EBS – Engineered Barrier System; DGR – Deep Geological Repository; SNF – Spent Nuclear Fuel; HLW – Vitrified High Level Waste; LL-ILW – Long-lived Intermediate Level Waste.

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TYPICAL ENGINEERED BARRIER SYSTEM GOALS PURSED BY NATIONAL RWM PROGRAMMES

This section provides a goals breakdown structure (GBS) for the EURAD roadmap theme 3 on engineered barrier systems. It is organised in a hierarchy of three levels according to theme > sub-themes > domains.

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<tr><td rowspan="2">3.4 Confirm integrated EBS system understanding and identify compatible EBS designs and materials for facilities containing multiple wasteforms (EBS system integration)</td><td>3.4.1 Confirm complete and integrated EBS system understanding, including the design of an optimized interface EBS/repository and the understanding of the interaction with the repository nearfield environment (EBS system)</td></tr>
<tr><td>3.4.2 Confirm that interactions between different EBS materials in disposal areas for different waste types do not compromise the performance of the disposal system (Co-disposal)</td></tr>
</table>

ENGINEERED BARRIER SYSTEM ACTIVITIES IN A DGR PROGRAMME

This section describes the activities that are required to achieve the generic goals in theme 3 on engineered barrier systems.

3.1 Confirm waste form compositions, properties and behaviour under storage and disposal conditions, including radionuclide immobilisation and impact on the disposal environment (Waste forms)

A good understanding of the available waste forms is crucial before the selection of engineered barriers can be made:

- Most important is the inventory of radionuclides, since this will determine the timescale needed for repository performance, as well as the heat generation.
- The total volumes of a particular waste stream have a significant impact on the choice of EBS in terms of. Metal containers are typically not feasible for high-volume, low-level waste, both from manufacturing and cost implications.
- The physical and chemical characteristics of the waste forms, including waste packages, are needed to ensure that the selected EBS will be compatible, geometrically and chemically, with the waste form.
- The dissolution rate of the waste form matrix in groundwater/pore water and the release rate of radionuclides and potential secondary phase formation under realistic disposal conditions.

For most waste forms, this information will be available from the waste producers. There may however be uncertainties, especially regarding waste from ongoing nuclear operations (i.e. future waste arisings) as well as from poorly documented legacy waste.

A good starting point for the repository design are the generic designs, developed in other national programmes, conceptual designs for siting, technical design for initial construction licensing, towards detailed design for construction, operation, expansion, and closure, provided by the IAEA [1], [2]. The design of each disposal system shall be tailored to the characteristics (physical and chemical form) and volume of the waste inventory destined for disposal, together with the characteristics of the geological environmental at the site of the disposal facility. The overall layout of the underground facilities should be developed by using criteria for maintaining the favourable properties of the selected host rock and its integrity. In case of vertical borehole disposal for example, the distance between the deposition tunnels needs to be adjusted so that the maximum temperatures in the deposition holes remain at an acceptable level.

In this regard

- A first step in designing a repository are the decisions upon suitable disposal options like vertical or horizontal borehole disposal or drift disposal and the definition of design requirements related to the chosen disposal option. At this point, there is a link to roadmap domain 1.5.2 (Options and Concept Selection) dealing with identification and selection of appropriate disposal concepts for the national radioactive waste inventory. The facility design needs to be tailored to the corresponding disposal technology and thus to the necessary transport and handling equipment. In case of a vertical borehole disposal option, for example, the necessary volume of drift excavation is significantly different compared to a horizontal drift disposal option. The space necessary for a displacement machine manufactured for vertical borehole disposal is the determining factor. With regard to the transport equipment the decision whether to use shafts or ramps for waste transport to the underground facilities should be made at an early point in the programme since both, the design of the transport equipment/routes and the hazards assessment are completely different.

- Another important step is to think about geotechnical barriers. The development and description of the design basis is an important aspect. This includes the definition of safety functions, performance targets and design specifications. Work on the design basis in the European DOPAS project has allowed assessment of current practice with regard to both the process used to develop and describe the design basis and the content of the design basis [5], [6], [7].
- Programmes considering reversibility and retrievability have to make sure that the facility design is tailored to the corresponding needs with regard to space, transport routes, waste handling, and radiation protection.
- Facility design, especially for clay and salt rock environments, needs to be adapted to the depth level and the stress situation in the rock respectively. The design (thickness, stiffness, etc.) of the drift, shaft/ramp support strongly depends on the rock stress field and the convergence behaviour of the host rock. The repository depth needs to be decided as early as possible as it affects the design and construction of the access routes.
- An important issue for the facility design is the role of the canister and the engineered barrier system within the safety assessment. If for example the canister is designed to act as the main barrier [3], the role of plugs and seals in drift and shafts/ramps are limited with regard to the long-term safety. If the canister is assumed to fail at some point in time then the safety assessment needs to rely much more on the other geotechnical barriers like buffer, backfill, as well as plugs and seals. That means the facility design should be developed in relation to the safety assessment concept.
- From the safety assessment, necessary design specifications for individual geotechnical barriers can be deduced in order to meet their safety function(s). Facility design should include potential locations for plugs and seals, at best selected by a transparent methodology using selection criteria tailored to the host rock. An example for crystalline rock is given in [4].
- Programmes shall ensure that the design of the disposal system, including waste handling and emplacement as well as retrieval equipment continues to be refined and optimised during the operational phase. Barriers and seals for repository closure are to be checked continuously for potential optimization needs. Conceptual models and computational models of the geosphere, biosphere, and engineered systems are to be updated and refined during the construction and operation activities.
- In general, programmes should establish an iterative process for design development using a systems integrated approach linked to the steps and major milestones of the national programme implementation plan. Milestones related to facility design might be:

    - Establishing a requirements management system (see domain 1.2.6 Requirements Management) and development of a safety concept,
    - selection of a disposal option (see domain 1.5.2 Options and Concept Selection),
    - application of a safety assessment concept based on the disposal option(s),
    - based on the first three bullets: definition of design requirements for the underground facilities, the canister, the handling and transport equipment, and the geotechnical barrier system including safety functions and performance targets,
    - layout of the underground facilities including the geotechnical barrier system based on the design requirements.

- Based on the current knowledge and knowledge gaps, the implementer should develop an overarching R&D plan for repository implementation (see domain 1.25 RD&D Strategy).

5.2 Demonstrate and verify that facility components and geotechnical barriers can be practically manufactured, constructed and installed in accordance with detailed design requirements and specifications (Constructability, demonstration and verification testing)

An important issue is to demonstrate that all necessary repository components can be constructed properly and that the allocated safety function(s) can be met.

In this regard

- Programmes shall use available and mature technologies and well-tried materials, components and systems as far as possible in order to minimise project risks.
- Programmes are required to demonstrate that detailed designs of repository equipment and technical components can be constructed and operated safely during construction, operation, and closure.
- It cannot be excluded that new machines need to be developed and prototypes be built depending on the disposal and barrier concepts. The implementer needs to consider that new machines need to be qualified and approved, which may need a lot of time. Development and tests of machines and prototypes need to be planned and performed as early as possible since this may take a lot of time as well.
- The methods and the ability to produce the disposal facility and its components according to the design requirements and design specifications must be demonstrated.
- One important aspect to be considered when constructing the repository is that due to excavation activities an excavative damage zone (EDZ) will occur, which might act as a preferential pathway for radionuclide migration. The extension of the EDZ depends on the host rock as well as on the excavation method. Excavation technologies shall be tested and evaluated with respect to their impact on EDZ extensions and suitable technologies for the considered host rock shall be selected. A good description of EDZ aspects in crystalline rocks are compiled in [8]. From the large European project NF-PRO significant insights have been gained for EDZ evolution in other host rocks as well [9].
- One way of demonstrating the constructability of facility components and geotechnical barriers in particular is the use of an Underground Research Facility (URF). The implementer shall consider the construction of an URF in a similar rock body compared to the selected host rock or as part of the planned repository in a designated area. This kind of facility is built and operated for the primary purpose of obtaining data and information from in-situ experiments and investigations to support the development and implementation of a DGR programme, or to acquire a more detailed general understanding of a deep geological disposal concept, for long-lived intermediate or high-level radioactive waste. To that effect, these facilities are used to:

    - develop the technology and methodology required for underground experimentation
    - provide data to understand the behaviour and assess the performance of the repository system and of its interactions
    - demonstrate the robustness of the design and to show the potential areas of optimisation of engineering components and processes
    - train personnel for safe operation of a repository
    - build confidence with stakeholders for their understanding of the important processes governing repository performance

An alternative option would be the use of existing URF around the world.

- Whether or not the implementer considers the use of an URF, the implementer in particular must verify that the defined reference designs of the canisters and of all the geotechnical barrier components are in line with the design specifications. An example regarding the canister can be found in [10]. In that sense, an absolute necessity is the development of an adequate quality assurance programme tailored to suitably verify the correct implementation of each individual component. This implies possibilities to find potential manufacturing or installation errors or other deviations in material, equipment and handling. Establishing and qualifying all aspects of the quality control system is a considerable undertaking, as many of the quality needs and requirements will be unique for the repository.

- In addition to the qualified production, the implementer has to demonstrate the functionality for long-term safety as it is specified in the safety case (See 7 Safety Case). That means programmes need to confirm that structures, systems and components will perform their allocated safety function(s) for the duration of their operational lives. This leads to the necessity of a safety demonstration concept or qualification procedures to check whether the defined performance targets of the individual barriers are met right after implementation or can be achieved during barrier evolution.
- For testing and verification, the implementer shall consider the use of full-scale experiments (1:1) either in a specified test area of the repository or at an URF. A lot of experience from international URFs in Äspö (Sweden), Bure (France), Tournemire (France), Mol (Belgium), Mt. Terri (Switzerland) GTS (Switzerland), Bukov (Czech Republic) is available and published. An additional option would be the use of a specific monitoring programme as explained in section 5.5.

5.3 Prevent theft of nuclear material or sabotage of nuclear facilities and protect sensitive technology, software and information (Security and safeguards)

Repository design layout will need to consider certain activities and facilities (dedicated zones) to meet physical security, radiation protection and nuclear safeguard requirements. Recommendations specific to physical security are provided by IAEA [11].

In this regard

- In [11] it is said that “The operator […] should define credible scenarios by which adversaries could carry out sabotage of nuclear facilities and nuclear material”. Since a geological repository is seen as a nuclear facility, this needs to be addressed. The implementer should design a physical protection system that is effective against the defined sabotage scenarios and the protection system should be designed as an element of an integrated system to prevent the potential consequences of sabotage by taking into account the robustness of the engineered safety and operational features, and the fire protection, radiation protection and emergency preparedness measures.
- Any programme needs to consider nuclear material safeguards. A recent publication of an IAEA guidance was developed to assist facility designers and operators in considering at an early stage the safeguards activities relevant to particular nuclear fuel cycle facility types [12]. Safeguards should be considered early in the design process to minimize the risk of impacts on scope, schedule or budget [13], and to facilitate better integration with other design considerations such as those relating to operations including retrievability actions as well as safety and security [14], [15]. An international status of Safeguards approaches are compiled in [16].
- The operation of a repository needs to recognize the aspects of cyber security and the necessity of a cyber-risk assessment. The National Cyber Security Alliance (NCSA) recommends a top-down approach to cyber security [17]. NCSA advises that organisations must be prepared to respond to the inevitable cyber incident and restore normal operations. NCSA’s guidelines for conducting cyber risk assessments focus on three key areas:
    - identifying the most valuable information requiring protection
    - identifying the threats and risks facing that information and
    - outlining the damage that would occur should that data be lost or wrongfully exposed

5.4 Develop and maintain operational safety case to demonstrate that the construction, operation and closure of the disposal facility will meet safety standards and be robust against potential faults such that the associated risks are restricted to levels that are as low as reasonable practicable (Operational safety)

The submission and approval of an operational safety case (OSC) is a prerequisite for construction and operation of a repository. In this context, regulatory compliance activities consist of coordination of the safety case for operations and closure, and preparation of the associated license applications.

In this regard

- The implementer needs to develop an operational safety case (OSC) and needs to get an approval prior to start.
- The implementer shall conduct industrial risks assessments and needs to guarantee that occupational exposures to radiation and toxic substances will be in an acceptable level during repository construction and operation, and closure.
- Detailed quality assurance procedures related to operational activities need to be developed, implemented, and adapted during the operational phase. Staff training, health, safety, and environmental protection activities may be adapted during the construction, operation, and closure phase, with increased emphasis on worker and public safety.
- Programmes should develop a knowledge management system with regard to control activities especially related to waste handling and transport operations, waste emplacement as well as backfilling activities and the implementation of plugs and seals.
- In the recent draft of the IAEA Roadmap document [18] it is said that worker safety during construction and operation of the repository is an important aspect of a disposal programme and will be a key part of any regulatory structure. Hazard analyses shall be conducted to determine what possible event sequences (for example, dropping of waste packages followed by a container breach) could lead to radiation releases during construction, either within the confines of the repository underground or above ground, and will include analyses as to the potential impact on members of the public. Measures need to be implemented to eliminate impacts or provide a means of preventing the outcome, protecting those affected and reducing the consequences.
- In addition to analysing risks, the operational safety case needs to include a range of potential accident scenarios and the development of robust responses including mitigation options for risk reduction for identified faults.
- Last but not least, an important issue to consider is the balancing of operational safety and long-term safety, although operational safety issues are considered a lower priority. Extensive discussions on this issue are summarized in the summary record of the topical session of 10th Meeting of the IGSC in 2008 [19]. On the part of the IAEA, the idea of an operational safety case was taken forward through the international GEOSAF project [20], [21], [22]. Current results are focussing on hazards identification and assessment methodology as well as on the relationships between post-closure safety and operational safety [23].

5.5 Establish and implement an overall plan for meeting with national requirements for monitoring, and if required, reversibility and/or retrievability requirements. (Monitoring and Retrievability)

Monitoring of repositories has been attached great importance since about the turn of the millennium. On the part of the IAEA, a first document about repository monitoring was developed highlighting opportunities and goals of a monitoring programme [24]. Based on that, the European Thematic Network (ETN) project [25] was launched to discuss specific aspect of monitoring high-level waste repositories. In the year 2011, the IAEA started to set the issue of monitoring into the context of the safety case and developed a document about specific safety requirements (SSR-5) [26]. In the following years, monitoring activities became more and more important. In this regard, a groundbreaking project was initiated and funded by the European commission, which was called the MoDeRn project [27]. As a result of this project, a reference framework [28] for the development and implementation of a monitoring programme for high-level waste repositories was presented and first approaches for involvement of stakeholders were discussed. This reference framework provides the so-called “MoDeRn-Monitoring-Workflow”, which can be seen as a first guidance for the development of a monitoring programme.

In permanent exchange with the MoDeRn project, the “Specific Safety Guide” SSG-31 [29] was developed by IAEA anchoring the topic of monitoring as an international safety standard.

By monitoring parameters affecting safety functions of repository components it can potentially be demonstrated whether performance targets are going to be achieved.

The issue of identification of parameters worth monitoring has been set as a big task in the MODERN2020 project [30] resulting in the so-called “Screening Methodology”.

At the time of writing, the IAEA is developing a new technical document [31], a specific objective of which is to develop, how a monitoring programme is part of the decision-making in a safety case based context for the repository phases. The document as well discusses challenges and limitations of monitoring, and states that a balance has to be strived for between the request of information via monitoring and the request for passive safety of a repository.

In this regard

- Implementers are recommended to develop a monitoring programme in strong relation or as an inherent part of the safety case [28].
- Implementers are recommended to use the “MoDeRn-Monitoring-Workflow” [27] as a basis for developing a monitoring programme.
- Implementers are recommended to use the “Parameter Screening Methodology” [29] for identification of parameters worth monitoring.

In recent years, the issue of retrievability has been considered as increasingly important in a number of countries. In France and Germany for example the option for retrievability and reversibility is a legal requirement. A good overview of the issue of retrievability is given in [32] where retrievability was considered with regard to design, safety, socio-political aspects, monitoring, and safeguard. A good introduction into reversibility and retrievability can as well be found [33]. It is well accepted that a staged decision-making process in which decisions are not irrevocable would reassure stakeholder groups.

As a consequence

- Implementers are encouraged to monitoring the disposal process and to develop a disposal system enabling reversibility, if desired. For identifying the relevant parameters necessary to be monitored, the use of the above mentioned parameter screening method is recommended. If monitoring data were to indicate a failure to reach the required design specifications or performance targets, or if the data were to indicate that the repository system behave in an unacceptable way, this could bring about a need for corrective actions. The ultimate corrective action would be waste retrieval.

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FACILITY DESIGN AND OPTIMISATION ACTIVITIES OVER DIFFERENT PHASES OF IMPLEMENTATION

This section provides examples of typical actions completed in disposal facility design and optimisation, based on the experience of advanced programmes, over different phases of implementation.

Programme Initiation (Phase 1)

Programme Implementation (integrated actions in theme 5 on disposal facility design and optimisation linked to activities in other themes)

- The implementer is encouraged to apply a systems engineering approach, involving the use of a requirements management system (RMS) which is extremely important in the early stage to collect all requirements that need to be taken into account. This engineering approach needs to be linked to a work breakdown structure (WBS) to identify and organise activities, ensuring the timely delivery of outputs against project milestones (*See 1.1.1 Timetable for decision making*). In the early stages of the overall management programme, only quite general requirements can be established. As specific projects/facilities are identified, formulation of detailed requirements will develop iteratively, based on feedback from, for example, safety case development (*See 7 Safety Case*) and engineering (*See 5.1 Design specification*).
- In view of the later design and construction of the repository, regulators should start developing applicable regulatory requirements in accordance with well-accepted international bases and initiate interactions with the implementer (*See 6.3 Licensing*).
- The implementer needs to identify and understand the factors that affect the disposal programme. This includes the legal and regulatory framework, other national policies affecting the programme, available technical options (within the country and abroad) and preferences of stakeholders (*See 6.3.1 Stakeholder Involvement*).

Design

- In preparation of design activities for the repository, the implementer needs to develop preliminary repository concepts with respect to the available geological options. Repository concepts developed in other programmes should be assessed in order to identify, whether these options are likely to form a basis also in the programme under consideration or whether entirely novel concepts need to be developed.
- In preparation of design activities, criteria need to be defined to accept or reject locations to be used for disposal (at different scales)
- In view of the safety case, the implementer should develop and establish a methodology for conducting repository design layouts and compile and implement all necessary tools and information to do the work.
- Implementer shall assess the reliability of the data on the waste as a basis for any layout activities.
- Implementer shall take the properties (e.g. heat production) of the waste canisters into account and the range of possible geological disposal environments (potential host rocks like clay, salt or crystalline rock) as well as their regional extensions, and develop generic designs for safety evaluations for each of the possible geological disposal environments. The basic design layouts shall include potential disposal volumes and possible repository footprint requirements to feed into site screening and initial cost estimations.

Constructability, demonstration and verification testing

- The implementer shall evaluate the need to construct one or more URFs.

- The implementer is encouraged to consider participation in research and testing activities in already existing URFs around the world.

Security and safeguards

- A basic exercise for the implementer is to compile and understand all necessary requirements and boundary conditions with regard to nuclear material safeguards (IAEA 2018).

Operational safety

- Prepare for developing a safety programme for repository construction and an operational safety case (OSC) by compiling all necessary requirements and by screening internationally available approaches.

Monitoring and retrievability

- Clarify the necessity whether retrievability is to be considered in the disposal programme or not as this has a strong influence on the design of the repository.
- Become familiar with the way of developing a monitoring concept (MoDeRn 2013, MODERN2020 2019, and IAEA 2014).

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Site identification and selection for a DGR (Phase 2)

Programme Implementation (integrated actions in theme 5 on disposal facility design and optimisation linked to activities in other themes)

The key activity for the implementer is to plan and later implement a programme for site investigation and site selection (*See 6 Siting and Licensing*). Implementer, regulator and other stakeholders, should identify and agree the activities involved in the different steps in the site identification, site investigation and final site selection (*See 6 Siting and Licensing*).

That means:

- The implementer needs to prepare plans for site investigations. These plans should be based on safety analyses performed as part of a preliminary safety case (See 7.3.1 Quantification of components evolution). The basic design layouts obtained during Phase 1 may act as in input to the safety analyses from which those kind of information can be extracted that is of vital importance for the safety assessment and thus important to obtain during the site investigation. This ensures that the plans for site investigations focus on the most safety relevant information, which is to be seen as a first optimisation activity.

- In dialogue with the regulatory bodies and other agencies, the implementer should continue to discuss the legal requirements, including security, safeguards, occupational, safety, health and environmental regulations, that are involved in the different steps (*See 5.3 Safeguards and Security), 5.4 Operational Safety, 6.3.2 Regulatory licensing*).
- The implementer needs to continue the dialogue with relevant stakeholders to explore their concerns and to solicit their input to the site and repository concept selection process (*See 6.3.1 Stakeholder Involvement*).
- The implementer should produce the evidence needed to satisfy regulatory requirements and meet the legal permits to start investigations, provided the site identification would evolve into a site characterisation phase (*See, 6 Siting and Licensing, 7 Safety Case*).
- Regulatory agencies will have to evaluate submissions of the implementer and issue any requisite approvals to move to the next phase of work.

Design

- The implementer should develop requirements, from high level requirements to implementation-related requirements always with the verification aspect in mind. At least a preliminary set of conceptual-level requirements is needed.
- In preparation of the design of the repository, the implementer needs to develop preliminary concepts for canister designs, as this is a prerequisite for facility design and handling equipment design (See 2.2 waste package solutions and 3.2 Container materials and design).
- The implementer should develop reference conceptual designs of the different disposal systems tailored to the considered host rocks as input to safety analyses feeding final site selection.
- The implementer should develop reference designs of the surface facilities tailored to the regional possibilities.

Constructability, demonstration and verification testing

- The implementer should consider participation in research activities in already existing URFs around the world.
- Additionally, the construction of generic URFs may as well help to inform scientific understanding.
- As a third option, the implementer should consider constructing one or more site-specific URFs. It has to be noted that the construction of a URF needs to be based on a decision in principle and a license to go underground. Additionally, the implementer needs to demonstrate the ability to construct the necessary underground excavations for the URF and the later repository.

Security and safeguards

An ever-evolving field, cyber security best practices must evolve to accommodate the increasingly sophisticated attacks carried out by attackers. Combining sound cyber security measures with an educated and security-minded employee base provides the best defence against cyber criminals attempting to gain access to the implementer's sensitive data.

In this regard:

- Perform a preliminary cyber-risk assessment
- Develop and implement a plan to mitigate cyber risk, protect the most valuable data outlined in the risk assessment, and effectively detect and respond to security incidents. This plan should encompass both the processes and technologies required to build a mature cyber security program.

Safeguard measures may affect repository design. In this regard:

- While preparing for repository design activities perform a screening of existing safeguards approaches for high-level waste repositories around the world to check for their potential application or adaptation.

Operational safety

- Implementer should develop generic scenarios for operational safety assessments and discuss and agreed with the regulator for their application.

Monitoring and retrievability

- Based on the development of reference conceptual designs of the disposal systems tailored to the considered sites as mentioned above, the implementer should develop a preliminary monitoring concept (MoDeRn 2013a) related to the disposal systems. If retrievability is to be considered in the disposal process, identify monitoring needs the results of which may support decision-making with regard to the retrievability option and include this in the monitoring concept. Examples for designing a monitoring programme are given in (MoDeRn 2013b).
- As a key part of the monitoring concept, the implementer needs to identify processes and corresponding parameters (MODERN2020 2019) worth monitoring in close relation to the safety case.
- After getting a clear view of the processes and parameters to be monitored during the different phases of a repository, prepare a plan for baseline monitoring in readiness for the commencement of site characterisation.

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Site characterisation (Phase 3)

Programme Implementation (integrated actions in theme 5 on disposal facility design and optimisation linked to activities in other themes)

- The implementer has to carry out the programme for site investigation including the identification of the constraints imposed by the site, final site selection and repository concept development, leading to a construction license application (*See 6 Siting and Licensing*).
- Regulatory agencies should define procedures and requirements for any programme of review and inspection that will be carried out during the site characterisation phase.
- The implementer should update the RMS for the repository, based on the knowledge gained from the assessment of key design and safety aspects from Phase 2 (*See 5.1.1 Design specification*).
- Waste producers and the implementer should agree upon an approach to pre-disposal management of wastes to ensure eventual disposability in the emerging repository design.
- The implementer has to develop a safety case supporting the construction license (*See 7 Safety Case*). In support of the Safety Case, the implementer should update the reference repository design developed during Phase 2 and adapt it to the selected site based on information obtained during site characterisation.
- In relation to the updated design and the host rock conditions at the selected site, the implementer should develop a preliminary design layout of the engineered barrier system (EBS). This includes the identification of the potential site specific loads on the EBS (See 3.3 Material identification and 3.4 Compatible EBS designs)
- In addition to qualification measures, the implementer needs to develop a programme for repository monitoring based on the activities in Phase 2 leading to the implementation of the baseline monitoring during this phase. The regulator should approve the baseline monitoring.
- Continue the dialogue between implementer, regulatory agencies and other relevant stakeholders to explore stakeholders concerns and to solicit their input to the licensing process (*See 6.3.1 Stakeholder Involvement*).
- The implementer should develop plans for repository construction as well as plans for detailed underground investigations (*See 6.2.2 Site Characterisation*).
- The implementer should consider to implement a test facility.
- The implementer has to carry out all activities needed to prepare the necessary documents for licensing (*See 6.3.2 Regulatory Licensing*).
- Regulatory agencies to receive construction license application, review and, if approved, issue a license, with any conditions considered necessary.

Design

- The implementer needs to develop a detailed design of the underground facilities tailored to the selected site and its geological boundary conditions. The design needs to cover explicitly that (in most cases) the repository operational phase includes further construction of the repository. That means, enough transport routes need to be available to guaranty a separation of waste transport and normal mine activities.
- In parallel, the implementer needs to develop a detailed design of the aboveground facilities including an encapsulation plant.
- The design needs an decision of the kind of access routes via either shafts or ramps or a combination of both and an early communication to the regional public. This design shall be used for the license application to construct the repository.
- In addition to the underground facilities, the implementer should develop a detailed design of the surface facilities and communicate it to the regional public and stakeholders. External feedbacks should be considered and included in the designs as much as reasonable.
- Based on the underground facility design the implementer shall develop the designs for
    - waste handling equipment,

- waste transport equipment,
- waste conditioning infrastructure,
- waste emplacement equipment, and
- (if necessary) additional equipment for waste retrieval.

- In case of new and specific equipment development, the implementer must get an approval for application, which needs to be initiated at an early stage.
- In view of all the equipment, operational procedures for waste handling, transport, conditioning, emplacement, and retrieval need to be developed.
- The implementer should develop preliminary designs for the geotechnical barriers based on their designated locations in the underground facilities (White, M. & Doudou, S. 2016).

Constructability, demonstration and verification testing

- The implementer needs to develop a plan for the construction activities of the underground and aboveground facilities and discuss this plan with the regulator to get the license to go underground.
- The implementer needs to conduct tests to demonstrate and optimise construction approaches and methods in the selected host rock. A good way of doing this would be the use of a host rock specific URF.
- The implementer is encouraged to have a close look at Onkalo® which provided a lot of in-situ information on constructability, demonstration and verification of the concept.
- The implementer needs to conduct tests to demonstrate and optimise equipment for waste handling, transport, emplacement, and retrieval. In Germany, this has been done prior and in parallel to the excavation of the first repository exploration mine, which allows for extensive testing and optimization prior to application (Bollingerfehr et al. 2009).
- The implementer needs to conduct tests to demonstrate and optimise the operational procedures for waste handling, transport, emplacement, and retrieval (Nagra 2019).
- The implementer needs to conduct small and large scale tests to demonstrate and optimise the design of individual geotechnical barriers. Helpful information from the large European Sealing project DOPAS are compiled in White et al. (2016).
- Procedures of quality assurance need to be tested especially regarding the implementation of the different geotechnical barriers to evaluate the meeting of the design specifications (Posiva/SKB 2017).
- Long-term tests of the evolution of different geotechnical barriers shall be planned in detail, initiated and then performed in order to demonstrate that the designated performance targets can be met. This is especially valid for those barriers, which will achieve their full sealing ability only after longer periods of time (e.g. bentonite seals). Useful information on this topic can be obtained from the RESEAL experiment (Van Geet et al. 2005) and the PRACLAY experiment (Van Marcke et al. 2013).

Security and safeguards

- The implementer should continue and potentially update the existing cyber security programme.
- The implementer needs to design physical security measures to ensure compliance with regulatory security arrangements for transport and disposal of radioactive materials.
- Based on the design of the underground and surface facilities and the waste transport procedures mentioned above, the implementer should develop a concept for nuclear material safeguards and communicate this to the responsible authorities to get feedback (IAEA 2018).
- The implementer needs to planning the access control, identification of personnel that goes in and out.

Operational safety

- Following the preparation during last phases, the implementer should develop a concept for an operational safety case. Internal and external hazards should be identified and addressed (OECD/NEA 2016, IAEA 2020).

- This concept of the operational safety case should discuss the relationships between post-closure safety and operational safety (IAEA 2016).
- With regard to the fact that (in most cases) the repository operational phase includes further construction of the repository, operational procedures are to be developed by the implementer and approved by the regulator, which ensure a separation of routine mine activities and handling and transport of waste packages in the underground facilities.
- As part of the operational safety case concept, developed during Phase 2, the implementer should perform a scenario development and a corresponding detailed risk analysis (see for example ANDRA 2016). This analysis should focus on getting the licence application for construction of the repository.
- The implementer should develop an accident management plan including a detailed list of potential accidents and corresponding response procedures. This accident plan should be discussed and agreed with the regulator for getting the license application for construction of the repository.
- The implementer should apply the generic models for safety assessments developed during Phase 3 and perform safety calculations. He should also provide the regulator with the results as part of the license application for construction of the repository.

Monitoring and retrievability

- With regard to the prepared and approved plan for baseline monitoring during Phase 3, the WMO needs to implement and start the baseline-monitoring programme at the selected site.
- Making good use of monitoring results requires a good understanding of how data relate to the safety assessment. If prior steps in identifying objectives - deriving them from safety functions and linking them to the basis for evaluating expected performances – were followed as recommended by the "Modern Reference Framework" (MoDeRn 2013), this should already be understood and documented.
- The implementer is encouraged to develop response plans for monitoring results indicating a deviating behaviour from expected repository component evolutions. A detailed discussion about responding to monitoring results is provided in White et al. (2019).
- The implementer needs to initiate or continue the dialogue with relevant stakeholders to explore their interest to be involved in the monitoring programme and the evaluation of the results. First discussions with citizen stakeholders and ideas for stakeholder involvement with regard to monitoring are presented in three reports produced during the MODERN2020 project (Lagerlöf et al. 2018, Bergmans et al. 2019, Meyermans 2019). Meyermans et al. (2019) developed a so-called "Stakeholder Guide", which is assumed to be of great help initiating discussions with local stakeholders.

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Construction (Phase 4)

Programme Implementation (integrated actions in theme 5 on disposal facility design and optimisation linked to activities in other themes)

- The implementer needs to develop a plan for the construction activities of the underground emplacement infrastructural areas and discuss this plan with the regulator to get the license for construction.
- The main work of the implementer in this phase is to carry out the initial construction of the repository and prepare for repository operation. This includes any test and demonstration activities considered necessary (See 5.2 Demonstration and verification).
- The implementer is encouraged to update the RMS for the repository based on the knowledge gained from the assessment from Phase 3 (*See 5.1.1 Design specification*).
- The implementer needs to finalise repository design and waste emplacement systems, and further adapt it to the site conditions encountered as construction progresses. This further design development would be especially important if the repository operational phase includes further construction of the repository.
- The implementer needs to finalize the engineered barrier designs and adapt it to the site conditions at the dedicated position (See 3.3 Buffer, backfill, plugs and seals).
- In parallel, the implementer should develop plans for the qualification and quality control needed to ensure that the repository construction and the manufacturing and implementation of the EBS components meet the design specifications. The regulator should approve this qualification procedure.
- The implementer and regulator should agree to implement the underground monitoring programme as mentioned in Phase 3, and further update it to cover monitoring needs during the operational phase (*See 5.5.2 Monitoring during construction and operation*).
- The implementer and the regulator should continue the dialogue with other relevant stakeholders but at this stage, this dialogue is likely to be formalised in accordance with stipulations from the construction license (*See 6.3.1 Stakeholder Involvement*).
- The implementer needs to carry out all activities necessary for the application for repository operation and prepare the necessary documents (*See 6 Siting and Licensing, 7 Safety Case*).
- The regulator should plan an inspection programme for the construction process and agree with the implementer to consider the inspections in the schedule.
- The regulator should prepare for receiving and reviewing an application from the implementer for an operating license. This is due, when sufficient construction work has been completed, leading to issuance of license with any conditions considered necessary.

Design

- The implementer should finalize the design of the underground facilities, especially for disposal holes or disposal drifts based on the knowledge about the rock behaviour obtained during initial construction and at best based on rock suitability criteria. A good example for crystalline rock is given in Railo et al. (2016).
- The implementer should finalize the necessary technical equipment components, especially waste handling and emplacement equipment, after successful demonstration and testing activities performed in Phase 3 for license application for operation.
- If needed, the implementer should refine the design of surface facilities for the license application for operation.
- The implementer should consider optimising operational procedures for waste handling and waste emplacement and discuss this with the regulator for future application.
- The implementer should finalize the engineered barrier system design of those components that are intended to be placed in the already excavated part of the underground facilities based on their designated locations and adapt it to the found hydro-geological conditions.

Constructability, demonstration and verification testing

- The implementer should continue to conduct tests to demonstrate and optimise construction approaches and methods in the selected host rock. A good way of doing this would be the use of a designated area (test area) of the already excavated part of the underground facilities or the use of a host rock specific URF. Both options would make full use of learning opportunities offered by in situ testing. In addition, demonstration activities may increase the confidence of stakeholders and the general public in the safety of the actual repository operation.
- The implementer should continue to conduct tests to demonstrate and optimise equipment for waste handling, transport, emplacement, and retrieval. Helpful information are compiled in e.g. Halvarsson et al. (2008).
- The implementer should continue to conduct tests to demonstrate and optimise the operational procedures for waste handling, transport, emplacement, and retrieval (Nagra 2019).
- As an important step in this phase, the implementer needs is to carry out commissioning tests of both construction and waste disposal activities at the repository site using the equipment to be used during operation and with staff planned to be used during operation.
- The implementer should continue to conduct tests to demonstrate and optimise the design of individual geotechnical barriers. Procedures of quality assurance need to be tested especially regarding the implementation of the different geotechnical barriers to evaluate the meeting of the design specifications (Alonso et al. 2008, Posiva/SKB 2017).
- Long-term tests of the evolution of different geotechnical barriers shall be continued in order to demonstrate that the designated performance targets can be met. This is especially valid for those barriers, which will achieve their full sealing ability only after longer periods of time, e.g. bentonite seals. Helpful information from the large European Sealing project DOPAS with regard to barrier performance are compiled in White et al. (2016).

Security and safeguards

- The implementer should continue and potentially update the existing cyber security programme.
- Based on the design from Phase 3, the implementer needs to provide physical security measures to ensure compliance with regulatory security arrangements for transport and disposal of radioactive materials.
- The implementer is encouraged to carry out security exercises and training.
- Based on the potentially updated design of the underground and surface facilities and the waste transport procedures after initial construction, the implementer should check for the need to update the concept for nuclear material safeguards and communicate this to the responsible authorities to get feedback and finally agree with the authorities on the method of verification/identification of the waste form (IAEA 2018).
- The implementer should get in contact to the ESARDA group, which is an association of European organisations formed to advance and harmonise research and development in the area of safeguards and amongst others intends to improve the quality, the efficiency and cost-effectiveness of nuclear material safeguards (ESARDA 2020).

Operational safety

- The implementer is encouraged to develop a safety culture in repository management and workforce. Hazards and accidents can be minimized when the management and workforce adopt a safety culture that puts safety at the forefront of operations.
- As part of the operational safety case concept, developed during Phase 2, the implementer should continue to perform scenario developments and a corresponding detailed risk analysis. This analysis should focus on getting the licence application for operation (Posiva 2017).
- The implementer should consider an update of the accident management plan and discuss it with the regulator for getting the license application for operation.

- Based on experiences gained during initial construction, the implementer should consider an update of the generic models for safety assessments developed during Phase 3 and perform safety calculations. Provide the regulator with the results as part of the license application for operation.

Monitoring and retrievability

- The implementer has to continue the baseline-monitoring programme started in Phase 3 to check for any changes due to construction activities.
- Based on the monitoring concept developed during Phase 2 and as a follow-up of the baseline-monitoring programme implemented in Phase 3, the WMO needs to implement the monitoring programme related to repository initial construction including potential test or pilot facilities.
- An implementation strategy should be followed, which enhances the ability of the implementer to monitor and provide information in response to the monitoring objectives (MoDeRn 2013). This strategy should include evaluation of the ability to:
    - provide representative locations for monitoring without the risk of monitoring having a negative impact on long term safety
    - provide options for monitoring to minimise or suppress interference with construction activities.
- The implementer needs to continue the dialogue with relevant stakeholders with regard to the monitoring programme and the evaluation of the results (White et al. 2019).

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Operations & Closure (Phase 5)

Programme Implementation (integrated actions in theme 5 on disposal facility design and optimisation linked to activities in other themes)

- During this phase, the implementer has to carry out repository operation activities including waste transport and emplacement. The implementer is encouraged to start extremely slowly with a pilot of operations to take into account experience and lessons learned.
- In parallel to waste transport and emplacement, the implementer has to carry our further underground excavations and constructions and to ensure the separation of both activities considering radiation protection.
- The implementer is encouraged to update the RMS on a regular basis considering experiences from the operation and repeated safety assessments (See 7 Safety Case).
- The implementer should consider revising repository design specifications, based on updates to the RMS, if judged necessary or beneficial.
- In preparation of final closure, the implementer should check for a potential update of the engineered barrier designs based on experiences gained from ongoing construction and adapt them to the site conditions at the dedicated position (See 3.3 Buffer, backfill, plugs and seals, 3.4 EBS system confirmation).
- The implementer and regulator should agree to implement the underground monitoring programme as mentioned in Phase 3, and further update it to cover monitoring needs during the operational phase.
- The implementer and the regulator should continue the dialogue with relevant stakeholders with regard to the monitoring programme (*See 6.3.1 Stakeholder Involvement*).
- The implementer needs to carry out all activities necessary for the application for repository closure and prepare the necessary documents (*See 6 Siting and Licensing, 7 Safety Case*).
- The regulator should implement an inspection programme during operation.
- The implementer should update the safety case periodically and in accordance with any stipulations in the operational license (See 7 Safety Case).
- The regulator should prepare for receiving and reviewing an application from the implementer for a closing license. This application should include the intended final closing activities as well as any post-closure actions assumed to be beneficial (See 6 Siting and Licensing).
- After getting the closing license, the implementer has to backfill all remaining openings and seal the access routes to the surface. The surface facilities have to be dismantled.

Design

- The implementer may optimize the engineered barrier system design, especially of those components that are intended to be placed during the final closure activities, e.g. in the access routes to the surface. Monitoring of barrier components may provide useful information for optimizing the design as describe in the monitoring chapter below. The performance targets and design requirements are set for closure (Sievänen et al. 2012). Plugs and seals need to be adapted to the found hydro-geological conditions at their designated positions (SKB 2010).

Constructability, demonstration and verification testing

- The implementer should make sure that the equipment for waste handling and transport is in good shape, especially to be prepared for potential retrieval activities. Waste handling and transport equipment is to be checked periodically during the whole operational phase.
- Tests should be performed to demonstrate and optimise the operational procedures for a potential waste retrieval prior to final closure.
- The implementer should continue to conduct tests to demonstrate and optimise the design of individual geotechnical barriers, especially for those needed for final closure. Doing this in a test or demonstration facility is highly recommended. Procedures of quality assurance need to be applied,

especially regarding the implementation of the different geotechnical barriers to evaluate the meeting of the design specifications (SKB 2010, Posiva/SKB 2017).

- Long-term tests of the evolution of different geotechnical barriers shall be continued in order to demonstrate that the designated performance targets can be achieved. This is especially valid for those barriers, which will achieve their full sealing ability only after longer periods of time (e.g. bentonite seals).
- In preparation for closure, the implementer should clarify whether the general closure requirements as well as the manufacturing and installation requirements are sufficiently well-developed for implementation.

Security and safeguards

- Prior to the very first waste canister emplacement, the WMO has to implement the nuclear material safeguards concept developed during the previous phases. The implementer has to perform a corresponding safeguards monitoring to check for compliance. Monitoring activities and their result have to be communicated to the IAEA periodically.
- The implementer should continue and update the existing cyber security programme.
- Based on the design from previous phases, the implementer needs to provide physical security measures to ensure compliance with regulatory security arrangements for transport and emplacement of the waste canisters during the whole operational and closure phase.
- The implementer is encouraged to carry out security exercises and training.

Operational safety

- The implementer has to apply the stipulations of the operational safety case developed during previous phases including monitoring activities for operational safety.
- A radiation protection plan has to implemented and operated during the entire operational phase.
- During the operational phase, the implementer should perform detailed risk analyses on a periodic basis and discuss the results with the regulator. Helpful information about risk management can be obtained from ANDRA (2016).
- With regard to the gained experiences during further construction and operation, the implementer should check the accident management plan, consider potential updates in view of the closing activities, and discuss it with the regulator (ANDRA 2016).
- Based on experiences gained during further construction and operation, the implementer should consider an update of the generic models for safety assessments developed during previous phases and perform final safety calculations. Provide the regulator with the results as part of the license application for closure.

Monitoring and retrievability

- The implementer should continue to monitor the parameters, which are part of the baseline-monitoring and include these monitoring activities into the general monitoring programme.
- Based on the monitoring concept developed during Phase 2, the WMO needs to implement the monitoring programme related to repository operation, further construction, and closure (MoDeRn 2013, MODERN2020 2019a).
- In case retrievability and reversibility is an option in the national programme (like in France or Germany), the corresponding monitoring plan has to be implemented to support a continuous evaluation of the possibility of waste retrieval. As an example, the ANDRA Monitoring Strategy Cigéo 2015 is described in (IAEA 202X).
- Depending on the repository concept, the host rock, and the role of the geotechnical barriers within the long-term safety assessment, monitoring of the evolution of individual barrier components may be beneficial. Information obtained from barrier evolution could help optimizing the design of engineered barriers to be implemented at later times, specifically during closure (IAEA 202X). The implementer should be aware that monitoring equipment need to go through a qualification process

prior to implementation in important areas. Helpful information regarding that issue can be obtained from (MODERN2020 2019b).

- An implementation strategy should be followed, which enhances the ability of the implementer to monitor and provide information in response to the monitoring objectives (MoDeRn 2013). This strategy should include evaluation of the ability to:
    - provide representative locations for monitoring without the risk of monitoring having a negative impact on long term safety
    - provide options for monitoring to minimise or suppress interference with construction, operation, emplacement and closure activities.
- The implementer needs to continue the dialogue with relevant stakeholders with regard to the monitoring programme and the evaluation of the results (IAEA 202X, White et al. 2019).

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AVAILABLE CAPABILITIES: STATUS AND OUTLOOK

This section describes programme capability needs (including infrastructure) that are required to successfully complete the activities and actions recommended to achieve generic goals on disposal facility design and optimisation.

Knowledge and understanding

At a very early stage, it is essential to get into contact with local and/or regional citizen stakeholders. The implementer should be the one demonstrating that he is honestly willing to communicate, be transparent and to take concerns of regional stakeholders into consideration. Designing the repository may be of regional interest since the design not only covers the underground facilities but also the access routes to the surface and the surface facilities. Communication to the public should be an in-house competence of the implementer since this is the basis for any trust.

Experts and practical skills

Development of design layouts of the underground facilities, especially the waste emplacement areas and the engineered barrier system should be an in-house competence of the implementer. Both are main issues with regard to safety demonstration and should be established as a core competence of the implementer. Keeping this as an in-house competence, necessary adaptations or optimizations can be done on a continuous knowledge base, without loss of time, and without any dependencies on third parties. It has to be noted that any changes may affect the long-term evolution. Thus, an update of the safety assessment is obligatory in that case.

Thus, a core activity in a national programme should be the concept development and the performance of large-scale demonstration and verification tests either in an URF or in designated test areas of the real repository or in a pilot repository. These demonstration activities should be part of an existing overarching R&D plan for repository implementation.

Another core activity should be the continuous long-term safety evaluation needed for design optimisation for the periodic updates of the safety case.

The regulator should define corresponding criteria and verification procedures to check for meeting design specifications and performance targets (Posiva/SKB 2017).

The development and implementation of a radiation protection system and protection procedures for operational safety should be a core competence of the implementer. The regulator should define corresponding safety criteria and verification procedures to check for compliance.

Also nuclear safety calculations, especially criticality safety calculations, should be a core activity as it involves the handling of classified information on the one hand and on the other hand if criticality cannot be excluded in the underground facilities, it might be solved by changing the design of the facilities.

Development of a repository monitoring programme should be an in-house competence of the implementer since it is related to the safety case and the safety assessment. The development of a monitoring programme as well as the evaluation of monitoring results should consider the involvement of stakeholders, in particular local communities. The development of robust response plans to monitoring results indicating deviating evolutions should be a core competence of the implementer and such response plans should be provided beforehand (White et al. 2019). The implementer should make clear to everybody that he knows what to do in case of unexpected evolutions. This is one basis for getting trust.

Laboratories and centres of excellence

A useful network to access available large scale infrastructures that could support a national programme with establishing a large scale demonstration testing programme would be the IAEA Underground Research Facilities (URF) Network for Geological Disposal (https://nucleus.iaea.org/sites/connect/URFpublic/Pages/default.aspx).

Equipment, tools and technology

In principle, the development of technical equipment can be out sourced but the development of the corresponding design requirements and design specifications should be kept in-house as they relate to the safety assessments.

Technical equipment for excavation activities in the underground facilities can be taken from the open market of the mining industry. This is also valid for loading and transport equipment for routine mining activities.

Technologies for ventilation and fire security are assumed to be mature enough and can thus be taken from the open market.

Mine water management systems can be obtained from the open market of the mining industry. The connection to the radiation protection system, especially clearance measurements of mine water, has to be under the responsibility of the implementer.

In lower strength rock (e.g. clay), a support of underground openings will be necessary. Equipment and material are assumed to be non-critical if taken from the open market. Implementation procedures should be an in-house competence as part of the operational safety case.

With regard to crucial equipment for waste packaging, handling, transport, emplacement, and potential retrieval, and all under radiation protection, the implementer should inform himself by getting into contact with advanced programmes, especially programmes that have a similar disposal concept. This kind of equipment is rather unique and any experiences from other programmes may be helpful for development, licensing, and application.

With regard to equipment for repository monitoring, many technical systems are available on the open European market and are potentially useful (MODERN2020 2019b). Nevertheless, a good knowledge and expertise is necessary to evaluate an implementation of specific tools without impairing long-term safety aspects of repository components. The issue of impairment evaluation is an inherent part of the “Screening Methodology” as part of the feasibility screening for monitoring techniques (MODERN2020 2019a).

Industrial facilities and manufacturing

From the experience of the writer, there is no critical infrastructure at risk, as long as routine mining infrastructure is concerned. At the time being, no overloads or short supply can be seen. This may of course be different in the future since, for example, providers can go out of business. So, there should always be more than one supplier available.

When speaking about unique equipment for any kind of waste handling and transport, the issue is different. The implementer is well advised to design, develop and extensively test any kind of waste handling equipment at an early stage and get an agreement from the regulator. In Germany, this has been done prior and in parallel to the excavation of the first repository exploration mine, which allows for extensive testing and optimization prior to application (Bollingerfehr et al. 2009).

Contractors and human/material resources

One of the most important expertise is the safety-case know-how as safety cases are updated only after 10-15 years during the operational phase, so the expertise could be at risk. Thus, the implementer needs to make sure that the expertise is transferred and maintained in due time.

Also, knowledge of what was done in past safety assessments (or safety case) and past discussions with the regulator are important, hence this knowledge should be actively retained and transferred. A possible way of mitigating against loss of historic safety case developments might be the development of a safety assessment database designed to store the key input and output of the safety case so that the impact of design changes can be tracked along the safety case modelling chain.

The issue of cyber–security is a fast evolving issue, which needs continuous adaptation of security systems. Although there are suitable security systems available on the market, the implementer is well advised to hold up well-educated and trained staff responsible for cyber-security in the company right from the beginning.

In programmes where plugs and seals play a significant role in the safety case, designing and optimization of plugs and seals and the EBS as a whole needs a broad knowledge about sealing material, production of seal components, their proper implementation and evolution over time once installed. During the past decades, a lot of knowledge has been generated by development and testing activities all over the world. Extensive experience in long-term testing and verification is necessary that can hardly be provided by junior staff. The implementer shall make sure that knowledge transfer and training of staff, dealing with the EBS, is guaranteed.

From the writer's point of view, the development of a monitoring concept may be a critical expertise at risk. In the past, the role of repository monitoring has been rather limited. Nowadays, monitoring is seen to be a valuable tool for obtaining information for optimizing repository components during the operational phase of a repository. However, the development of a suitable monitoring programme needs a good knowledge about the safety case since monitoring should be very much related to it. Additionally, it needs a good knowledge about the capabilities of available monitoring technologies and last but not least, about the possibilities and limitations of monitoring systems, especially for long-term applications without impairing safety. Thus, a broad and deep knowledge is required, which needs an early education and training of staff.

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