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Roadmap for Implementing a Geological Disposal Programme

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ROADMAP FOR IMPLEMENTING A GEOLOGICAL DISPOSAL PROGRAMME

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology. While the guidance provided in IAEA Nuclear Energy Series publications does not constitute Member States' consensus, it has undergone internal peer review and been made available to Member States for comment prior to publication.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

Implementation of a geological disposal programme for radioactive waste is a major undertaking, given the long time over which the programme operates, the technical assurance that needs to be demonstrated to ensure long term safety and security, and the socially and politically sensitive nature of radioactive materials management. This publication provides a roadmap for developing and implementing a geological disposal programme for spent nuclear fuel declared to be waste, other high level waste and intermediate level waste. It identifies the major activities and deliverables for each phase of the programme that are the responsibility of the implementing organization in order to construct and operate a geological disposal repository in a manner consistent with existing international experience.

The roadmap is generic in nature, describing the activities common to each phase of the programme but not specifying the method required or the time allotted to complete the activity. Rather, the roadmap reflects good practice and lessons learnt, thereby aiming to help reduce risks, especially for new programmes or those entering a different phase. The publication also describes how several advanced programmes have progressed along their respective roadmaps toward the siting, construction and operation of a geological repository.

The IAEA is grateful to the experts and organizations that contributed to the case studies and to the broader understanding summarized in this publication. The IAEA officers responsible for this publication were H. Jung, K. Lange and S. Mayer of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The term 'geological disposal' refers to the disposal of radioactive waste in a disposal facility located underground in a stable geological formation to provide long term containment and isolation of the waste from the accessible biosphere [1]. The IAEA has a mature set of safety standards and guidance on this subject [2–6]. Feasibility studies, site specific safety cases, and construction and operational experience (OPEX) have strengthened confidence in the safety of geological disposal [7]. The existence of numerous potentially suitable repository sites in a variety of host rocks is also well established.

Implementation of a geological disposal programme for radioactive waste is a major undertaking, given the long time period over which the programme will operate, the technical assurance that needs to be demonstrated to ensure long term safety [1], and the societal and political aspects related to radioactive waste management. This publication provides a roadmap for developing and implementing a geological disposal programme based on relevant international experience.

The development and implementation phases of a geological disposal programme can be grouped into initiation, siting, disposal (i.e. construction, operations and closure of the repository) and post-closure. This publication lists the activities that are commonly planned and executed for each of these phases in a clear and systematic manner.

IAEA-TECDOC-1755, Planning and Design Considerations for Geological Repository Programmes of Radioactive Waste [3], provides a high level summary of different aspects of a geological repository programme, including country specific typical durations for some repository development phases. Since its publication in 2014, several developments have taken place.

With respect to construction, the Finnish waste management organization (Posiva Oy) obtained a licence to construct a deep geological repository (DGR) for spent nuclear fuel in 2015 [8] at the Olkiluoto site and construction started in 2016. Posiva Oy submitted the operating licence application for the DGR to the Finnish Radiation and Nuclear Safety Authority (STUK) in 2021 [9]. The Swedish Nuclear Fuel and Waste Management Company (SKB) proposed to build a repository for spent nuclear fuel in Forsmark in Östhammar Municipality [10] and an encapsulation plant in Oskarshamn; the Swedish government approved this project in 2022.

In terms of advanced licensing applications, the French National Radioactive Waste Management Agency (Andra) submitted its construction licence application for a DGR, the Cigéo project, for high level waste (HLW) and intermediate level waste (ILW) in 2023 [11]. Prior to this, in July 2022, the French official journal published a decree recognizing the public utility of the Cigéo project — a decision acknowledging the general interest of Cigéo as a final disposal solution for the most radioactive waste produced in France. The Cigéo repository stands on the border between the Meuse and Haute-Marne departments in France.

In terms of siting, the Swiss organization, the National Cooperative for the Disposal of Radioactive Waste (Nagra), selected the site Nördlich Lägern for a DGR in September 2022 and is preparing general licence applications [12]. The Canadian Nuclear Waste Management Organization (NWMO) continues to engage with volunteer communities and plans to identify a site to host a DGR for spent fuel in 2024 [13]. A new siting process in England (United Kingdom) was launched in December 2018 and another in Wales (United Kingdom) in January 2019. The siting process could take up to 20 years, during which time Radioactive Waste Management (RWM) — a wholly owned subsidiary of the UK Nuclear Decommissioning Authority — would conduct detailed technical work at potential sites to assess their suitability [14].

In Germany, construction work started in 2008 to convert the former iron ore mine Konrad [15] into a new geological repository for low and intermediate level waste (LILW). In addition, a site selection process was started in 2017 in Germany to identify a site for a geological repository for HLW and spent fuel [16].

The Czech Radioactive Waste Repository Authority (RAWRA) has completed the surfaced based exploration of nine potential sites for a geological disposal facility and has selected four of these sites for more detailed characterization [17].

There are currently no operating geological repositories for HLW, including spent nuclear fuel, but there are operating geological repositories (>200 m depth) for transuranic waste at the Waste Isolation Pilot Plant (USA) and for ILW at Bataapati (Hungary), while there are geological facilities in the closure phase containing LILW, such as the one at Morsleben (Germany).

Progress in these Member States has come after many decades of research and development (R&D), with a significant part of the research being carried out in underground research facilities (URFs). URFs have provided an in situ geological environment to perform basic research and characterization while simultaneously allowing for human resource capacity building in a realistic environment. As of 2023, there are 13 URFs operating worldwide.

The last few decades have also shown a steady and productive increase in the attention paid to continued and thoughtful engagement with the public. Experience and knowledge from stakeholder involvement are described in this publication to provide a baseline for consideration during the development of geological repositories in other countries.

In view of this substantial progress, and to share information on advanced programmes with Member States that are newly embarking on a geological disposal initiative, it was deemed useful to provide a comprehensive and generically applicable roadmap to assist operating organizations (e.g. waste management organizations (WMOs)) in the implementation of a geological disposal programme.

1.2. OBJECTIVE

The objective of this publication is to provide a roadmap for the development and implementation of a geological disposal programme consistent with international safety standards and best practices. It also promotes collaboration and sharing of knowledge among the stakeholders in radioactive waste management.

The activities and deliverables for each phase of a geological repository programme are described with an emphasis on how they support decision making within each phase for proceeding to the subsequent phase. The roadmap is generic in nature, describing the activities common to each phase but not specifying in a prescriptive sense the method to complete the activity or time allotment. Rather, it is presented to reflect good practice and lessons learned, thereby aiming to help reduce risks for new programmes. The publication also describes how several advanced programmes have progressed along their respective roadmaps towards operating a geological repository.

Individual circumstances in Member States may require different approaches, and therefore Member States are advised to evaluate and adapt the roadmap accordingly. Guidance and recommendations provided here in relation to identified good practices represent expert opinion but are not made on the basis of a consensus of all Member States.

1.3. SCOPE

The scope of the roadmap applies to the geological disposal of spent nuclear fuel declared as waste, other HLW and ILW, and any additional waste that may have been identified in the Member State for this type of disposal. The emphasis is on the series of activities typically conducted and the deliverables typically attained during the different phases of developing and implementing a geological disposal programme. This publication also provides roadmaps for several advanced programmes, including highlighting key deliverables and milestones over time.

Further details on specific activities in the roadmap and associated good practices, as well as on the safety requirements they are intended to meet, can be found in a range of IAEA publications, some of which are further identified as references throughout this publication. Specifically, IAEA Safety Standards Series No. GSR Part 1 (Rev. 1), Governmental, Legal and Regulatory Framework for Safety [18], is foundational to the roadmap in terms of capturing legal and organization infrastructure. IAEA Safety Standards Series No. SSG-14, Geological Disposal Facilities for Radioactive Waste [1], provides a basis for the roadmap in terms of describing the safety approach, safety case development and the stepwise approach.

This publication is intended for engineers, scientists, decision makers, managers and policy makers involved in a geological disposal programme. The roadmap may also be used as a tool to facilitate communication and dialogue among decision makers, funding and operating organizations, and other stakeholders regarding the tasks and kinds of activities necessary for effective implementation of the disposal programme.

The broader national context of geological disposal, such as actions by regulatory bodies and policy makers, is outside the scope of this report. Predisposal waste management activities, such as conditioning, transport and storage, are also outside the scope of the report. However, interactions with these disciplines and other relevant stakeholders, to engage on progress, plans and proposals for implementation are clearly within the scope of this guidance publication.

Discussions on multinational repository projects for radioactive waste disposal continue to be carried out in the international community and several IAEA publications present considerations relevant to the implementation of a multinational disposal programme [19]. While many of the generic considerations presented in this roadmap are equally applicable to any such multinational endeavours, the specificities of the associated legal and regulatory framework and international agreements, as well as the broader range of stakeholder interactions and contributions to the main decision points, are not addressed. Therefore, any of the aspects specific to a multinational geological disposal programme are outside the scope of this publication.

1.4. STRUCTURE

This publication is divided into five main sections. Section 1 presents the background, objectives, scope and structure of the publication. Section 2 reviews the prerequisites and constraints for the roadmap and describes the overall timeline and key milestones of a geological disposal programme. Section 3 presents the roadmap for a geological disposal programme, outlining the major project work elements, activities and associated deliverables in a work breakdown structure format. Section 4 provides a roadmap matrix of activities, which describes the work breakdown structure for each phase of the disposal programme. Conclusions are presented in Section 5. Illustrations of the applicability of the IAEA generic roadmap to ten national programmes are provided in Annex I. Annex II, available as an on-line supplement, provides a series of matrices that illustrate the work breakdown structure for each phase of the roadmap.

2. PREREQUISITES AND CONSTRAINTS, PHASES AND TIMELINE

2.1. PREREQUISITES AND CONSTRAINTS

Implementing a geological disposal programme is a major undertaking that requires careful planning, preparation, investment of time and resources, and public interaction. The prerequisites and constraints for such a programme are described in several IAEA publications [1–5] and are briefly reviewed herein.

2.1.1. National, legal and organizational framework

Aspects of supporting the national, legal and organizational framework for geological disposal are described in SSG-14 [1] and include the following tasks:

“(a) Defining the national policy for the long term management of radioactive waste of different types;
(b) Setting clearly defined legal, technical and financial responsibilities for organizations that are to be involved in the development of geological disposal facilities;
(c) Ensuring the adequacy and security of financial provisions, for example, by requiring the owners of the waste to establish segregated funds;
(d) Defining the overall process for the development, operation and closure of geological disposal facilities, including the legal and regulatory requirements at each step, and the processes for decision making and the involvement of interested parties;
(e) Ensuring that the necessary scientific and technical expertise is available to support site and facility development, regulatory review and other national review functions;
(f) Defining legal, technical and financial responsibilities and, if necessary, providing for any institutional arrangements that are envisaged after closure, including any monitoring and any other arrangements that may be required for ensuring the security of the disposed waste.”

These aspects also form part of the basis for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [20]. Through this mechanism, contracting parties report on many aspects pertinent to geological disposal, including the waste inventory, spent fuel management and disposal plans, policies and practices, and the applicable legislative and regulatory system.

Furthermore, the IAEA, in collaboration with the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) and the European Commission, publishes a global overview of the status of radioactive waste and spent fuel management, concerning inventories, programmes, current practices, technologies and trends, on a periodic basis [21].

2.1.2. Waste inventory

The waste inventory is a primary consideration in planning for disposal, as it will inform the design and the scale of operations, and may also influence the timing and duration of a repository programme. Long lived wastes destined for geological disposal can comprise a variety of materials conditioned and packaged in many ways [21]. The IAEA waste classification system identifies six separate waste classes corresponding to increasingly stringent requirements for isolation and containment [22]. The principal waste types considered in this publication are spent nuclear fuel declared to be waste, vitrified HLW and ILW. Between the start of nuclear power based electricity production in 1954 and the end of 2016, about 390 000 t HM of spent fuel was discharged from all nuclear power plants worldwide [21].

Reference [21] provides a breakdown of inventories worldwide, including ILW and low level waste (LLW). Some Member States plan to colocate ILW and/or LLW into the same geological repository as spent fuel and/or HLW.

The waste acceptance criteria (WAC) are formal criteria which define the qualities of waste packages (including the waste) that are accepted for emplacement in the facility.

As per requirement 20 of SSR-5 [2]: "**Waste packages and unpackaged waste accepted for emplacement in a disposal facility shall conform to criteria that are fully consistent with, and are derived from, the safety case for the disposal facility in operation and after closure.**"

The WAC is developed by the WMO in cooperation with the waste generator.

2.1.3. Responsibilities of the operator

The operator of a geological disposal facility is required to ensure the safety of the programme:

> "**The operator of a disposal facility for radioactive waste shall be responsible for its safety. The operator shall carry out safety assessment and develop and maintain a safety case, and shall carry out all the necessary activities for site selection and evaluation, design, construction, operation, closure and, if necessary, surveillance after closure, in accordance with national strategy, in compliance with the regulatory requirements and within the legal and regulatory infrastructure**" [2].

Many Member States have assigned the duty of carrying out the national waste management strategy and planning for geological disposal of HLW to a single administrative entity, the WMO, with it being responsible for coordinating the development of such plans [23]. Recognizing that, in some Member States, the range of development and implementation activities might be divided and shared among several operating organizations, this publication refers to the collective group of these organizations as a WMO.

The development of a geological disposal facility is undertaken within a complex environment in which, typically, a WMO has to interface with a diverse range of external stakeholders, including government, regulators, affected communities and the supply chain (contractors and consultants). To be able to manage repository development, a WMO is responsible for a wide range of management activities and systems to deal with topics, such as:

- Financial and commercial management;
- Human resources management;
- Programme management;
- Quality management;
- Information management;
- The management of communication and stakeholder interactions.

2.1.4. Safety case

The safety case is a key tool used to document and demonstrate that a geological disposal facility will meet the fundamental safety objective, which is to protect people and the environment from harmful effects of ionizing radiation. "The safety case (i.e. the collection of arguments and evidence to demonstrate the safety of a facility) for a disposal facility will be developed together with the development of the facility" [2]. The safety case and safety assessment and their use in demonstrating and documenting the safety of a radioactive waste disposal facility are described in IAEA Safety Standards Series No. SSG-23, The Safety Case and Safety Assessment for the Disposal of Radioactive Waste [5]. Within a geological disposal programme, the safety case guides programme planning, is a key input for decision making, provides the framework for supporting R&D and is an important communication tool. As such, the safety case forms the basis for the roadmap.

2.1.5. Constraints

Several constraints on a geological disposal programme may exist and are often related to the individual circumstances of each Member State. Geological and geographical conditions in a particular country may limit the viable options for the development of a geological disposal programme. In addition, relationships with neighbouring countries and existing international agreements may need to be considered in the development of a repository, particularly near international borders. Other constraints that can lead to delays in disposal programmes include legal challenges, changing national policies or strategies, insufficient funding and unsustainable funding mechanisms.

2.1.5.1. Retrievability

Disposal refers to the placement of radioactive waste into a facility or a location with no intention of retrieving the waste. The term disposal implies that retrieval is not intended. However, this does not mean that retrieval of the radioactive waste is not possible, and some Member States are incorporating some form of retrieval into their programmes [24]. The technological implications of a requirement to be able to retrieve waste from a DGR in terms of the design of the disposal system and the associated repository infrastructure are described in Ref. [24]. One of the principles guiding the design of the Cigéo project (France) is to have reversibility of disposal; this relies upon the ability to remove waste packages from a deep geological disposal facility throughout its service life. For the Cigéo project, this lasts hundreds of years [11].

2.2. PROGRAMME PHASES AND TIMELINE

A geological disposal programme takes place over several or more decades. In some large programmes it will take more than 100 years from initiation to post-closure activities. This long timescale and the numerous activities implemented during the life of a programme make it necessary to subdivide a geological disposal programme into several steps or phases [1].

The generic timeline, programme phases and the decision points in the development of a geological disposal facility from the perspectives of radiological safety are provided in SSG-14 [1], which defines the main phases of a geological disposal programme as pre-construction, construction, operational, closure and post-closure. This roadmap further elaborates on those phases with experiences and lessons learned from the WMO, which is responsible for the safety of a geological disposal facility. Specifically, the pre-construction phase is more often referred to as the 'initiation' and 'siting' phases by WMOs [4].

The geological disposal programme herein is divided into the main phases and subphases (consistent with Ref. [4]):

(a) Initiation phase;
(b) Siting phase — site(s) survey and selection, site(s) investigation;
(c) Disposal phase — construction (including commissioning), operation, closure;
(d) Post-closure phase

Certain activities, such as the engineering design of the facility, remain ongoing through several steps in the development of the disposal facility [1]. For example, a generic design is developed at an early stage of the repository programme, and then it is continuously informed with increasing knowledge of the site specific boundary conditions, experiences from repository construction and knowledge of the expected future evolution.

At the completion of each phase of the programme, the WMO and other stakeholders review and assess the data collected thus far and major deliverables are produced. From these reviews, a recalibration of the technical, administrative and political landscape can be undertaken, if this is deemed necessary.

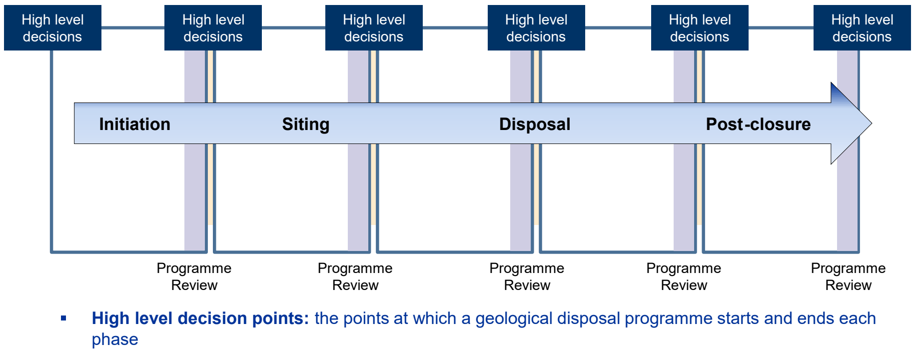

FIG. 1. Phased approach to geological disposal programme implementation.

A high level decision will need to be taken on whether and how to move to the next phase. These high level decisions are typically made at the national level. They are based on contributions from all stakeholders according to their roles and responsibilities in accordance with the national policy and framework and are underpinned with sound scientific and technical information and the results of a safety case and assessment. These decisions require a well defined, clear and transparent presentation of technical arguments that will provide confidence in the feasibility and safety of the geological disposal facility. A generic illustration of the phased approach is shown in Fig. 1.

The primary high level decision points for a geological disposal programme are identified as follows:

— Initiation of a geological disposal programme;
— Initiation of siting process;
— Site selection for further investigations;
— Authorization for construction;
— Authorization for operation;
— Authorization for closure.

Initiation of the geological disposal programme entails a national commitment to pursue the entire suite of activities needed to develop the disposal system. One of the most important aspects of this commitment is to designate or create the WMO (or to define the responsible organization(s), which would be treated as the WMO) with the role of administering and implementing the disposal programme. Other necessities include the creation of the management system and structure, setting up budgetary and project controls, and establishing interfaces with other organizations in the radioactive waste management system, such as regulatory bodies.

It is prudent to prepare a safety case early in a geological disposal programme to guide siting activities, R&D, design and planning [1]. Since data may be limited at this stage to desktop reviews, a generic safety case including several conceptual designs for the disposal system may be developed. Generic R&D on the scientific and engineering bases for the geological disposal programme may also be pursued in the initiation phase.

The goal of the siting phase of the disposal programme is to select a suitable site to host the geological repository. The high level decision to start the siting phase acknowledges the readiness of a Member State and a governmental decision to allow the WMO to pursue those activities needed to screen and evaluate potential sites, including developing site selection criteria. At the start of the process a list of potential sites is first identified. Then, a shorter list of sites is identified for detailed evaluation. Ultimately a single site is selected that can provide for the required isolation and containment of the waste. In parallel with the site selection process, the associated disposal system design, licensing and engineering studies in preparation for construction and operation are undertaken. For example, during its siting process, in

2002, Nagra published the safety report, Demonstration of Disposal Feasibility for Spent Fuel, Vitrified High-Level Waste and Long-Lived Intermediate-Level Waste (Entsorgungsnachweis) [25]. This report considered several design options for the disposal of spent fuel, HLW and ILW in a DGR in the Opalinus Clay of the Zürcher Weinland region.

Depending on the Member State, the decision about the final selection of the candidate site could be undertaken by the WMO, the government or other designated entity (such as a national geological survey or a specially established commission), or a combination thereof. Stakeholder involvement is an important component of the entire geological disposal programme but plays a particularly critical role in the siting phase. It is generally accepted that an authorization for repository construction is only likely to be achieved with local acceptance if communities are involved from the beginning and willing to give their consent (if investigations show that local geology proves suitable) [26].

Once a site is selected, all characterization data from the site are used to inform the final design and final safety assessment. At the point where there is significant knowledge of the site and engineering design, and a well supported safety case, as developed by the WMO, an application for authorization to construct the repository is submitted in accordance with the laws of the Member State.

In addition, during the siting phase, a URF can play an important supporting role in site investigations, site confirmation, disposal system testing and safety case assurance. URFs may be generic or site specific and often provide a collaborative technical link to other international geological disposal programmes. For instance, Andra has been carrying out a R&D programme in a URF to support the French deep geological disposal project, including characterization of the host rock in real repository like conditions, since 1999 [27]. Similarly, the Finnish WMO, Posiva Oy, constructed an underground facility at Onkalo for characterization of the host rock at the disposal site before the submission of the construction licence application [8].

The disposal phase includes construction (including commissioning), operation and closure of the disposal facility. The transition from the siting phase to the disposal phase constitutes a major shift in the disposal programme — from a development oriented programme to an industrial programme. The disposal phase is initiated by the authorization for construction. Authorization for construction of the disposal facility, typically in the form of a licence to prepare a site and construct the facility, is a major regulatory or governmental decision that acknowledges sufficient confidence in the selected site and the disposal facility design to proceed with the financial investment for construction. The construction of the facility proceeds in accordance with the approved facility design including any approved design modifications that may be necessary after the commencement of construction [1]. The construction of the underground facility will provide additional information about the site to support site characterization conclusions, as built engineering records and further documentation of the safety case. Similarly, disposal operations and closure activities are initiated by authorizations typically granted by the national level regulatory body.

As a nuclear facility, the geological disposal system will undergo a commissioning process prior to disposal operations. Commissioning typically involves rigorous inspection of surface and subsurface facilities, with demonstrations of waste handling systems. Prior to proceeding to the operational phase, Posiva will conduct a trial run of final disposal (TRFD) in 2024. The TRFD comprises the whole disposal process with final disposal systems and machinery, organization and procedures, but will be performed with dummy fuel assemblies [9]. For the Cigéo project (France), the pilot industrial phase is a legal requirement enshrined in the environmental code [11].

The authorization for operation is a high level decision, entrusting the WMO with the responsibility of receiving radioactive waste and the initiation of operations at the disposal facility. The major responsibility of the WMO during the disposal phase is implementation of disposal operations in accordance with the safety case approved by the regulatory body, including assurance of operational safety. The operation of the disposal facility is coordinated with other aspects of the radioactive waste management system, such as transportation and activities by waste producers.

An operational licence also requires documentation and demonstration by the WMO of its ability to safely store, handle and emplace the waste.

Closure of a geological disposal facility consists of backfilling and sealing the underground tunnels and openings in such a manner as to restore, as far as practicable, the initial natural conditions of the host rock. Closure of a geological disposal facility also includes decommissioning of surface facilities. The high level decision of authorization for closure is supported by the entirety of the information accumulated by the WMO during siting, construction and disposal operations regarding the long term safety of the geological disposal facility. This includes updating the safety case to reflect new information from the as built repository.

The post-closure phase of the disposal programme begins after closure, when the facility is in its final state. Geological disposal facilities are designed to be passively safe to the fullest extent possible and this minimizes the need for actions to ensure safety after closure [1]. Nevertheless, most programmes are exploring how to control land use and potentially place markers at the site for a defined period; generally, these plans remain flexible and open to future considerations. Other institutional controls, such as monitoring, may also be applied for a period after closure of a geological disposal facility; for example, to address public concerns and licensing requirements [1].

Authorization for termination of the nuclear licence is the regulatory or governmental decision that marks the completion of the disposal phase, following full closure of the disposal facility and potentially a period of time into the post-closure phase. Responsibility of the WMO may end or be transferred to the government in the same period, depending on the national policy.

It is noted that progress along the programme timeline is not necessarily linear or continuous. Several geological disposal programmes have experienced interruptions or regressions to previous phases in response to obstacles encountered during the process. Establishing a schedule with clear goals, milestones and dates is the responsibility of each Member State. For this reason, and given the long timeline, it is beneficial for the programme to be as flexible as possible to accommodate potentially changing sociopolitical expectations and technical uncertainties, for example related to the characteristics of the site geology and its possible future behaviour.

A disposal programme will generally undergo a programme review at the end of each phase in accordance with Requirement 11 of SSR-5 [2]. A formalized programme review process aims to revisit all activities, results and documentation and is reported to relevant stakeholders. In addition, a programme review provides a definitive basis for proceeding to the next phase of the disposal programme. Continuity of R&D efforts during the transition from one phase to the next is important for the geological disposal programme to maintain the technical basis and capacities of the WMO and the regulatory body.

3. ROADMAP TO IMPLEMENT A GEOLOGICAL DISPOSAL PROGRAMME

The roadmap to implement a geological disposal programme is presented in a work breakdown structure (WBS) format, a classical project management tool. The WBS identifies the work to be performed to achieve the major goals and deliverables for a geological disposal programme. This structure helps to convey the extensive list of activities and individual tasks that occur over the duration of the programme.

First, major elements of the roadmap are identified and described. For the purposes of the roadmap presented here the programme is subdivided into five major elements: (a) disposal programme management; (b) stakeholder involvement; (c) disposal system development; (d) URF activities; (e) disposal implementation. This set of five elements is consistent with a companion IAEA report on cost estimates and financing for a geological disposal programme [28]. Second, these elements are broken down into subelements. Third, more detailed activities or tasks for each subelement are described. Figure 2 illustrates this concept. The triangle on the right of the diagram shows how the work is broken down into manageable and traceable activities. This work informs the boxes on the left, which are the resulting deliverables.

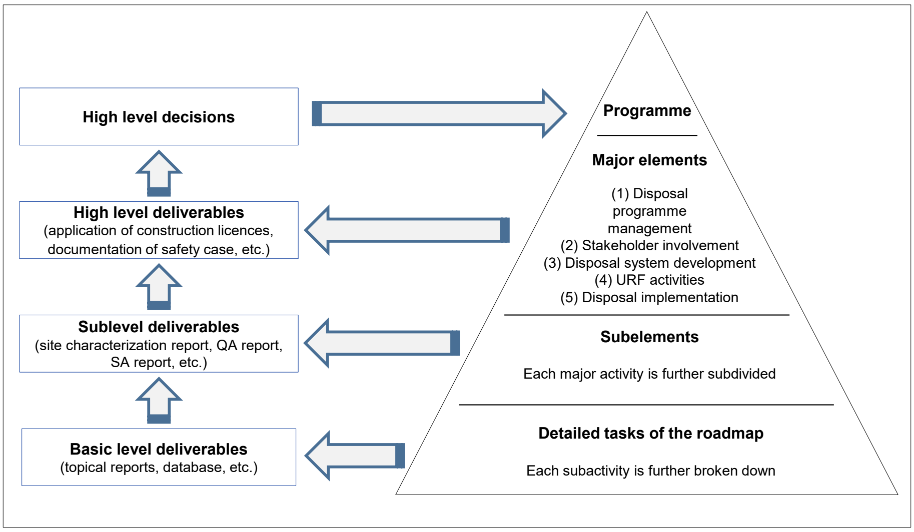

FIG. 2. Work breakdown structure for the roadmap and associated levels of deliverables to support a geological disposal programme.

At the bottom of the structure are foundational, detailed deliverables, such as the topical reports on research areas or a database. Next, sublevel deliverables build on these detailed reports and include items such as the safety assessment and site characterization report. Finally, high level deliverables build on these subsets of documents and demonstrate how requirements for the programme are being met (e.g. safety case, licence application). These deliverables form the basis of high level decisions, which ultimately direct the progress of the disposal programme, as indicated by the arrow from the top box, pointing towards the top of the triangle.

There are various ways in which any project or programme can be decomposed into a WBS, and individual Member States are advised to consider their circumstances in defining a geological disposal programme structure.

The roadmap to a geological repository is shown in Fig. 3. The high level decisions and phases of the programme are indicated in the top two rows. The main figure shows how each major element relates to the timeline, with darker shading representing a greater number of activities for certain phases. It is noted that programme management, disposal system development and programme implementation, corresponding to the first, third and fifth of the major elements defined in this publication and are common to all industrial development programmes. The elements for stakeholder involvement and URF activities are uniquely important to a geological disposal programme.

As noted in Section 1.3, the geological disposal programme roadmap developed here is for disposal, and excludes other aspects of waste management, such as overall waste policy, regulatory framework, waste treatment, storage or transportation.

Many of the roadmap activities are iterative, in conformity with the safety case concept. Key aspects of the geological disposal programme, such as the safety assessment and disposal system design, are repeatedly updated and refined as new information is obtained.

The following sections describe each of the five work elements, subelements and activities.

3.1. DISPOSAL PROGRAMME MANAGEMENT

Disposal programme management is the coordination of the broad range of activities and responsibilities that extend over the entire timeline of geological disposal programme implementation. At the highest level, the role of programme management is to provide a system of administration that directs the activities of all participants. Disposal programme management can delegate authority and the

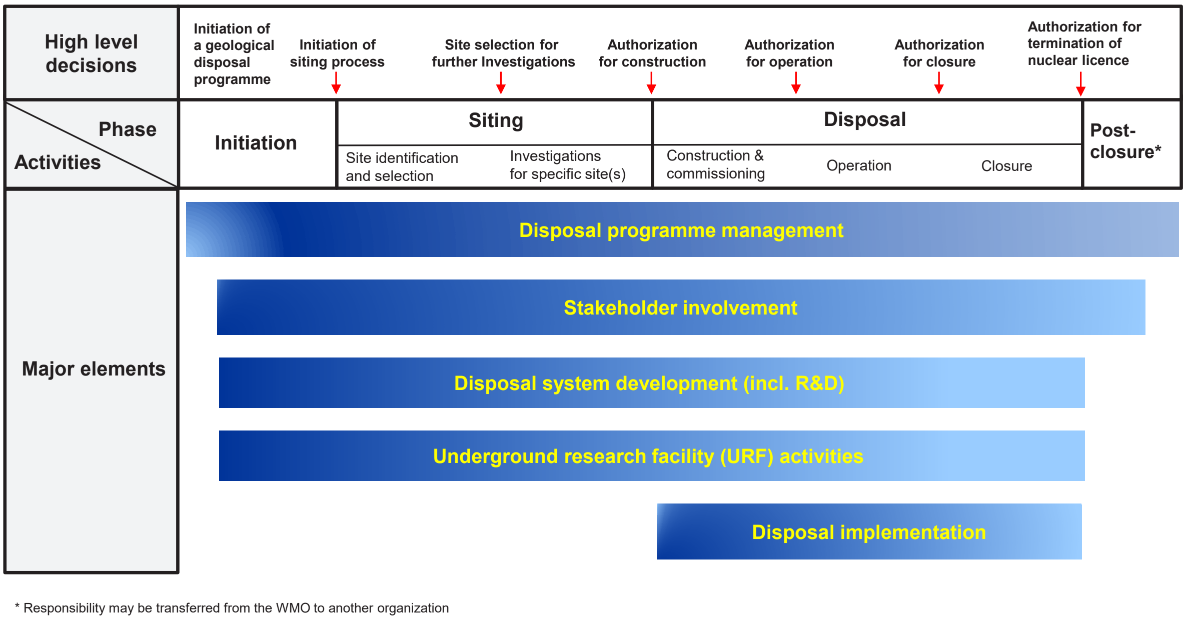

FIG. 3. Roadmap for a geological repository: relationship between high level decisions and phases, and major work elements.

responsibility to obtain input from all team members, but ultimately decision making authority resides in this element.

Leadership for a geological disposal programme is provided primarily by the WMO management. That leadership manifests itself in the form of programme strategy, planning and organization, which define the roles, responsibilities and authority for all participants. A management system supports the development, implementation and continued enhancement of a pragmatic and strong safety culture and promotes the adoption of best practices for all waste disposal activities [29, 30]. Senior management have a significant influence over the safety culture of an organization and as such are expected to provide leadership in this area, showing visibility, accessibility and responsiveness to the views of staff and stakeholders on safety related matters.

Disposal programme management also ensures effective knowledge transfer (e.g. documenting and archiving information) and succession planning for continuing good leadership [29].

The roles and functions of disposal programme management include the following subelements:

- — Strategy and planning;
- — Programme requirements management;
- — Licensing and permitting;
- — Nuclear security and safeguards;
- — Protection of health, safety and the environment;
- — Corporate services;
- — Quality management and management systems;
- — Knowledge management;
- — International cooperation.

3.1.1. Strategy and planning

The WMO develops and maintains a strategy aimed at reaching the long term objectives of the disposal programme in a systematic way. The strategy maps out milestones and clear time frames for achieving those milestones. At the start of the programme this involves assignment of project managers, preparation of organizational charts and definition of the project structure, as well as procedure identification and development. Planning ensures consistency among all aspects of the programme, including the safety strategy, safety case, stakeholder involvement, timeline and budgetary considerations. This subelement also includes developing and updating the disposal programme WBS and schedule throughout the lifetime of the programme.

Estimated costs for the disposal programme are analysed from the programme's inception and are updated periodically. Programmatic risks and opportunities are monitored and managed to maximize the probability of successfully achieving programme goals.

Senior management has the responsibility for ensuring that the goals, strategies and objectives for the organization are consistent with the organization's safety policy as per Requirement 4 of GSR Part 2 [29].

3.1.2. Programme requirements management

One of the key functions of the WMO is to identify and manage a set of programme requirements. The requirements at the highest level originate from company and project goals, policy and regulatory standards, international requirements and other stakeholder positions. From these high level requirements, functional (system) level requirements are defined and documented [4]. In line with these higher level requirements, technical requirements, including design requirements and design criteria, are developed. These requirements then form the bases for developing the specifications, drawings, system descriptions, etc., required for the final design, construction and commissioning of the facility. Verification and validation processes are applied accordingly.

Requirements management can be defined as three distinct activities:

(a) Requirement identification: "The requirements are decomposed, classified, grouped, ranked and prioritized during this stage. It is important that stakeholders ensure the requirements are correctly defined, captured and interpreted … This activity is concluded with the agreement and approval of all stakeholders that a valid and applicable requirement has been identified" [31].
(b) Requirement commitment: "The commitments needed to meet requirements are identified, documented and approved by stakeholders. Note that some requirements result directly in implementation, e.g. codes and standards" [31].
(c) Requirement implementation: "These activities are focused on implementing requirements and associated commitment(s)" [31].

The WMO may elect to manage project requirements in a series of separated systems (e.g. requirements from the regulator might be tracked in a database dedicated to regulatory commitments, whereas financial commitments would be managed by the finance department) or in an integrated manner using a centralized method.

3.1.3. Licensing and permitting

This disposal programme management subelement is related to the preparation of licence applications and compliance with applicable regulatory requirements, codes and standards, including the environmental impact assessment (EIA). Legal services are often needed to support licensing activities and typical organizational functions, such as contracting. The licence application for construction and operation also addresses how regulations that apply to industrial (e.g. mining) or construction operations are being met. This subelement also includes 'pre-licensing' processes which can entail early review and feedback from the regulator related to selected aspects of the project (e.g. container design).

3.1.4. Nuclear security

Nuclear security principles and obligations related to radioactive materials have to be maintained throughout the programme, including during the disposal phase. With respect to security concerns, some forms of radioactive waste may pose a security risk from the perspective of malicious radiological use and need to be protected accordingly. Standard security measures by the WMO are needed to protect programme assets from theft and prevent unauthorized access to programme facilities, and for the protection of information and cybersecurity. These actions account for the physical safety and integrity of the waste materials.

3.1.5. Nuclear safeguards

For a disposal facility, the general safeguards activity is divided into three distinct phases:

(a) During design and construction;
(b) During operation;
(c) After the facility has been closed.

The goal of safeguards measures at any of these phases is to provide independent verification that nuclear material has not been diverted to a non-peaceful activity — which can include further covert processing of the spent fuel in an undeclared operation within the repository itself, or elsewhere in the State. This verification is typically achieved through a combination of material accountancy, containment and surveillance measures providing continuity of knowledge, and both in-field and headquarters based verification activities that may involve remote data transmission and monitoring.

During the design and construction phase, the safeguards by design (SBD) concept may be employed. SBD is defined as:

> "a voluntary process to facilitate the improved implementation of existing safeguards requirements, providing an opportunity for stakeholders to work together to reduce the potential of unforeseen impacts on nuclear facility operators during the construction, startup, operation and decommissioning of new facilities" [32].

The SBD concept is applied to geological repositories, as it promotes the practice of ensuring that space and flexible infrastructure are considered and allocated in the early stages of the geological repository programme for the implementation of safeguards equipment. This may also include the implementation of design changes to reduce the eventual burden of verification measures, the development or modification of dedicated IAEA equipment that would reside and operate in the facility during the operational phase, and the development of joint procedures for sharing of equipment and/or information between the State and the IAEA. Furthermore, during the construction phase, the design information provided by the State will typically be confirmed by the competent authorities to ensure that the disposal facility is constructed as declared (i.e. there are no undeclared tunnels, access shafts, drifts, etc., where material could be diverted or covert processing could take place) and this will then be repeated periodically throughout the lifetime of the facility. This recurring activity also confirms the declared flow of nuclear material above ground (during receipt and encapsulation) as well as below ground (emplacement).

Safeguards measures will already have been applied to the spent fuel as part of the safeguards approach for the State. During the operational phase of the geological repository, the spent fuel will undergo final verification before being transferred to its final emplacement location. Depending on the type of disposal facility and whether additional processes such as encapsulation are involved, the spent fuel may be verified at an earlier stage in the process (such as at the interim storage location), before being placed under containment and surveillance measures in order to maintain continuity of knowledge concerning the spent fuel, which may extend to or past the final emplacement of the fuel. These measures are typically specified in detail in the subsidiary arrangements for the safeguards agreement in force.

The post-closure safeguards approach will need to be agreed between the State and the IAEA to ensure that there is no undeclared access to the material in the repository. It should be noted that the facility will be operating as intended when closed and that, under the current understanding of safeguards obligations, safeguards will continue to apply. The specific post-closure safeguards approach will be developed closer to the point at which the repository will be closed. This strategy, while adding some degree of uncertainty in the present, allows flexibility for the application of the full future repertoire of safeguards measures that will be available (noting that closure typically occurs for a repository many decades to a century following the start of operations).

Currently, the SBD concept has been applied to the DGR and encapsulation plant in Finland, which was under construction at the time of publication [8]. This enables each of the international safeguards inspectorates (the European Atomic Energy Community (Euratom) and the IAEA), as well as the national authority (STUK), to effectively and efficiently fulfil their mandates related to the implementation of safeguards [8, 33]. Further information on safeguards measures for geological disposal and the technical implications of safeguards requirements in the implementation of a geological disposal programme are provided in Ref. [32].

3.1.6. Protection of health and safety and the environment

Protection of the health and safety of workers and the public, as well as protection of the environment, are also considered to be part of programme management. The occupational health and safety management system is a framework that allows the organization to consistently identify and control its health and safety risks, including radiological and environmental risks, reduce the potential for incidents, help achieve compliance with legislation and regulatory codes and standards, and continually improve its performance. Implementation of health and safety and environmental protection plans and procedures will involve compliance with multiple legal and regulatory codes and standards during various phases of the programme.

The environmental monitoring programme is carried out over the lifetime of the facility to monitor for any changes in the environmental baseline conditions. This programme is based to a large extent on inputs and findings from the EIA, covered in Section 3.3.11.

3.1.7. Corporate services

Corporate services are necessary for any large scale construction programme and include the following activities:

- Human resources and training;
- Budgeting, financial controls and procurement;
- Legal services.

Specific attention is paid to the management of human resources in the field of nuclear energy because of the high standards of performance expected in this field and the considerable time needed to develop such specialists. IAEA Nuclear Energy Series No. NG-G-2.1, Managing Human Resources in the Field of Nuclear Energy [34], addresses this subject area, including ensuring that individuals have the competence needed to perform their assigned tasks, organizing work effectively, anticipating human resources needs, and monitoring and continually improving performance.

The nuclear industry is a complex assemblage of technologies, systems and a very well defined regulatory regime. In order to ensure that society gains the benefits of this technology safely and at a reasonable cost, it is essential that staff working in nuclear facilities are well trained and acquire the relevant skills and experience. To achieve this the industry has been a leader in developing and deploying a systematic approach to training (SAT). This system examines jobs at the individual task level and comprehensively defines the sum of the training requirements for each job category. Professional trainers using advanced tools and training methods then tailor the learning processes to deliver the best training possible. This system has been so successful and widely recognized that it is mandated in regulations and has been adopted by most high technology businesses. In order to build upon the initial training programmes, continuous refresher training with the integration of relevant OPEX is delivered at defined times.

Once the activities of the disposal programme have been identified in the WBS, the costs associated with each activity are assessed to obtain an estimation of the overall overnight cost of the programme [28]. This requires building a database including the quantities or durations of the WBS items and their estimated unit costs. These unit costs can include labour costs, material costs, infrastructure work costs (such as the building of roads) and the cost of consumables (such as electricity, water or fuel). Guidelines on developing a cost database specific to a waste disposal programme are provided in Section 5.2 of Ref. [28]. Procurement and contracting, which include putting arrangements with vendors, contractors and suppliers into place, are specialized functions and should be carefully managed by suitably qualified and experienced personnel.

Legal services are often needed to support licensing activities and typical organizational needs, such as contracting. Regulatory approval granting authorization for construction, operational and other activities by the geological disposal programme may be conducted in a formal legal framework, requiring careful analysis by legal services within the WMO. The need for such services typically increases significantly prior to the submission of major licence applications. In addition, the disposal programme likely requires legal expertise for functions that are typical of any large organization, depending on the circumstances in the Member State.

3.1.8. Quality management and management systems

A quality assurance and quality control programme for the disposal system and associated activities from early siting to operation and closure is established to achieve compliance with the design basis and with regulations. Quality management for a radioactive waste disposal facility is usually considered to be a part of the WMO's overall management system: "The term 'management system' includes all the initial concepts of quality control (controlling the quality of products) and its evolution through quality assurance (the system for ensuring the quality of products) and quality management (the system for managing quality)" [2]. In essence, an effective management system integrates all aspects of managing a facility, including the safety, health, environmental, security, quality and economic requirements, into a single coherent system assurance programme.

Management system requirements and planning, and the establishment of management system procedures and methodologies relevant to different stages of repository development are described in IAEA Safety Standards Series No. GSG-16, Leadership, Management and Culture for Safety in Radioactive Waste Management [30], and IAEA Nuclear Energy Series No. NW-T-1.2, The Management System for the Development of Disposal Facilities for Radioactive Waste [35]. The development of the management system for an organization will be influenced by:

- Internationally recognized standards such as the International Organization for Standardization (ISO) 9000 [36] and 14000 [37] families;
- Guidance associated with the defined regulatory and statutory requirements of States;
- Standard practices of the nuclear industry;
- The organization's own standard practices.

The management system manual describes how the whole organization works, and includes its mission, vision, policies, processes, procedures and instructions or references to locate them.

In terms of responsibilities, it is noted that:

> "Senior management should ensure that all radioactive waste management activities are undertaken in compliance with the management system. Senior management should ensure that the management system continues to be properly implemented, assessed and improved, especially during periods of

> change, and that relevant personnel are informed of any changes and the reason for their introduction and are trained in the new processes and procedures" [30].

Quality control activities typically generate documentation that contains test or inspection results and may act as a record of conformance or acceptance. Quality assurance activities are governed by documented management system processes and their subprocesses [38]. This information is also important for any reassessment of the facility in the future.

Typically, the quality manual, or the quality management system manual, specifies and describes identified processes, methods, criteria and responsibilities belonging to the quality management system. The role of the quality manual is to make it easier for personnel to understand how quality activities are implemented in their organization. Furthermore, the quality manual is extended appropriately to cover external suppliers of products and services.

3.1.9. Knowledge management

The extensive data generated from a geological disposal programme, when considered with the different and often lengthy phases involved, indicate the need for a provision for and a commitment towards long term data gathering, the wide transmission of knowledge and sustained expertise [30]. There is an evident risk that in the absence of knowledge transfer plans, essential knowledge can be lost between different phases of a nuclear facility lifetime, for a variety of reasons, if it is not properly codified and/or transferred in advance [39]. Managing information and knowledge is an integral part of the WMO's management system [40]. As stated in GSG-16 [30]:

> "The management system should include a process for ensuring that lessons, knowledge and experience from comparable facilities and projects, including those conducted nationally and internationally, are taken into account at all stages in the design of a radioactive waste management facility."

The process of knowledge management focuses on workers and organizational culture to foster and promote the sharing and use of knowledge; on processes or methods to find, develop, capture and share knowledge; and on technology to store knowledge and make it accessible and allow individuals to work together without needing to be in the same place.

The long term preservation of information and the evolution of organizational structures are key aspects to be considered at an early stage when planning knowledge management for all phases of a nuclear project. Member States and other international organizations, such as the NEA, have ongoing initiatives in this area and have issued some publications specific to the area of radioactive waste management, including on memory preservation [41] and applications of metadata [42].

As it is not possible to foresee the entire technological evolution of information management, the knowledge assets of the project need to be captured and codified using open, extensible and standardized technologies and media formats, which will ensure that knowledge will be available across all phases [41].

3.1.10. International cooperation in research and development

Many geological disposal programmes have included a significant component of international collaboration. There are benefits to both parties in international collaboration via joint R&D activities, which are best coordinated in the disposal programme management element. These collaborative activities typically include scientific and engineering research in URFs as well as in other types of laboratories and above ground facilities. The operator of the disposal programme URF often benefits from technical expertise and funding supplied by outside collaborators. The outside collaborator benefits from access to the URF and the research support infrastructure already in place at the URF. Both parties benefit from access to the data generated by the scientific or engineering research activities. Public confidence in the geological disposal programme tends to be enhanced by the participation of the broader international research community. Disposal programmes that are at an early phase of development or in Member States with smaller nuclear programmes may find particular benefit in using information from existing URFs in their preferred geological medium and in participating as international collaborators in those URFs.

In summary, the activities for programme management and deliverables for a geological repository programme are briefly described here but follow standard project management and management systems concepts already described in earlier IAEA publications (see Refs [4, 5, 31] and others).

3.2. STAKEHOLDER INVOLVEMENT

Stakeholder involvement is identified as a separate element because of its recognized role in disposal programme success and the global nature of its function in the programme. The objective of stakeholder involvement is for the WMO to obtain the active participation of outside groups, organizations, or individuals who have an interest in the outcome of the geological disposal programme. This element is active from the initiation of the programme. The activities related to stakeholder involvement cover a wide range and may include establishing a communication strategy, web sites, public education programmes, interactive workshops, formalized exchanges of information, citizens' panels and site tours, and obtaining public review comments for programme documents. More detailed information on stakeholder engagement principles and activities is given in Ref. [43]. Some stakeholders, such as government entities and regulatory bodies, have explicit decision making authority. Stakeholders can be categorized as:

- National government;
- Local/regional government;
- Regulatory bodies;
- Advisory/consultative bodies;
- Waste producers;
- The public (including the local community);
- Indigenous peoples;
- Other stakeholders (e.g. media, non-governmental organizations, the scientific and academic community).

A good practice is for the WMO to engage each category of stakeholder in a manner that is understandable and clear to that stakeholder, while meeting the objectives of the geological disposal programme. Consequently, an overarching stakeholder engagement strategy and plan is devised and updated as the programme progresses. Important components of the engagement plan include identifying and prioritizing stakeholder groups; identifying the important issues for each group; identifying the means, tools and approaches for engagement; and designing an evaluation component [43]. Stakeholder engagement activities can range from a straightforward two way dialogue of informing and listening through to more structured approaches, including consulting, exchanging, collaborating and joint decision making. In any case, it is important to define the roles of the stakeholders from the start of the programme in a way that each of them knows whether and/or how they can participate in decision making.

3.2.1. National government

Public authorities of national governments generally interact with a disposal programme in formalized and often legally mandated ways. The national government is the source of the radioactive waste management policy that governs the WMO and the geological disposal programme [23]. The national government also directs funding for the disposal programme and exercises some form of programmatic oversight. In addition, the national government has a key role in making the high level decisions that govern the progress of the disposal programme. As such, the relationship between the national government and the disposal programme is highly important and is a crucial aspect of stakeholder involvement.

3.2.2. Local/regional government

Several local and regional governmental representatives are important stakeholders that require engagement on a broad range of potential topics, including environmental impacts, land use policy, transportation, economic policy and cultural issues. Local government and community organizations are typically an influential category of stakeholders. Such stakeholders represent the public who would be most impacted by a disposal programme during the development, disposal and post-closure time periods. Disposal programme engagement with these stakeholders evolves with time and begins with the consideration of a particular site for programme activities, such as site investigations or construction of a URF.

Interest of local community stakeholders often peaks during the site selection and construction licensing periods of the disposal programme but remains an important factor into the disposal phase. Engagement with local community stakeholders presents an opportunity for the WMO to explore the scientific aspects as well as the economic benefits (e.g. employment, commercial development, infrastructure improvements, tax revenues) of the geological disposal programme. Such potential community benefits become increasingly important in the time period leading up to the submission of the licence application for construction. A transparent site selection process in which the scientific basis and fairness of the process are apparent will help to strengthen acceptance for the selected site.

3.2.3. Regulatory bodies

Regulatory bodies are stakeholders with an ongoing, clearly defined role in the progression of the geological disposal programme. The role of the regulator in a geological disposal programme is to establish regulatory requirements for the various stages of the licensing process. It sets out conditions for the development, operation and closure of each disposal facility and carries out activities to ensure that requirements are met [1].

The regulatory body will interact with the WMO over the course of the life cycle of the programme to conduct reviews, assessments and inspections. The WMO's engagement with regulatory bodies is not limited to submission of the licence applications but may involve periodic exchanges of information that inform the regulatory bodies of technical progress by the disposal programme and provide them with opportunities to express opinions and concerns about the safety case and its technical basis. It is common for multiple regulatory bodies associated with different aspects of the disposal programme, such as nuclear, industrial, mining and environmental safety matters, to be engaged with the programme.

3.2.4. Advisory/consultative bodies

Commissions or advisory groups with expertise that is relevant to the geological disposal programme are often created by the national government to review, oversee and/or comment on it. These groups have a mandated role as stakeholders in the development of the geological disposal programme. Formal interactions with these stakeholders are typically ongoing and are an important contributor to public confidence in the disposal programme. In Switzerland, the Waste Management Advisory Council acts as an independent advisory group and plays an important role in promoting dialogue among all stakeholders [44]. In the UK, the Committee on Radioactive Waste Management aims to provide independent advice on proposals, plans and programmes to deliver geological disposal for radioactive waste [45]. The Committee has published position papers on various topics in the development of a geological repository, including safety requirements, retrievability considerations and site selection, and has engaged in outreach activities in the siting process. Other advisory or consultative bodies may have an informal or non-statutory role in stakeholder involvement. Such groups may consist of local organizations or citizen associations that are self-organized around issues related to the geological disposal programme. A WMO that remains flexible and open to the involvement of these stakeholder bodies as they form and express interest in engagement with the programme will mitigate potential risks to the programme.

3.2.5. Waste producer

Engagement with waste producers is a generally straightforward, but is a critical component of the stakeholder engagement process. Disposal programme development requires detailed knowledge of the characteristics, form and volume of the waste. Stakeholder involvement with waste producers may include negotiations over WAC. During operations, close coordination between the WMO and the waste producers is needed for efficient delivery and scheduling of waste shipments.

3.2.6. Public (including local community)

Experience shows that public acceptance and confidence in a nuclear project stem from engagement at the national, regional and local levels. As with all stakeholders interacting with the WMO, openness and transparency are essential for members of the public. Interactions with each of these populations may require individual planning that tailors the engagement to the issues involved. Interaction with members of the public at the national level may emphasize broader issues regarding geological disposal in general, whereas engagement with local community members may focus on detailed safety concerns, scientific findings and the potential impacts of the disposal programme. Engagement with local community members during the selection of a specific site may play a pivotal role in the ultimate success of the disposal programme. Active interaction with the local community may result in improved planning for the development of the disposal programme. For example, communication between Andra and the community of Bure led to the relocation of surface handling facilities in the disposal system design to address the concerns of local citizens [46].

The specific roles and responsibilities of the public are defined within the national framework and can provide a degree of influence as the project proceeds. For example, for the empowerment of local people, the local right of veto on siting was introduced in 1987 in the Finnish Atomic Energy Act, which was considered of high importance by the local public. With the right of veto, local people could trust that they would have a say in the final decision making on siting and, in this case, there were never strong objections to Posiva's investigative activities at the candidate sites [9].

3.2.7. Indigenous peoples

By virtue of their unique rights, cultures, and use and knowledge of the land, as recognized in the United Nations Declaration on the Rights of Indigenous Peoples [47], Indigenous peoples may be important stakeholders in the engagement process associated with the disposal programme in some Member States. Engagement may be further guided by associated legislation, treaties, land claim agreements or other regulations in a Member State. Open and transparent engagement with Indigenous peoples by the WMO throughout all phases of the disposal programme will ultimately benefit the programme development and implementation.

3.2.8. Other stakeholders

The media is an important means of communication between the disposal programme and other stakeholders, particularly the general population. In addition, the media may play a significant role in influencing public opinion regarding the programme. Stakeholder involvement with the media is continuous and timely, but conducted in an organized, consistent and professional manner. Considerable expertise is available in managing public relations through the media and can be employed by the programme. The chosen medium (e.g. written, digital, face to face) for communication will differ depending on the situation (e.g. audience, budget, desired message); it is, however, prudent to continually review and revisit the most effective and appropriate channels given the changing media landscape [43].

Several other organizations and entities also serve as stakeholders, requiring engagement from the disposal programme. These include environmental organizations, non-governmental organizations and any other groups that are motivated to be involved in the disposal programme process. A wide range of individuals and organizations with specialized technical expertise relevant to the geological disposal programme, from academia and elsewhere, compose a potentially important class of stakeholders. Although interactions with some entities may remain adversarial, it is ultimately beneficial to the disposal programme to maintain involvement with all groups willing to participate in the process.

3.3. DISPOSAL SYSTEM DEVELOPMENT

This major element consists of developing the technical and scientific basis for the geological disposal repository. The technical basis for disposal is repeatedly refined as additional information is obtained and as analyses and assessments are conducted. In general, the level of effort in this element ramps up quickly during the initiation phase, remains high during the siting phase, and ramps down during the latter part of the disposal phase. Major categories of activities in this major element include:

— Safety strategy;
— Waste inventory and characterization;
— Site investigations and characterization;
— Supporting R&D;
— Disposal system design and engineering;
— Conceptualization and modelling (simulation);
— Safety case development;
— Operational safety assessment;
— Post-closure safety assessment;
— Monitoring and surveillance;
— EIA.

3.3.1. Safety strategy

Safety strategy sets out the approach and management plan for achieving safe disposal. It addresses key principles and objectives such as defence in depth, containment and isolation of the waste, demonstrations of safety related features, efficiency and interdependences with the pre-disposal management of the waste [1]. It serves as a fundamental basis for the safety case and as such is developed at an early stage of the programme.

For example, in the geological disposal programme for spent fuel disposal in Finland, Posiva has articulated the safety strategy to rely primarily on long term isolation and containment, and secondarily on retention and retardation of radionuclides [9]. The related safety principles for that programme involve a multibarrier system consisting of the engineered system and the host rock, providing safety through defence in depth.

The safety strategy is re-evaluated periodically for validity as the programme develops and any evolution of the strategy is documented.

3.3.2. Waste inventory and characterization

This publication is mainly focused on the disposal of spent fuel, HLW and ILW generated from nuclear reactors. However, it is well recognized that some Member States have identified other types of radioactive wastes for disposal as well into a geological disposal facility. The composition of spent fuel depends on the reactor type and fuel source. In general, spent fuel from a pressurized water reactor (PWR) would have in general about 95% ^{238}U and about 1% ^{235}U, with the remaining 4% being plutonium, activation and fission products, and transuranics.

There are two approaches for managing spent nuclear fuel. One is an open or once through fuel cycle, in which spent fuel is considered as waste and after a period of storage, is encapsulated with a container suitable for disposal and then is emplaced into a geological disposal facility. The other is the closed cycle (including the partially closed cycle), in which spent fuel is separated into uranium, plutonium and HLW (containing minor actinides, fission and activation products). The HLW (along with other waste such as LLW and ILW) resulting from reprocessing is then stored to allow the decay heat to be reduced pending future disposal, normally in a geological disposal facility as well [21].

Characterization of the inventory — defining the radiological, physical, chemical, radiochemical and other characteristics of the waste — is required at a level of detail sufficient to support major aspects of the disposal programme, including design and safety assessment as well as development of the facility's WAC. This is especially true for the part of the inventory that has the largest impact on the assessed doses and risks. With respect to this, it is important that the waste generator (e.g. nuclear power plant operators) provide and quality assure the data required to calculate the radionuclide inventory.

The WMO develops the WAC in coordination with relevant stakeholders to establish the disposal facility's requirements for the receipt, evaluation and acceptance of waste. The WAC specifies requirements and limits with respect to, but not limited to, radionuclide content and activity properties, heat output, properties of the waste form and packaging, identification data and other physical and chemical properties. Planning early for both waste characterization and the WAC at the facility helps to inform waste related activities earlier in the waste management process.

3.3.3. Site investigations and characterization

Site investigations and characterization obtain geological, hydrogeological and environmental data. These data support understanding of the natural features, events and processes (FEPs) at a site. As stated in SSG-14 [1]:

> "The site characterization programme should be conducted at spatial and temporal scales and of a scope sufficient to acquire an adequate understanding of the phenomena that could affect site safety for the time periods of interest and also to develop credible physical process models."

Given the large number of potential scientific and technical investigations that could be pursued, it is advisable to prioritize site characterization activities based on the relevance and importance of the associated data to the safety case and safety assessment. Appendix I of SSG-14 [1] provides recommendations, in particular for the detailed site characterization stage of a geological repository programme.

Site characterization activities should begin at the earliest possible time within a repository development programme before the perturbations caused by repository construction and operation start to accumulate. This early information is important because it allows for an understanding of the nature and properties of the natural, 'undisturbed' environment of the disposal system to be developed.

Fortunately, an extensive body of geoscientific knowledge concerning site investigation methods and approaches to site characterization for several potential geological disposal media has now been acquired by the international community and is available to Member States to support their disposal programmes. A description of the data acquisition and interpretation techniques used by WMOs to support site investigations is found in Ref. [48].

3.3.4. Supporting research and development

Scientific and engineering R&D provides a sound technical basis for the repository programme, supporting aspects of repository design and engineering, waste package encapsulation design and waste package emplacement operations. In terms of the safety case, R&D is critical in understanding coupled thermal, hydrological, chemical, radiological and mechanical processes that influence the behaviour and evolution of the disposal system environment, including the host rock, waste packages, buffer, backfill and seals. The process of R&D will continue after the construction licence is granted, in part to further reduce uncertainties in the post-closure safety assessment of the final repository and to support the continued development and optimization of the facility.

Large research projects have been carried out successfully through joint international work. Since the 1960s, several IAEA Member States have been conducting experimental programmes in URFs that have been purposely built or created from existing mines and galleries; R&D activities in URFs are described in the major element entitled URF activities.

3.3.5. Disposal system design and engineering

Starting with a generic design at an early stage of the repository programme, the design will be continuously updated with additional details as more is learnt about the site specific boundary conditions. The disposal system of confinement consists of the waste form, container, sealing materials, backfill, repository structure (including shafts, ramps, ventilation), host rock and surrounding environment. IAEA Nuclear Energy Series No. NW-T-1.27, Design Principles and Approaches for Radioactive Waste Repositories [4], provides an overview of the typical design stages during a repository life cycle: generic designs, conceptual designs for siting, technical designs for construction licensing, detailed designs for construction and operation, continued detailed designs for operation and expansion and designs for closure. In addition, this publication describes the important principles that guide engineering design of geological repositories in detail, including the use of a requirements driven design basis; the multiple barrier safety concept; the use of safe, reliable, available and maintainable technology; iterative development and optimization of the design; the maintenance of design integrity; the production of a transparent and auditable design; and the incorporation of nuclear safeguards and security [4].

As outlined in SSG-14 [1], geological repository design and engineering is an iterative process that may be modified based on:

(a) Further definition of the inventory and the WAC;
(b) The results of the safety assessment;
(c) Optimization of operational considerations, such as radiation protection and conventional safety (e.g. changing the configuration of emplacement rooms to minimize exposure in line with the as low as reasonably achievable (ALARA) principle in certain areas);
(d) New data concerning the site generated during site investigations.

Engineering is responsible for developing and testing emplacement processes, the fabrication of specialized prototype equipment and components, and general industrial processes. Disposal system design also entails analysis and mitigation of nuclear criticality during waste handling, temporary storage and emplacement.

The engineered design is updated iteratively during the siting phase in concert with increasingly detailed site characterization information and the evolution of the safety case, including relevant R&D. For example, the disposal system design in granite for the SKB disposal programme in Sweden has undergone development over a long period of R&D, resulting in the KBS-3 repository design, which has been adopted by other disposal programmes [49]. Similarly, after years of research and testing, NWMO's reference design fuel container, referred to internally as the Mark II, departed from the previous reference design (Mark I) by utilizing a pressure vessel grade pipe as the shell material, an integral copper coating as a corrosion barrier and hemispherical heads [50].

3.3.6. Conceptualization and modelling (simulation)

Conceptual and numerical models are used in the interpretation of site characterization data, understanding the behaviour of the natural and engineered barrier systems and safety assessments. Conceptualization and modelling typically consist of a hierarchy ranging from detailed process level models to the integrated and abstracted total system performance assessment model. Model development is an iterative process in which newly acquired data are incorporated into successive versions of the models. In addition, insights from model sensitivity analyses are used to prioritize the acquisition of additional data and to guide further model development.

Modelling and assessment activity are conducted in parallel with site characterization and disposal system design. Relevant technical topics regarding the evolution of the natural system potentially include climate change, erosion, glaciation, sea level change and the changing biosphere. Topics potentially impacting on the safety of the engineered barrier system include corrosion, chemical and mechanical interaction with the geosphere, thermal impacts and radiation effects. The post-closure safety assessment model considers all of these FEPs in the evaluation of the long term safety of the repository and the potential impacts on human health and the environment [5].

The development of the various numerical models cannot be accomplished independent of a means of physically testing and calibrating their outputs via a large scale field demonstration where natural processes can be allowed to occur. In many numerical models, their input parameters or boundary conditions need to be adjusted to better reflect the reality of field performance. This kind of activity has been carried out extensively at URFs with respect to geological repository research and is elaborated upon in Section 3.3.12.

3.3.7. Safety case development

The WMO prepares and updates the safety case and safety assessment. Safety assessment by itself is not sufficient to make a case for safety. The entire suite of scientific and engineering studies performed in support of the long term safety evaluation needs to be presented, including discussion of uncertainties and of what additional data are to be obtained to either reduce or more fully understand uncertainties.

The IAEA defines the safety case as [5]:

> "the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility."

As per SSG-23 [5]:

> "Safety assessment is the main component of the safety case and involves assessment of a number of aspects … The fundamental element of the safety assessment is the assessment of the radiological impact on humans and the environment in terms of both radiation dose and radiation risks. The other important aspects subject to safety assessment are site and engineering aspects, operational safety, non-radiological impacts and the management system."

As mentioned in Chapter 2, the safety case and supporting safety assessment are reviewed and updated as necessary (prior to each major decision point as well as periodically) to reflect increasing knowledge and experience.

3.3.8. Operational safety assessment

The operational safety assessment considers safety during the disposal (i.e. construction, commissioning, operation) and closure phases.

Operational safety considers factors such as public health, the environment, public and worker safety, and security and safeguards. Worker safety during construction and operation of the repository is an important aspect of a geological disposal programme and will form a key part of any regulatory framework; experience from conventional mining and civil engineering projects informs this aspect. Mining and operational safety may be considered with long term safety in a single safety case submission or be the subject of separate, parallel submissions; regulatory requirements may also stipulate a specific approach.

Potential radiological impacts to workers and the public, both from normal day to day operations and from unplanned or unforeseen events during the operational period, are assessed. The requirements applying to radiological protection during the implementation of geological disposal are similar to those for operation in other nuclear facilities. The containment of radionuclides is ensured by the design of the facility and packaging (e.g. stainless steel canisters for vitrified waste and metal overpacks, and exhaust air filtering). Hazard analyses may be conducted to determine possible event sequences (e.g. dropping of waste packages followed by a container breach) that could lead to radiation releases during construction, either within the confines of the repository underground or above ground, and will include analyses concerning the potential impact on workers and members of the public. In addition to analysing risks, the operational safety assessment supports the development of robust responses in terms of prevention measures and procedures for mitigation for different accident scenarios.

Impacts from operational safety measures on long term safety are also evaluated. It is prudent for the WMO to take measures in advance to avoid and mitigate potential conflicts of interest between efforts to address long term safety objectives and efforts to attain operational objectives [1].

3.3.9. Post-closure safety assessment

The post-closure safety assessment evaluates the long term performance of the repository and quantifies its impact on human health and the environment. The post-closure period begins after the facility is closed. The potential migration of radioactive substances from the disposal facility, contaminant transport in the environment and the resulting radiation risks are quantitatively analysed by way of conceptual and mathematical models. Scenarios and FEPs that could influence the performance of the disposal system are addressed in the assessment. As stated in SSG-23 [5], "it should be shown that all potentially significant migration pathways from the facility have been considered and that possible evolutions of the system have been taken into account." Typically, the evaluation continues until the radioactive decay has reduced the hazard posed by the waste, although differences in how regulations are structured can influence how safety assessments are conducted.

Those FEPs that could give rise to safety concerns will need to be investigated and mitigated if necessary. For example, if the interactions of engineered components with each other or with the geological environment give rise to safety concerns, the design or materials may need to be enhanced, or the WAC may need to be adapted. Elements that are important for the post-closure phase are identified at the design stage together with the activities to be implemented. For example, in France, for the Cigéo project, Andra has outlined the need to control the intensity and extent of any disruption caused by excavation and emplacement, and in the event of an accident liable to alter the transport and retention properties of the Callovo–Oxfordian layer [46].

3.3.10. Monitoring and surveillance

This subsection focuses on monitoring and surveillance programmes that support the safety case. Monitoring data are expected to contribute regularly and routinely to decision making throughout the geological disposal programme. The main objectives of monitoring and surveillance of disposal facilities for radioactive waste are to [51]:

(a) Verify compliance with regulations and requirements;
(b) Confirm the performance of the barrier systems and other system components;
(c) Validate models and data input for modelling;
(d) Inform stakeholders, including the public, about the site and facility;
(e) Collect environmental data and develop a comprehensive database.

The extent and type of these activities will change throughout the lifetime of the facility. The management system supports this subelement in several ways, including in maintaining the continuity of data collection and adaptability to new approaches for the collection and interpretation of data.

A monitoring and surveillance programme can enhance public interaction and confidence. In that sense, consideration of public and societal concerns and interests may provide useful information to complement these activities.

3.3.11. Environmental impact assessment

The EIA is a process to identify and assess all of the environmental and socioeconomic impacts of a major project [1]. This assessment is often governed by environmental protection legislation that is separate from radiological control regulations and constitutes an additional component of the safety case. The EIA report presents the analysis and findings of the process in a holistic manner. It describes the baseline conditions of the environment and surrounding population, identifies the impacts of the project on the environment and population in all its phases and evaluates whether the impacts are significant. IAEA Safety Standards Series No. GSG-10, Prospective Radiological Environmental Impact Assessment for Facilities and Activities [52], provides recommendations and guidance on a general framework for performing prospective radiological impact assessments for facilities and activities, to estimate and control the radiological effects on the public and on the environment.

3.4. UNDERGROUND RESEARCH FACILITY ACTIVITIES

Within the country (at the disposal site or elsewhere) and/or abroad, URFs play an important role in establishing the technical basis for the safety of geological disposal and enable many activities to be carried out and tested under realistic geological conditions in the subsurface.

A generic URF is typically sited in an area that has geological conditions representative of the disposal concepts under consideration. There may be an opportunity to site a generic URF using a pre-existing facility such as a mine and a tunnel [6]. Generic URF studies may be more quickly and efficiently implemented in existing international URFs via cooperation with established geological disposal programmes, particularly for Member States with small disposal programmes or in the early stages of a disposal programme.

Site specific URFs are facilities that are located at specific sites or areas considered to be potential locations for a geological disposal facility. The development of one or more URFs is a legal requirement in some Member States (e.g. France [11], Germany [15] and the Republic of Korea [53]). Several Member States are embarking on a new URF programme at the time of writing, including China [54] and the Russian Federation [55].

Although individual R&D activities in the URF may satisfy multiple functions, the primary functions of the URF include the following subelements:

— Planning, design, construction, operation and maintenance of the URF;
— In situ site characterization;

— Scientific and engineering R&D;
— Technology testing, demonstration and optimization;
— Training and professional development;
— Stakeholder outreach.

This subelement includes a wide range of activities necessary to site, plan, design, permit, construct, operate, maintain and manage the URF. Many of these basic URF activities parallel the activities needed to develop the geological disposal facility, but on a smaller scale. Planning for URF activities is coordinated closely with the disposal programme, with the goal of reducing uncertainties relevant to the safety case. Initially, the need for a generic or site specific URF for a geological disposal programme is evaluated. For a generic URF, the siting process likely includes screening, stakeholder involvement, some level of site characterization, and property acquisition. URF planning involves consideration of the types of scientific and engineering experiments to be conducted, the engineering design of the facility, scheduling and budgetary planning. Although typically not a nuclear facility, the URF complies with regulatory requirements for a subsurface facility and may require a licence or a permit. Excavation and construction of the URF are major efforts that accommodate the unique characteristics of such a facility. Maintenance of the URF and the supporting subsurface infrastructure is an ongoing effort, needed for a safe work environment, and it is conducted in communication with scientists and engineers conducting studies in the facility.

3.4.1. In situ site characterization

When detailed scientific measurements of the natural geological system are not possible with surface based methods, the physical and chemical characteristics of the host rock in the immediate vicinity of the repository are measured in detail in the case of a site specific URF. In many cases, scientific data from the URF can be obtained on a larger scale, reducing the need to 'scale' up from borehole measurements or laboratory. The body of scientific information obtained from the URF provides added confidence to the conclusions about disposal system safety derived from surface based investigations.

3.4.2. Scientific and engineering research and development

Scientific research is often the primary function of a URF and is directed principally at supporting the safety case for the geological disposal programme. Such research addresses FEPs that have been identified as relevant to the isolation or mobility of radionuclides in the engineered barrier system and geosphere. Associated development activities often involve the development and implementation of innovative experimental methods related to the unique research conducted in a URF. Instrumentation and monitoring technologies may also be subjects of these activities.

Engineering R&D in the URF provides information on the performance of engineered systems, such as drifts, liners, waste containers, buffers, backfill and seals, in the geological environment of the repository. Engineering research in the URF works in tandem with scientific research in the analysis of FEPs and the evaluation of disposal system safety, particularly with respect to the functioning of the engineered barrier system and the coupled thermal, hydrological, chemical and mechanical processes. Engineering research also provides in situ information used in the disposal system design and geological engineering of subsurface excavations for the disposal programme.

3.4.3. Technology demonstration and optimization

Technology demonstration and optimization in the URF consists of activities associated with the development, testing and demonstration of unproven technologies that are unique to the geological disposal programme. Such technologies are generally related to disposal operations, such as special excavation methods, subsurface waste canister transport, waste canister emplacement, buffer materials, sealing and backfilling techniques. Instrumentation and monitoring technologies may also be subjects of these activities. In addition, full scale, in situ experience with construction, waste canister handling and waste canister emplacement provides an opportunity for optimization of the associated technologies, procedures and materials. Optimization of the disposal system may be performed for both safety and cost.

3.4.4. Training and professional development

URFs may serve an important function in training personnel within the geological disposal programme and provide a valuable opportunity for the professional development of key scientific and engineering staff. Many of the technical skills (and much of the experience) needed in a disposal programme, while based on basic scientific and engineering expertise, are unique to the field of radioactive waste repository science. A URF assists in the acquisition of these skills and provides the venue for scientific research and publications that are important for the professional development of highly qualified and motivated personnel. In addition, the URF may also provide a location for the training of skilled repository workers and tradespersons in the excavation, construction and operation of the repository.

3.4.5. Stakeholder outreach

A disposal programme URF also offers an opportunity for stakeholder engagement and outreach to the public. Operation of the URF helps to demonstrate the disposal programme's commitment to scientific integrity and safety. It can also serve as a tool for public education and stakeholder involvement by offering surface and/or subsurface tours. As mentioned in Section 3.1.10, international collaboration in the URF can enhance public confidence in the disposal programme.

3.5. DISPOSAL IMPLEMENTATION

Disposal implementation encompasses those activities directly associated with the excavation, construction, operation and closure of the disposal facility. It is important to note that the responsibilities of the WMO, as related to the geological disposal programme documented in this publication, are limited to on-site activities and do not include waste transportation or off-site storage. Excavation, construction and operational tasks would typically entail the largest budget and longest duration in the programme. The initial period of the disposal phase generally involves extensive construction of features providing access to the subsurface, such as shafts and access ramps. The activities of the disposal implementation element increase during the latter part of the siting phase and are fully underway at the time of the regulatory or governmental decision to grant a construction licence. Optimization of the design continues during the construction and commissioning subphase in preparation for waste disposal operations. Many construction and operational activities in the subsurface and surface facilities are closely linked and need to be coordinated accordingly. For programmes with a site specific URF, some of the surface and subsurface facilities associated with the URF may be in place prior to the disposal phase and may be incorporated into the disposal facility.

Some geological disposal programmes construct and operate a pilot facility prior to going for a full scale implementation. In France, a pilot phase will be carried out to test the repository's capacity prior to starting its operation [27]. In Switzerland, there will also be a pilot facility close to the repository, where waste will be emplaced and observed during the entire operational and monitoring phase [56].

The subelements of disposal implementation include:

- — Construction of surface facilities;
- — Construction of subsurface facilities;
- — Commissioning of the disposal facility;

— Surface operations;
— Subsurface operations;
— Closure of the subsurface facilities;
— Decommissioning of the surface facilities.

Non-nuclear surface facilities include a wide range of standard physical infrastructure associated with an industrial site. These features may include office buildings, laboratories, workshops, roads, railways, water supply, electrical supply, sewage treatment, communications infrastructure, security structures and firefighting infrastructure. Such facilities are not unique to a geological disposal facility and do not pose any special challenges regarding design or implementation; however, they do constitute a significant budgetary investment. In addition, because the disposal site is a nuclear facility, safety and security features are generally more robust than at a standard industrial site.

Nuclear surface facilities are specialized facilities for the safe handling of radioactive materials. These facilities include any structures in which the waste is handled, stored, processed, conditioned, or repackaged. Such facilities are generally custom designed and built to stringent standards to meet nuclear safety requirements. Special features of these nuclear facilities may include radiation shielding, air filtration systems, remote handling equipment, specialized fire suppression and robust seismic protection, among many other potential features. Consequently, the nuclear surface facilities are generally high cost components of the waste disposal system. Facilities for receiving and transferring waste from transportation shipments are designed to implement the transition from the shipping system to the disposal facility system. Verification that waste shipments conform to the WAC at the disposal facility is always conducted at the receiving facility. Implementation of an emergency response plan is also an aspect of the facility that is covered in this subelement.

Construction of surface and subsurface facilities is preceded by significant effort in planning, organizational development, procurement and contracting for construction services. Management of disposal system facilities is typically transferred from the construction contractor to the operator when construction is complete, and commissioning has been performed successfully.

3.5.1. Construction of subsurface facilities

The subsurface disposal facilities consist of the excavated workings of the repository, along with associated subsurface transport and emplacement equipment. Typically, excavation and construction of the disposal galleries in a subsurface disposal facility are ongoing activities that continue in parallel with the waste emplacement operations [57]. Subsurface access facilities include those features of the disposal system that provide communication between the ground surface and the subsurface disposal facility. Subsurface facilities also include ventilation, electrical power, water, and maintenance infrastructure and equipment typical of underground mining. Such facilities may include shafts, hoists, ramps and conveyance. Activities in this subelement include maintenance of subsurface facilities during operations and closure, such as dewatering and repair. Implementation of a mine safety and emergency response plan is also an aspect of the subsurface facilities that is covered in this subelement.

3.5.2. Commissioning of disposal facility

This subelement consists of the verification and testing of surface and subsurface facilities prior to waste disposal operations to assure compliance with the design specifications, as defined in the safety case. In general, commissioning refers to “The *process* by means of which *systems* and *components* of *facilities and activities*, having been constructed, are made operational and verified to be in accordance with the *design* and to have met the required performance criteria” [58]. The commissioning process for a geological disposal facility consists of many of the same components required in the commissioning of other nuclear facilities. The commissioning process covers the full range of facility conditions needed for the disposal system design and the safety case and it is governed by a plan developed to demonstrate readiness for operations. Processes related to waste emplacement are typically first verified using non-radioactive materials and then continued with radioactive waste containers.

3.5.3. Surface operations

Surface operations consist of activities associated with the receipt, acceptance, handling, processing, storage and repackaging of waste packages, and the transfer of waste containers to the subsurface. In addition, surface operations involve a wide range of supporting activities, including facilities maintenance, testing and laboratory work, personnel support, management support and site security. Monitoring is conducted to assure worker safety and environmental protection, and to detect potential radiological leakage. Surveillance and inspection of surface facilities and operations are conducted on an ongoing basis. A waste inventory tracking and accountability system is also implemented for surface operations.

3.5.4. Subsurface operations

Subsurface disposal operations include transport of waste containers within the subsurface, emplacement of the containers, installation of buffers, implementation of any grouting or sealing procedures, backfilling of disposal galleries if required, and the erection of any barriers included in the disposal design. Subsurface operations also entail maintenance of the subsurface facilities, including drifts, galleries, equipment and infrastructure, such as power distribution, communication, safety systems and ventilation. Monitoring is conducted to assure worker safety and to detect potential radiological leakage. Surveillance and inspection of subsurface facilities and operations are conducted on an ongoing basis. A waste inventory tracking and accountability system is also implemented for subsurface operations. There may be a period of monitoring and surveillance of the disposal system prior to final closure and decommissioning of subsurface facilities.

3.5.5. Closure of subsurface facilities

Closure of the disposal facility commences following the authorization for closure that comes as a regulatory or governmental decision. Typically, portions of the subsurface facility will have been filled with waste canisters, closed and sealed in a sequential manner over the duration of the operation subphase. Closure in the subsurface entails verification that design features such as backfill, barriers and seals have been properly installed. Waste handling equipment may be surveyed for radiological contamination and cleared for salvage or may be disposed of in place in the subsurface. Finally, subsurface access features such as drifts and shafts are sealed and backfilled in accordance with closure design requirements.

3.5.6. Decommissioning of surface facilities

Decommissioning of surface facilities entails verification that structures, equipment and the surface environment are free of contamination from activities by the disposal programme. Commonly, surface structures are demolished, and the resulting debris and equipment are removed from the site. Following decommissioning of the subsurface and surface facilities, termination of the nuclear licence for the facility is granted. Some disposal programmes require long lived markers for the site to warn future generations regarding the presence of the disposal facility in the subsurface.

3.6. MAJOR DELIVERABLES

The high level deliverables and supporting sublevel deliverables (see Fig. 2) that are the responsibility of the WMO are described in this section. They correspond to the roadmap major work elements and subelements. The deliverables provide supporting information for the high level decisions that are necessary to move forward through the phases of the disposal programme. In addition, they are designed to demonstrate scientific and technical readiness by the WMO. It is noteworthy that specific deliverables can vary depending on national geological disposal programmes. Table 1 provides a summary of the high level deliverables and supporting sublevel deliverables for each phase major roadmap element and phase.

3.6.1. Disposal programme management

The deliverables in the disposal programme management element are applicable for the entire time span of the programme. During the initiation phase, the programme management plan lays out a broad roadmap for administration and implementation of the disposal programme, such as programme plans or strategies, including siting, R&D, URFs, knowledge management, etc. Deliverables in this element demonstrate institutional readiness before the programme proceeds to the siting phase. The disposal programme management makes site recommendations at some intermediate time during the siting phase. At the end of the siting phase, deliverables include the licence application for construction and an updated programme management plan in preparation for the disposal phase. During the construction and commissioning phases, the programme management element is associated with the licence application for operation prior to the receipt of waste for disposal, supported by multiple sublevel deliverables for planning and programme control. During the operation subphase, disposal programme management has a major deliverable: the licence application for closure at the end of waste disposal activities. Updated programme management plans are also produced as deliverables for major shifts during the disposal phase. Finally, the disposal programme management element is associated with the application for licence termination of nuclear activities at the end of closure (and decommissioning). During the post-closure phase, the disposal programme management element is potentially associated with safeguards measurements and archiving of programme information.

3.6.2. Stakeholder involvement

During the initiation phase, the high level deliverables for the stakeholder involvement WBS element comprise an initial list of potential issues or concerns raised by the stakeholders, which incorporates the sublevel deliverables of support from society, decision makers and waste producers for initiating the programme and proceeding with the siting process. The high level deliverables for the identification and selection of site(s) subphase consist of the approval of decision makers of site identification. For the investigation of specific site(s) subphase, they consist of the approval of decision makers of both site identification and siting investigations. These deliverables are underpinned by the sublevel deliverables of appropriate local and general societal support, and updated lists of potential stakeholder issues. During the disposal phase, the stakeholder involvement work element is associated with the deliverables of approval by decision makers for construction, operation and closure of the disposal facility in a sequential manner. The approval of decision makers for these programme subphases is supported by maintaining and updating appropriate levels of stakeholder trust and community benefits, coordination with waste producers and updating the list of stakeholders' issues or concerns.

3.6.3. Disposal system development

An extensive series of deliverables fall under the purview of the disposal system development element.

The safety case provides a conceptual framework for the roadmap for the geological disposal programme and constitutes a repeatedly updated series of high level deliverables of increasingly detailed and specific information. During the initiation phase, the generic safety case document is the high level deliverable of the disposal system development element and informs the regulatory or governmental decision to begin the siting process. The safety case is a synthesis of other sublevel deliverables, which evolve as the programme progresses. Important sublevel deliverables document the safety strategy, waste inventory and WAC, site investigations and characterization data, disposal system design, the safety

TABLE 1. DELIVERABLES FOR MAJOR ELEMENTS OF A GEOLOGICAL DISPOSAL PROGRAMME

Phase	Subphase	Disposal programme management	Stakeholder involvement	Disposal system development	URF[a] activities	Disposal implementation
Initiation		— Programme plans, strategies — Programme requirements — Quality management system — Costing and procurement procedures — Database and archive — Readiness evaluation for siting	— Initial list of potential issues of concern — Appropriate societal support — Stakeholder engagement plan — Decision makers' acceptance of siting process — Waste producers' support for process	— Generic safety case — Generic safety strategy — Initial waste inventory, preliminary WAC — Information on national geology and geodynamics — Literature survey for disposal concept — Generic disposal system design and options — Generic safety assessment report — Supplementary studies for the EIA	— Evaluation of the need to construct generic URF(s) — Review of international URF results	

TABLE 1. DELIVERABLES FOR MAJOR ELEMENTS OF A GEOLOGICAL DISPOSAL PROGRAMME (cont.)

Phase	Subphase	Disposal programme management	Stakeholder involvement	Disposal system development	URF[a] activities	Disposal implementation
Siting	Site(s) identification and selection	— Site(s) recommendation — Updated programme plans, strategies — Programme requirements for safety and industrial safety — Updated quality management system for site identification — Occupational health and safety and environment plans — Updated cost estimate, procurement, legal service — Updated database and archive	— Approval of decision makers for site identification — Appropriate local and societal trust — Updated list of potential issues of concern for sites — Decision makers' approval of process	— Updated safety case based on site information — Detailed generic safety strategy — Updated waste inventory, WAC — Preliminary site description report — Preliminary R&D for disposal system — Conceptual design for disposal system — Conceptual model of long term evolution of barriers — Preliminary safety assessment report — Preliminary EIA studies report	— Generic URFs if required — Generic URF studies — Proposal and plan for site specific URF	

TABLE 1. DELIVERABLES FOR MAJOR ELEMENTS OF A GEOLOGICAL DISPOSAL PROGRAMME (cont.)

Phase	Subphase	Disposal programme management	Stakeholder involvement	Disposal system development	URF[a] activities	Disposal implementation
	Investigation for specific site(s)	— Licence application for construction — Updated programme plans, strategies — Programme requirements for construction licence — Safeguards plan for construction — Community safety and emergency response plan — Updated cost estimate, procurement, legal service — Updated quality management system for site investigation — Updated database and archive	— Approval of decision makers for site investigations — Appropriate local and general societal trust and engagement — Agreement for site investigations to extent needed	— Updated safety case for construction — Safety strategy for construction licence — Design waste inventory, WAC — Site characteristics report for construction licence — Detailed R&D for disposal system components and construction equipment — Design of disposal system for construction licence — Long term evolution of disposal barriers for construction licence — Updated safety assessment report for construction licence — EIA report for construction licence — Environmental monitoring for construction	— Site specific URF for construction licence — Collection of geological and engineering information — Site specific studies	— Construction plan for surface and subsurface facilities

TABLE 1. DELIVERABLES FOR MAJOR ELEMENTS OF A GEOLOGICAL DISPOSAL PROGRAMME (cont.)

Phase	Subphase	Disposal programme management	Stakeholder involvement	Disposal system development	URF[a] activities	Disposal implementation
Disposal	Excavation and construction	— Licence application for operation — Updated programme plans — Programme requirements for operations — Safeguards for operations — Updated community safety and emergency response plan — Updated cost estimate, procurement, legal service — Updated quality management system for construction — Updated database and archive	— Approval of decision makers for construction — Appropriate local and general societal trust and community benefits — Updated list of potential issues of concern for construction — Coordination with waste producers	— Updated safety case for operation — Safety strategy for operating licence — Final waste inventory, WAC — Updated site characterization report for operation licence — Additional R&D for disposal system components and operational equipment — Design optimization for emplacement operations — Long term evolution of disposal barriers for operation licence — Updated safety assessment report for operations — EIA report for operations — Environmental monitoring for operations	— URF studies for operation licence — Maintenance of site specific URF — Collection of geological and engineering information and design optimization	— Surface facilities and first phase of subsurface facilities — Construction of surface facilities and first phase of subsurface facilities — Emergency plans — Detailed plan of commissioning and implementation of commissioning — Detailed operational procedures for all facilities

TABLE 1. DELIVERABLES FOR MAJOR ELEMENTS OF A GEOLOGICAL DISPOSAL PROGRAMME (cont.)

Phase	Subphase	Disposal programme management	Stakeholder involvement	Disposal system development	URF[a] activities	Disposal implementation
	Operation	— Licence application for closure — Updated programme plans — Programme requirements for closure — Safeguards for closure — Updated community safety and emergency response plan — Updated cost estimate, procurement, legal service — Updated quality management system for operation — Updated database and archive	— Approval of decision makers for operation — Appropriate local and general societal trust and community benefits — Updated list of potential issues of concern for operation — Coordination with waste producers	— Updated safety case for closure — Verification of waste inventory, WAC — Safety strategy for closure — Updated site characterization for closure — Design optimization and final closure design — Long term evolution of disposal barriers for closure — Updated safety assessment report for closure — EIA report for closure — Environmental monitoring for closure	— URF studies for closure licence — Maintenance of a site specific URF — Collection of geological and engineering information	— Operation of surface and subsurface facilities and waste tracking system — Extension of subsurface facilities — Updated emergency plan — Waste emplacement completed — Detailed closure plan for surface and subsurface facilities

TABLE 1. DELIVERABLES FOR MAJOR ELEMENTS OF A GEOLOGICAL DISPOSAL PROGRAMME (cont.)

Phase	Subphase	Disposal programme management	Stakeholder involvement	Disposal system development	URF[a] activities	Disposal implementation
	Closure[b]	— Licence application for termination — Updated programme plans — Programme requirements for licence termination — Safeguards for closure (updated for post-closure phase) — Community safety and emergency response plan — Updated quality management system for closure — Occupational health and safety — Updated costing — Updated database and archive (continued for post-closure)	— Approval of decision makers for closure — Appropriate local and general societal trust and community benefits — Updated list of potential issues of concern for closure — Decision makers' approval	— Updated safety case for licence termination — Updated site characterization report for licence termination — Long term evolution of disposal barriers for licence termination — Updated post-closure safety assessment report for licence termination — EIA report for licence termination — Environmental and performance monitoring (continued during post-closure phase)	— URF studies for licence termination — Maintenance of a site specific URF	— Closure of surface and subsurface facilities — Waste tracking system — Decommissioning complete — Closure activities complete

[a] URF: underground research facility.
[b] Some of these activities would be continued post-closure. For details on activities during the post-closure phase, please refer to Sections 3 and 4.

assessment report, design optimization studies and the EIA. The high level deliverable during the site(s) identification and selection subphase of siting is an updated safety case that is based on information used in the site selection process and supports the decision to proceed with site investigations at one or more sites. During the investigation of specific site(s) subphase, the updated safety case for the construction licence is the high level deliverable from the disposal system development WBS element. The safety case is sequentially updated during the excavation and commissioning, operation, and closure and decommissioning subphases of the disposal phase to incorporate additional site and operational data and to support the licence applications for operation, closure and licence termination. Post-closure monitoring and surveillance may be the high level deliverable for the disposal system development work element during the post-closure phase for some disposal programmes.

3.6.4. Underground research facility activities

An evaluation of the need to construct one or more generic URFs could be documented as a high level deliverable during the initiation phase, based on a review of existing international URF studies and national circumstances. Generic URFs are high level deliverables during the site(s) identification and selection subphase of siting, if deemed necessary. Alternatively, generic collaborative studies from existing international URFs may serve the same purpose. The high level deliverable during investigation of specific site(s) is a site specific URF located at or near the potential disposal site, providing geoscientific information and site specific studies in support of the licence application for construction [59]. High level deliverables from the URF activities WBS element during the disposal phase consist of URF studies for the operational licence, the closure licence, and the licence termination for the excavation and commissioning, operation, and closure and decommissioning subphases.

3.6.5. Disposal implementation

Deliverables falling under the disposal implementation element support the disposal phase of the programme, as shown in Table 1. The construction plan for the surface and subsurface facilities deliverable describes the construction and operational plans and procedures needed to implement the detailed design of the disposal system and support the licence application for construction. The high level deliverable for the excavation and commissioning subphase of the programme under the disposal implementation WBS element is the surface facilities and the first phase of the subsurface facilities, as supported by sublevel deliverables, including commissioning and detailed operational procedures. Operation of the surface and subsurface facilities and waste tracking system is the high level deliverable of this work element during the operation subphase, in addition to the sublevel deliverables of waste emplacement completion and a detailed closure plan for the surface and subsurface facilities. The high level deliverable during the closure and decommissioning subphase of the disposal phase is complete closure of the surface and subsurface facilities.

4. ROADMAP MATRIX OF ACTIVITIES

This chapter describes how the major elements and activities described in Chapter 3 are aligned under each phase of the geological disposal programme. The sections in this chapter follow the five major work elements identified in Chapter 3: disposal programme management, stakeholder involvement, disposal system development, URFs and disposal implementation. A matrix showing the work breakdown structure for each major element over time is found in Annex II for a total of five matrices. Each matrix consists of rows of major WBS elements with corresponding subelements or categories, and columns for programme phases in the disposal programme. Individual activities listed in the matrices are intended to be generic. Activities may be of variable importance or scope depending on the nature of the disposal programme and the circumstances of the Member State. However, each activity is intended to provide generic guidance for an important aspect of an effective and efficient geological disposal programme. It should be noted that extensive documentation and international experience are available to Member States at the early stages of a geological disposal programme. These less mature programmes may save considerable time, effort and cost in many of the activities shown in the roadmap matrix by utilizing existing information, particularly concerning the safety strategy, design concepts and engineering R&D.

4.1. DISPOSAL PROGRAMME MANAGEMENT

4.1.1. Initiation

The institutional framework responsible for the disposal programme is established within the overall WMO structure and this framework is populated with members of the core team and the organizational units responsible for performing the necessary tasks. A baseline programme strategy and planning are developed in this phase to guide the activities of other roadmap elements and to establish a basis for the disposal programme schedule, work packages and budgets. A preliminary programme opportunity and risk management plan is also produced. An initial WBS and schedule is developed. Safety, health and environmental programmes are developed in compliance with the relevant regulatory requirements. Some Member States may undertake a feasibility study or readiness assessment for geological disposal before proceeding to the siting phase of the programme.

Financial controls, including cost estimation tools, budgets, reporting, audits, property management and procurement procedures, are also established during the initiation phase to assure accountability and transparency. Financial controls promote the efficient use of resources within the disposal programme. Human resource management practices are developed to assure the recruitment and retention of qualified staff for the disposal programme. Employee development programmes, including appropriate training, are developed.

Planning and approaches regarding licensing and compliance are undertaken in this phase. Legal services associated with this and other legal matters are anticipated and evaluated. A quality assurance and quality control programme for current and upcoming activities is developed. As noted in Chapter 3, quality management for a radioactive waste disposal facility is usually considered to be a part of the WMO's overall management system.

Knowledge management systems are planned and developed in the initiation phase and applied to the archival preservation of policies, decisions, analyses, data and designs. An effective knowledge management system is robust and searchable to achieve the goals of transparency and traceability of information.

International contacts with the scientific and engineering components of existing disposal programmes, including contacts with existing URF programmes, are established during this phase.

4.1.2. Siting

Activities within the disposal programme management element during the siting process largely consist of implementing the plans and schedules developed in the initiation phase. The programme core team is maintained, and continuity of management and relevant knowledge is sustained. The programme strategies, policies, planning, procedures and organizational structure are updated during the siting phase based on the evolving circumstances of the programme and with a consideration of future needs. The programme risk management plan is also updated to reflect any changes in circumstances for the siting process. The disposal programme schedule, budgets and WBS organization are typically reassessed and adjusted on a periodic basis that can range from annually to several years. Licensing and permitting activities increase significantly during the siting phase, including the acquisition of permits for site investigations; potential licence application for a URF; compliance with occupational safety, health and environmental regulations; and submission of the licence application for construction at the end of the siting phase. This includes preparation of the environmental impact statement. The health, safety and environmental responsibilities of the disposal programme management element are fully implemented in this phase. Plans for nuclear security and safeguards are developed in preparation for the disposal phase.

Programme costs and budgets are regularly reviewed and updated. Detailed plans for the procurement of construction and operational services for the facilities are developed. The human resource and training systems established in the initiation phase are fully implemented and adapted to the evolving needs of the disposal programme. Regulatory compliance activities include legal support for the site selection decision, coordination of the documentation of the safety case for construction and preparation of the licence application. The management system programme is updated during the siting phase to provide detailed procedural guidance on scientific activities associated with site investigations and on engineering design studies. Knowledge management systems are fully implemented and expanded to accommodate the large quantities of data and analysis from site investigations, as well as disposal system design.

International collaboration typically increases during the siting phase to include active participation in existing URFs and laboratory studies and to promote participation by scientists and engineers from other disposal programmes in a site specific URF.

4.1.3. Disposal

Many activities in the disposal programme management element during the disposal phase, which has subphases of construction, operation and closure, are continuations of management system practices put in place during the siting phase. However, the transition from siting activities to disposal activities represents a major shift in focus from programme development to industrial implementation of disposal. Functions in the disposal programme management element are refocused accordingly. As described, programme organization, strategies, policies, schedule, budgets and WBS are re-evaluated and updated as the programme proceeds with construction, commissioning and disposal. The programme risk management plan is updated to reflect the new conditions of the disposal phase. Programme requirements and associated deliverables are evaluated and optimized based on experience gained during construction and disposal operations. Licensing and permitting activities continue in support of licence applications for operation, closure and eventual termination of the nuclear licence. The EIAs are also revised as part of the licensing process. Some disposal programmes, such as the Waste Isolation Pilot Plant (WIPP) in the USA, may require periodic relicensing of the disposal facility during the operational period. The health and safety responsibilities of the disposal programme management element are implemented for industrial disposal activities during this phase. Plans for nuclear security and safeguards are updated and fully implemented.

Financial controls and procurement services are expanded to cover large expenditures for facility construction and emplacement operations. The human resource and training systems are fully implemented and adapted to the evolving needs for the industrial disposal phase of the programme. Regulatory compliance activities include legal support for the licensing process for operations, closure and termination of the nuclear licence, as well as for permitting process for construction and operation. The management system, including the quality management programme, is updated during the disposal phase to provide detailed procedural guidance on construction and disposal activities. Training and auditing of programme activities by the management system assure proper and safe implementation of industrial processes during the disposal phase. Knowledge management and design control activities are expanded to include waste inventory tracking and as built records of the disposal system, barriers and seals. International collaboration continues during the disposal phase, but typically evolves towards an emphasis on engineering practices.

4.1.4. Post-closure

Disposal programme management activities by the WMO in the post-closure phase are limited or may be non-existent if responsibility for the site is transferred to another entity following the termination of the nuclear licence. Nuclear safeguards may be evaluated in this phase to assure that intrusion into the waste at the site does not occur. Disposal programme records and data are archived and maintained as part of the knowledge management system.

4.2. STAKEHOLDER INVOLVEMENT

4.2.1. Initiation

Activities in the stakeholder involvement element focus on engagement with stakeholders at the national level during the initiation phase of the disposal programme and broaden to include regional and local stakeholders as the programme advances to a specific site. During the initiation phase, an initial stakeholder engagement strategy is developed to enhance confidence in the integrity and safety of the geological disposal programme among the stakeholders and the public at large. The programme establishes liaisons with the national government, regulatory bodies, waste producers, indigenous peoples (if applicable) and other stakeholders, such as the media, non-governmental organizations and the scientific/academic community. Lists of potential issues of concern for all stakeholder groups are also developed. A stakeholder communication programme is developed in coordination with the overall strategy and planning developed in the disposal programme management element.

4.2.2. Siting

During the siting phase, the stakeholder involvement work element activities expand to include regional and local stakeholders and become more intensive in nature. Stakeholder engagement activities typically play their most important role in the geological disposal programme during the site selection and repository licensing processes. During non-site-specific investigations, communications with stakeholders are extended to regional public authorities and policy makers, and technical exchanges with regulatory and oversight agencies are formalized in periodic meetings. The list of potential issues of concern for public authorities, officials, waste producers and regional stakeholder groups is refined or developed by the disposal programme. As the programme shifts to site specific investigations, the stakeholder engagement strategy is updated accordingly. Periodic policy and technical exchanges are continued with public officials, waste producers and regional stakeholder groups, and are initiated with local stakeholders. The terms and conditions of the disposal programme are established with the local community. Such terms and conditions may include agreements about issues such as zoning, public utilities, traffic and controls on waste shipments. The results of site investigations and their relevance to the safety case are communicated in a timely manner to all interested parties and, in particular, to the local stakeholders. Interactions with regulatory bodies contribute to the licence for repository construction. The list of potential issues of concern for all stakeholders is maintained and updated as the disposal programme proceeds. Issues related to the WAC, waste conditioning, transportation and waste delivery schedule are coordinated between the disposal programme and the waste producers. The URF public outreach programme is coordinated with the stakeholder engagement strategy.

4.2.3. Disposal

Stakeholder involvement activities during the construction, operation and closure subphases of the programme include the continuation of activities related to siting and expand to operational safety issues. Details of the disposal system design and disposal system operations are discussed with stakeholders.

The list of potential issues of concern is maintained and updated. During excavation of the repository subsurface tours for stakeholders can be provided. Similarly, tours of waste emplacement operations and surface waste handling facilities are provided to stakeholders following the initiation of actual waste disposal operations, where feasible. Continuous communication and coordination with waste producers regarding waste characterization and delivery are typically required during the disposal operations subphase. Maintaining societal trust during the disposal operation subphase, which covers a long period, is important. This practice includes having open communication about related aspects, such as safety reviews, incidents, accidents, changing policy circumstances, relicensing, etc. Finally, closure activities and decisions are communicated to and discussed with stakeholders.

4.3. DISPOSAL SYSTEM DEVELOPMENT

4.3.1. Initiation

Activities in the disposal system development element during the initiation of the disposal programme are related to establishing the technical basis for radioactive waste disposal prior to the siting process. The major objectives of this element in the initiation phase are to support the regulatory or governmental decision regarding initiation of the siting process and to prepare the disposal programme for the siting process. A generic safety strategy is developed to address the multiple safety functions, defence in depth, containment, isolation and robustness of the generic geological disposal concept. Waste inventory, including potential future waste generation, as well as waste categorization methods and the preliminary WAC are analysed. National and regional geological conditions are surveyed, and a database of existing information is compiled. Preliminary conceptual models of natural systems, engineered barrier systems and the biosphere are developed to support the generic safety case during the initiation phase. A survey of potential site investigation and characterization methods and tools relevant to national geological conditions is conducted. An initial assessment of coupled processes in the disposal system is conducted. A survey of disposal concepts for potential geological media from the international community is conducted.

A generic design is developed for the disposal system, including the waste package design, based on a literature review of existing international design concepts. Generic conceptual models of the long term evolution of the geosphere, engineered barrier system and biosphere are developed in support of the generic safety case. Generic safety assessment methods and FEP analyses are also developed in support of the safety case. A database of input parameters and post-closure safety analysis models is developed and used to conduct a safety assessment in support of the generic safety case. A generic screening of radionuclides is performed to identify those relevant to post-closure safety. A generic safety case is developed based on the programme’s baseline safety strategy, potential geological host media, a preliminary analysis of the waste inventory and the generic safety assessment. An assessment of uncertainties in the generic safety case is made using a gap analysis. Supplemental information to support the EIA is gathered.

4.3.2. Siting

The activities in the disposal system development element are the focus of the programme during the siting phase, both before and after the selection of the disposal site. Development of the safety case for disposal system construction and the licence application for construction are the primary activities around which other programme activities are organized. A more detailed generic safety strategy is developed based on regional and site specific conditions. An updated analysis of the waste inventory, including potential future waste generation, is conducted as input for the safety assessment, and preliminary WAC are produced. Site investigations are conducted to address key gaps in regional geological information during the subphase prior to site selection.

Following site selection, detailed investigations of relevant geological conditions are undertaken to support the safety case and the licence application for construction. An updated assessment of engineered systems and coupled processes in the disposal system is conducted. Preliminary and detailed R&D for disposal system components and operational equipment is undertaken in support of the licence application for construction. The work on systematic requirements management is also typically started at this time.

The conceptual design of the disposal system, including waste package design, is developed in the earlier part of the siting phase, and is refined to a detailed design in support of the licence application for construction. An initial design for surface and subsurface facilities develops into a detailed design in this phase of the programme. The design of waste handling and emplacement equipment, as supported by engineering R&D, is also developed in support of the licence application for construction. Detailed conceptual models of the long term evolution of the geosphere, engineered barrier system and biosphere are developed and refined in support of the safety case. Detailed analyses of FEPs, safety functions and scenarios are conducted for the generic reference case and updated to support the licence application for construction. Mathematical and computational models implementing the conceptual models are developed and finalized. The database of input parameters and post-closure safety analysis models is refined and used in conducting the safety assessment in support of the safety case. Radionuclide screening analyses are updated based on site specific post-closure safety analysis models. Safety assessment models are updated and used to perform the site specific post-closure safety analysis in support of the licence application for construction. Risk analysis and scenario development are conducted for the operational safety assessment using generic models, followed by detailed modelling for the licence application for construction. Programmes are developed for the safety case in accordance with the management system, including detailed accident management procedures in support of operational safety. An environmental baseline monitoring programme is implemented at selected site(s). The safety case is updated using detailed and refined site specific information, disposal system design, radionuclide inventory, post-closure safety assessment, operational safety assessment and EIA to support the licence application for construction. Uncertainties in the safety case are also identified and evaluated. The EIA is developed in preliminary form and updated to its final form during the siting phase.

4.3.3. Disposal

Disposal system development activities during the construction, operation and closure subphases include updating of the safety case; confirmatory site investigations, optimization and refinement of the disposal system design; monitoring of the waste inventory; and updating of the long term evolution of the disposal system in support of the licence applications for operation and closure. A sequentially updated safety strategy is developed to address the multiple safety functions, defence in depth, containment, isolation and robustness of the disposal concept for the licence application for operation and closure. An updated analysis and verification of the waste inventory is conducted based on the as-built emplacement of waste to support the licence application for closure. Site investigations are conducted during the construction and operation of the disposal facility to provide confirmation of previously acquired information and to support engineering operations. Conceptual models of the geological, hydrogeological, geochemical and geotechnical properties and the biosphere are updated as needed, based on the additional information. An updated assessment of engineered systems and coupled processes in the disposal system is conducted using information acquired during the construction and operation. R&D for disposal system components and operational equipment is undertaken during the construction subphase to finalize and optimize operations for disposal.

The design of the disposal system, including waste handling and emplacement equipment, continues to be refined and optimized during the disposal phase of the programme. Barriers and seals for repository closure are designed in detail, demonstrated and optimized during the operation subphase of the programme. Conceptual and computational models of the geosphere, biosphere and engineered systems are updated and refined during the construction and operation subphases of disposal. Similarly, the FEP analysis, input data and post-closure safety analysis models to support the safety assessment are updated in preparation for the licence applications for operation and closure. Updated risk analysis and scenario development are conducted for the operational safety assessment prior to operations. The environmental monitoring programme is implemented throughout the disposal phase to provide assurance of safety by comparison to baseline results. Instrumentation and sensors are developed and deployed to monitor the disposal system during construction, operation and closure. The safety case is updated and refined as information continues to be acquired during the disposal phase. Updates to the safety case provide the primary bases for the licence applications for operation, closure and termination of the nuclear licence. Uncertainties in the safety case are evaluated and confirmed with the acquisition of additional data during the disposal phase. The EIA is updated iteratively in support of licence applications for operation, closure and termination of the nuclear licence.

4.3.4. Post-closure

The primary responsibility of the disposal system development element in the post-closure phase is the collection, analysis and interpretation of long term monitoring and surveillance data, if needed. The objectives of long term environmental monitoring include further verification of the safety case, informing environmental assessment follow-up plans, surveillance for potential defects or failures in the disposal system, and supporting the stakeholders' confidence in safety.

4.4. UNDERGROUND RESEARCH FACILITY ACTIVITIES

4.4.1. Initiation

During the initiation of the disposal programme, the URF activities element begins by evaluating the potential scientific and engineering needs that could be addressed by URF R&D, based on the initial disposal system conceptual design. A review of existing URF information from other disposal programmes potentially relevant to the geological host media under consideration is also conducted. An overall strategy is developed for the role of URF activities in the geological disposal programme, which anticipates the potential roles of work in international URF programmes abroad in a generic URF and/or in a site specific URF in meeting the programme's R&D needs. Staff training and participation in existing international URF programmes abroad may also be implemented in the initiation phase.

4.4.2. Siting

Activities during the siting phase include the evaluation of research needs and planning, design, construction and maintenance of a URF within the country or participation in a URF abroad. After site selection, going underground allows the acquisition of subsurface site characterization data that augment the geoscientific information collected from the surface. Scientific and engineering R&D activities include geoscientific investigations, the development of testing methods, experiments related to the interaction between engineered and natural components of the disposal system, characterization of the excavated environment and experiments investigating sealing and closure methods.

The URF activities may continue for technology demonstration and optimization in several areas, including demonstration of waste package retrieval technology and methods, if required; industrial demonstrations of operations such as excavation, waste handling and emplacement; and industrial demonstrations of sealing and closure methods. Training and professional development activities are conducted in the URF for the development of methods, equipment and experience for staff training; the augmentation of scientific and technical understanding by staff; training for academic and other relevant stakeholders; and training exercises for construction and operation by personnel. The URF provides an effective method for stakeholder involvement, including engaging stakeholders in information exchange, demonstration of safety, confidence building, stakeholder outreach and public education, and subsurface tours.

4.4.3. Disposal

Operation of a URF requires ongoing management and maintenance of the associated surface and subsurface infrastructure, including emergency response systems, although the operation of a site specific URF may be incorporated into the overall repository during the disposal phase. In situ site characterization activities may be continued into the disposal phase, depending on the nature of the investigations. Scientific and engineering R&D activities will likely continue in the form of experiments to develop long term monitoring techniques and technologies, and experiments investigating sealing and closure methods.

The URF activities may continue for technology demonstration and optimization in several areas, with an emphasis on industrial optimization. Training and professional development activities in the URF may continue for the development of methods, equipment and experience for staff training; augmentation of scientific and technical understanding by staff; training for academic and other relevant stakeholders; and training exercises for construction and operation by personnel. The URF continues to be an option to provide an effective method for stakeholder involvement, including engaging stakeholders in information exchange, demonstration of safety, confidence building, stakeholder outreach and public education, and subsurface tours.

4.5. DISPOSAL IMPLEMENTATION

Disposal implementation activities vary in size and scope during the construction, operation and closure subphases of the geological disposal programme. The transition from siting selection activities to disposal activities represents a major shift in emphasis from programme development to industrial implementation of disposal. A detailed plan is required for the commissioning of surface and subsurface facilities prior to licensing approval for construction.

Once land acquisition and site permitting are completed, contracting and construction of surface facilities proceed in tandem with the installation of site infrastructure and other site activities. An emergency response plan is implemented to provide mine safety and emergency services at the site.

Once construction is underway, and especially as turnover to operation begins, commissioning of the disposal programme facilities is undertaken. This consists of testing, verification and demonstration that design requirements have been met by the facilities and equipment. Commissioning activities include testing of nuclear facilities and equipment, with and without radioactive materials. Verification and testing associated with nuclear commissioning are updated for any changes in the as-built configuration in the disposal system design as operations proceed. All facilities are maintained continuously during the construction, operation and closure subphases.

Detailed operational procedures are developed for surface and subsurface facilities during the excavation and commissioning subphase, including waste emplacement, backfilling and sealing. Operational procedures for the receipt, handling, transfer and emplacement of waste are implemented over a typically extended period during the operational subphase. These procedures are validated during commissioning and updated periodically based on OPEX, additional scientific investigations and engineering systems development.

A plan for waste inventory tracking is developed during construction (or expanded upon if required prior to the application for the licence for construction) and implemented through the operation and closure subphases. Detailed plans for closure and decommissioning of subsurface facilities are developed during the operation subphase and implemented during the closure and decommissioning subphase. Backfilling and sealing of shafts and surface access ramps are also implemented during closure and decommissioning. Similarly, closure, demolition and decommissioning of surface facilities are planned and implemented towards the end of the disposal phase. Decommissioning of the site facilities may produce additional radioactive waste that may be disposed of on site or require removal and disposal at a separate disposal facility. Documentation for the termination of the nuclear licence is kept in archives for future reference.

5. CONCLUSIONS

As of 2016, approximately 390 000 t HM of spent fuel had been discharged from all nuclear power plants worldwide since 1954. Member States are progressing with the disposal of spent fuel declared to be waste, vitrified high level waste and intermediate level waste in deep geological repositories. The last 30 years of international OPEX has resulted in significant developments in technology, designs and documentation in this field, in addition to the lessons learned, to support effective geological disposal programmes.

This publication provides a roadmap for developing and implementing a geological disposal programme. It will be of use to those developing new programmes in benchmarking against current best practices, using the results as potential input to those newer programmes. Specifically, the series of activities conducted, and the deliverables typically produced during each phase of a programme, are described. The topical areas that are covered in the roadmap have been divided into the following five major elements: disposal programme management, stakeholder involvement, disposal system development, URFs and disposal implementation. Some of these elements, such as programme management, follow standard project management and management systems concepts already described in earlier IAEA publications (see references). On the other hand, R&D, including the operation of URFs, is unique to geological disposal, supporting aspects such as site characterization and long term performance of barrier systems.

The annexes to the publication include case studies describing how several programmes are progressing along the roadmap timeline. In general, these programmes follow the typical phases described in this publication — initiation, siting, disposal and post-closure — and there are many similarities with respect to major decision points for the respective governments, WMOs, regulators and other stakeholders. Given the long time periods associated with this type of facility, one common theme is to have a flexible and agile programme that can anticipate changes that may occur because of availability of new information or conditions (e.g. technical, regulatory, political).

The roadmap is generic in nature, describing only the activities common to each phase but not specifying the method to complete the activity or time allotment. This allows for innovation and site specific requirements to be considered. A review of the roadmap and case studies will provide good practices and lessons learned to guide and support future programmes or programmes entering the next phase.

Newer programmes may save considerable time, effort and cost for many of the activities by building upon the OPEX in terms of design concepts, safety requirements, engineering research and designs already developed in other countries.

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Annex I

ILLUSTRATIONS OF APPLICABILITY OF THE GENERIC ROADMAP TO NATIONAL GEOLOGICAL DISPOSAL PROGRAMMES

Note: The details contained in these annexes pertain to different periods as per their availability, and were collected in 2023. Some of the projections and facts may no longer apply, but the language has been retained keeping these statements as the most current.

I–1. COUNTRY: CANADA

I–1.1. Context

Nineteen Canada deuterium–uranium (CANDU) nuclear power reactor units, with a combined capacity of ~14 MW, are in operation in Canada. Six CANDU reactor units are permanently shut down. Nuclear power makes up ~15% of total electricity generation in Canada. Canada's inventory of spent nuclear fuel mostly results from the operation of the nuclear power plants. A small quantity, which is ~2% of the total inventory, comes from prototype reactors used to test full power reactor designs and from research reactors. Spent nuclear fuels generated from the nuclear power reactors, as well as research reactors, have been temporarily stored at on-site dry storage facilities and pools [I–1].

The approach selected by the Government of Canada for long term management of Canada's spent nuclear fuel is known as adaptive phased management (APM). APM is both a technical method and a management system. The technical method involves developing a deep geological repository (DGR) in a suitable rock formation to safely contain and isolate the spent nuclear fuel. The management system involves phased and adaptive decision making, supported by public engagement and continuous learning. The Canadian Nuclear Waste Management Organization (NWMO) is the radioactive waste management organization responsible for long term management of the spent nuclear fuel.

The Canadian geological disposal programme is currently in the siting phase. The site selection process was developed through a two year public consultation. NWMO was required to propose a process to the relevant Minister. NWMO subsequently initiated this process in 2010. Potential siting areas were first identified through a willing host (volunteer) approach. Twenty-two communities came forward to learn more and explore their suitability for the APM project. These areas were then examined for specific potentially suitable siting areas that met the technical and social acceptance criteria, with progressively more detailed studies. As the studies progressed, NWMO identified which areas had less potential to be successful. As of January 2020, two potential sites — one near Ignace in northern Ontario and one in South Bruce — remained in the site selection process. This narrowing down process was achieved through extensive social engagement and technical site evaluations to assess safety and the potential to build supportive and resilient partnerships. NWMO plans to identify a preferred site by 2024. At that point, detailed site characterization work will be initiated by NWMO at that site in preparation for licence application.

I–1.2. Timeline for implementing the geological disposal programme

The key historic milestones and planning time frame for the implementation of the APM plan [I–2] are presented in Table I–1. For context and completeness, this table includes key historic milestones and activities related to Canada's spent fuel waste management programme prior to the implementation of the APM [I–1]. Table I–1 is an illustration of some key aspects of the history of the disposal of spent fuel in

Canada and the current disposal programme and does not include full details on all of the activities and deliverables completed to date or planned for the future.

TABLE I–1. ROADMAP FOR THE CANADIAN GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL

Phase	High level decisions	Principal activities
Background	Canada's spent fuel waste management programme initiated by the governments of Canada and Ontario (1978)	— Several concepts for long term management of spent fuel considered and reviewed by a royal commission (1977) — DGR[a] concept within the plutonic rock of the Canadian Shield developed by the Atomic Energy of Canada Ltd — Generic URL[b] constructed in plutonic rock near Pinawa, Manitoba. Facility operated for 25 years — Environmental impact statement on the DGR concept in crystalline rock reviewed by a federal environmental assessment panel (1996–1997)
Initiation	The Parliament of Canada passed the NFWA[c] (2002)	— NWMO[d] is established by Canada's nuclear electricity producers, in accordance with the NFWA (2002) — NWMO completes three year study with interested individuals, including specialists, indigenous peoples and the Canadian public (2005)
	Government of Canada selects APM[e] and mandates the NWMO to begin implementation (2007)	— Siting process development (2008–2009)
Siting	Siting process initiated (2010)	— Siting process initiated with a programme to provide information, answer questions and build awareness (2010) — Twenty-two communities initially expressed interest. Initial screenings conducted by NWMO in collaboration with interested communities, followed by preliminary assessment desktop studies and community engagement (2010–2015) — Assessment of potential sites expanded to include field investigations. Areas with less potential eliminated from further consideration as the narrowing down process continues; two potential siting areas considered as of 2020 — Conceptual design starts. Generic post-closure safety assessments (or case studies) for hypothetical crystalline rock repository and hypothetical sedimentary rock repository prepared
	A single preferred site is identified (2024)	— Detailed site characterization begins — Project description submitted, triggering the federal impact assessment — Licence to prepare site application is submitted to the CNSC[f]

TABLE I–1. ROADMAP FOR THE CANADIAN GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL (cont.)

Phase	High level decisions	Principal activities
	The impact assessment is approved The licence to prepare site is granted	— Impact assessment studies are submitted as part of the regulatory process — Site preparation activities begin — Licence to construct application submitted to the CNSC
Disposal	Licence to construct is granted by the CNSC	— Design and construction begin (2033[g]) — Licence to operate application submitted
	Licence to operate is granted by the CNSC	— Operations of the DGR begin (2040–2045[g]) — Transportation of used nuclear fuel to the repository begins (2040–2045[g])

[a] DGR: deep geological repository.
[b] URL: underground research laboratory.
[c] NWFA: Nuclear Fuel Waste Act.
[d] NWMO: Nuclear Waste Management Organization.
[e] APM: adaptive phased management.
[f] CNSC: Canadian Nuclear Safety Commission.
[g] Dates assumed by NWMO for planning, dependent on regulatory decisions.

I–2. COUNTRY: CZECH REPUBLIC

I–2.1. Context

Two nuclear power plants are in operation in the Czech Republic, comprising a total of six units. In 2021, the two nuclear power plants accounted for more than 36% of the country’s total electricity production. Moreover, three research/training reactors are also in operation. Low and intermediate level nuclear waste is disposed of in three surface and near surface repositories.

Spent nuclear fuel generated by the nuclear power plants is being stored on a temporary basis on-site at the nuclear power plants. The current national policy anticipates the direct disposal of spent nuclear fuel in a DGR. The DGR will serve for the permanent disposal of the radioactive waste that cannot be disposed of in surface or near surface repositories (i.e. spent fuel from nuclear reactors and high level waste containing long lived radionuclides). The planned capacity of the DGR considers the current and anticipated future generation of the relevant types of waste.

The disposal concept envisages a crystalline rock environment and steel based, double walled disposal canisters with the use of bentonite in the engineered barrier system. The waste disposal package emplacement method has not yet been confirmed; both horizontal and vertical emplacement are seen as viable options. The encapsulation plant will form part of the infrastructure of the DGR complex. Czech Radioactive Waste Repository Authority (RAWRA) is the radioactive waste management organization responsible for the geological disposal programme in the Czech Republic. RAWRA’s activities are funded by the so called Nuclear Account to which radioactive waste producers are required to contribute by law.

I–2.2. Timeline for the implementation of the geological disposal programme

The objectives and time schedule for the disposal programme are set out in the Concept of Radioactive Waste and Spent Nuclear Fuel Management in the Czech Republic strategic document compiled by the Ministry of Trade and Industry. This has been updated several times in the past to reflect current needs. Updates were made in 2014 and 2017, and the latest updated version was approved by the Government on 26 August 2019 [I–3]. In 2017, a further document was compiled that described the DGR timeline in detail and provided a summary of all the related issues [I–4]. Detailed information on the milestones achieved in the past is available in RAWRA's annual reports [I–5]. Since the initiation of the disposal programme, the date of the planned commissioning of the DGR has been set at 2065. However, the whole of the DGR programme is currently being reconsidered in connection with EC directives on the impact of climate change on the environment and the attainment of carbon neutrality [I–6]. As a result, RAWRA, in cooperation with the Ministry of Trade and Industry, has compiled a study that addresses the conditions under which it would be possible to bring forward the date of the commissioning of the DGR to 2050. The timeline and milestones set for the Czech Republic's geological disposal programme can be found in Table I–2. The information up to 2020 is presented according to real developments, whereas the activities planned in the near future are presented without specific dates because at the time of writing they are the subject of ongoing discussion.

TABLE I–2. ROADMAP FOR THE CZECH REPUBLIC'S GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL AND OTHER HIGH LEVEL RADIOACTIVE WASTE

Phase	Milestone	Principal activities
Initiation	Establishment of RAWRA[a] (1997)	
	Approval of the Concept of Radioactive Waste and Spent Nuclear Fuel Management in the Czech Republic (Resolution No. 487/2002)	— Approval of 'the concept' was preceded by approval of the Report on the Adequacy of Storing Capacities for the Spent Nuclear Fuel (SNF) and on Procedure of the Selection of the Final Deep Repository by the Government of the Czech Republic (Resolution No. 695/2021)
Siting	Nine candidate sites defined for the location of the DGR[b] (2017)	— Selection of potentially suitable areas for the DGR by the Czech Geological Institute (in 1992, i.e. prior to the establishment of RAWRA) — Regional screening studies of 28 potential sites (1990s) — Selection of 11 potential sites in 3 different types of rock (2002) — Limitation of host rock formation to crystalline rocks (e.g. granites) (2003) — Characterization of six granitic rock sites by means of airborne geophysical studies, remote sensing analysis and limited geological mapping (2003–2006) — Initiation of the study of former military areas in terms of the siting of the DGR (2011) — Analysis of the Boletice military area; further research terminated

TABLE I–2. ROADMAP FOR THE CZECH REPUBLIC'S GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL AND OTHER HIGH LEVEL RADIOACTIVE WASTE (cont.)

Phase	Milestone	Principal activities
		— Definition of an additional candidate site (i.e. Kraví Hora) near the Rožná uranium mine (2011) — Characterization of two additional sites in the vicinity of the two nuclear power plants (2014–2017) — Identification of suitable rock blocks at the two sites in the vicinity of NPPs[c] — expansion of the number of candidate sites to nine (2017)
	Approval of four sites recommended for the location of the DGR (Resolution No. 1350/2020)	— Collection of geological and other data, stage by stage description and evaluation of the original nine sites via a number of projects (2003–2019) — Geophysical verification of both the near surface and deep geological structures in the wider vicinities of the sites (2017–2019) — Compilation of site evaluation reports considering safety, feasibility and environmental criteria for all sites (2019–2020) — Development of the site evaluation methodology and reduction of the number of sites from nine to four — Recommendation of four sites (i.e. Březový potok, Horka, Hrádek, Janoch) for the next assessment phase — Compilation of a synthesis report on the site reduction process [I–7]
	Evaluation and selection of the final site and the backup site	— Work in the geological 'research' mode (e.g. monitoring work, detailed geological mapping including geophysical measurements, etc.) — Work in the geological 'survey (exploration)' mode (i.e. deep boreholes, borehole logging, geophysics) following the approval of so called exploration areas by the Ministry of the Environment — Compilation of site studies to select the final site and backup site
	Completion of the final site survey	— Date TBD[d]
	Initiation of underground facility	— Initiation of mining exploration research: underground characterization facility, date TBD
	Site approval (siting licence) by the SÚJB[e]	
Construction	Construction approval (construction permit) from the regulator and authorities	— Date TBD
Operation	From 2065	

[a] RAWRA: the Czech Radioactive Waste Repository Authority.
[b] DGR: deep geological repository.
[c] NPP: nuclear power plant.
[d] TBD: to be determined.
[e] SÚJB: State Office for Nuclear Safety.

I–3. COUNTRY: FINLAND

I–3.1. Context

As of the beginning of 2021, two nuclear power plants are in operation in Finland. There are two boiling water reactor (BWR) units (890 MW each) at Olkiluoto and two pressurized water reactor (PWR) units (507 MW each) at Loviisa. In addition, one European pressurised water reactor (EPR) unit (1600 MW) is under construction at Olkiluoto and licensing is underway to construct a water water energetic reactor (WWER) (1200 MW) unit at Hanhikivi. Olkiluoto and Loviisa provide ~30% of the electricity produced in Finland. Repositories for low and intermediate level nuclear waste are in operation at both Olkiluoto and Loviisa [I–8].

The current policy is to dispose of the spent fuel in Finnish bedrock without reprocessing. The owners of the two nuclear power plants established a joint nuclear waste management company, Posiva Oy, in 1995 for the disposal of the spent fuel from the Olkiluoto and Loviisa reactors, and this takes care of all the preparations for, as well as the practical implementation of, geological disposal at Olkiluoto, near the Olkiluoto nuclear power plant.

The preparations as well as the implementation of spent disposal follow on from the Government decision of 1983 concerning the guidelines and time schedules for the final disposal of spent fuel.

To ensure the financing of the disposal facility, National Nuclear Waste Management Fund has been established. The fund collects, stores and invests the money that is going to be needed for future management of nuclear waste, including disposal and decommissioning of the nuclear facilities. The money is provided by the waste producers. The fund also finances research related to the safety of waste disposal.

I–3.2. Timeline for implementing the geological disposal programme

The selection of the Olkiluoto site for geological disposal of spent was confirmed by the so called decision in principle based on the application submitted by Posiva in 1999 [I–9]. Both the proposed site municipality and the regulator had the right of veto to reject the decision. However, neither the municipality nor the Finnish Radiation and Nuclear Safety Authority (STUK) raised objections, and the Government was able to make a positive decision in 2000, which Parliament endorsed in 2001.

The goals and time schedules of the disposal programme were defined by the Ministry of Trade and Industry (KTM; now the Ministry of Employment and Economic Affairs, or TEM) in their policy decision of 1983. This decision also defined the main intermediate milestones and checkpoints for the programme. The main milestones were site selection in 2000, the start of construction in 2010 and the start of operations in the early 2020s. The time schedule defined in 1983 has been followed with small modifications ever since.

The candidates for site selection were defined by the implementer (originally Teollisuuden Voima Oy, or TVO; now Posiva Oy) in 1986, but the proposal was reviewed by KTM, supported by the regulator, STUK, and various expert organizations. Similarly, the shortlisting of site candidates was based on the implementer's decision (in 1992), which was reviewed by the authorities and their experts.

The Finnish Government granted the construction licence for the disposal facility at Olkiluoto, including an underground geological repository at a depth of ~450 m and a surface based encapsulation facility, in 2015. According to the Finnish legislation, the licence is granted by the Government based on the review of STUK. Currently the construction of both facilities is in progress and Posiva has submitted the licence to operate application. Table I–3 shows the timeline and the milestones.

TABLE I–3. ROADMAP FOR FINLAND'S GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL

Phase	Major decision/milestone	Principal activities
Initiation	Government decision on the guidelines and time schedules for geological disposal of spent fuel (1983)	— Countrywide survey for candidates for preliminary site investigations (1984–1986) — Generic safety assessment of spent fuel disposal in Finnish bedrock according to the Swedish KBS-3 method (1985)
Siting	Selection of five sites for preliminary site investigations (1986)	— Start of drilling and other geological investigations at five sites (1987) — Geoscientific modelling of site characteristics — Start of development of safety assessment methodology — Start of development of the waste canister design and other KBS barrier technology — Start of research supporting safety assessment
	Shortlisting of three sites for detailed site investigations (1992)	— Summary and conclusions from the preliminary site investigations (1992) — TVO-92 safety assessment to support the shortlisting of site candidates (1992) — Overview of the status of technology development (1992) — Start of detailed site investigations at three sites (1993); the development of the technology and safety assessment methodology continues, together with supporting research on long term and operational safety — Interim report on detailed site investigations; TILA-96 interim safety assessment (1996) — Inclusion of an additional site in the detailed site characterization (1996) — Introduction of an ISO[a] 9001 based quality management system (1997)
	Start of EIA[b] process (1997)	— Preparation of EIA programme (1997) — Execution of EIA programme, including a broad range of stakeholder interaction (1997–1999) — Publication of the EIA report with conclusions on suitability of the site candidates for repository purposes (1999) [I–10]
	Submission of the application for decision in principle on the construction of a KBS-3 type repository at Olkiluoto (1999)	— Publication of summaries and conclusions from site investigations at four sites (1999) — TILA-99 safety assessment to support site selection (1999) — Preparations started for the construction of a site specific URF[b] at Olkiluoto — Publication of the long term research and technical design programme for the pre-construction phase (2000) [I–11]
	Decision in principle on the construction of a KBS-3 type repository at Olkiluoto (2001)	— Detailed design of the Onkalo URF started — Agreement on extensive cooperation with the Swedish SKB on the development of the KBS-3 method (2001)

TABLE I–3. ROADMAP FOR FINLAND'S GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL (cont.)

Phase	Major decision/milestone	Principal activities
	Ministry of Economic Affairs and Employment sets a target for submission of the application for the construction licence in 2012, requiring a preliminary licence application in 2009 (2003)	— Programme for underground investigations in Onkalo and the first three year research and technical design programme published (2003) — Start of excavation of the Onkalo URF in parallel with underground investigations and production of site descriptive models — Start of SKB–Posiva joint development of a variant disposal concept based on horizontal emplacement of canisters (i.e. the so called KBS-3H, amending the basic KBS-3 concept of vertical emplacement, sometimes denoted KBS-3V) (2003) — Testing of the technology needed for a KBS-3 type repository continues — Plan for the safety case to support the submission of application for the construction licence (2005) [I–12] — Introduction of a certified, process oriented management system based ISO and OHSAS[d] requirements (2005) — Technical and scientific tests begin at Onkalo (2006) — Introduction of the VAHA[e] requirements management system (2006) — Production of TURVA-2012 safety case reports begins (2006) — Start of work to establish rock suitability criteria for location of the repository tunnels and deposition holes (2007) — Configuration management established (2009)
	Start of the licensing process: submission of the preliminary licence application for construction (2009)	— Preparation of the full documentation for application for a construction licence finalized (2012)
	Submission of application for construction of a geological repository and encapsulation plant at Olkiluoto, including technical plans and detailed design descriptions of site, facilities and disposal technology, plans and procedures for construction, quality management and plant operations, assessments of operational and long term safety [I–13, I–14]	— Supply of additional information for regulatory review of the licence application; detailed design, including optimization, of disposal technology continues; facility construction plans further elaborated; purchase planning begins; planning of the safety case in support of the operational licence application begins (2013–2021)
Disposal	Construction licence granted by the Government; STUK[f] lists the safety issues that have to be resolved before submission of the operating licence application (2015) [I–8]	— Research and technical design work continues to resolve the safety issues indicated by STUK; process started for production of the documentation needed for operational licence, including a new safety case (SC-OLA — safety case for the operational licence application) (2015)

TABLE I–3. ROADMAP FOR FINLAND'S GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL (cont.)

Phase	Major decision/milestone	Principal activities
	Posiva decision on readiness to start building the repository (2016)	— Construction of the underground repository begins (Onkalo will become a part of it; 2016), fulfilling the licence requirement that construction should be started within two years of the construction licence being granted — Planning and preparations started for operating the disposal facility (2018)
	Posiva decision on readiness to start building encapsulation plant (2019)	— Start of construction of encapsulation facility (2019)
	Submission of application for operating licence (2021) [I–15]	

[a] ISO: International Organization for Standardization.
[b] EIA: environmental impact assessment.
[c] URF: underground research facility.
[d] OHSAS: Occupational Health and Safety Assessment Series.
[e] VAHA: the requirements management system at Posiva.
[f] STUK: Radiation and Nuclear Safety Authority.

I–4. COUNTRY: FRANCE

I–4.1. Context

As of June 2019, 58 nuclear power plant units are in operation in France, 1 unit is under construction and 13 units have been permanently shut down. Nuclear power makes up approximately 72% of total electricity generation in France. The spent fuel is reprocessed at La Hague reprocessing plant and, for the HLW, is transformed into vitrified waste [I–16].

The French National Radioactive Waste Management Agency (Andra) has been responsible for identifying, implementing and guaranteeing safe management solutions for all French radioactive waste since 1991. Andra is a publicly owned organization and is independent of waste producers.

The French Government adopted a law in June 2006 that endorses reversible deep disposal as the reference solution for the long term management of HLW and ILW-LL. A site in the Meuse/Haute-Marne district has been chosen for the construction of an underground research laboratory (URL) (1998) and later for a deep geological repository (2006). The construction licence application is planned to be submitted in 2022. An underground research laboratory has been in place since 2000 in Meuse/Haute-Marne. Two surface facilities are in operation for very low level waste (VLLW) and short lived low and intermediate level waste (LILW-SL).

The proposed repository for ILW-LL and HLW (codisposal) will be located in a thick and homogeneous clay layer at a depth of 500 m. The ILW-LL is in concrete containers and the HLW is in steel containers. Construction and operations will occur simultaneously.

I–4.2. Timeline for implementing the geological disposal programme

The timeline, decisions and milestones for the Cigéo geological disposal facility is shown in Table I–4.

TABLE I–4. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME FOR HLW AND ILW-LL IN FRANCE

Phase	Activities	Sub-activities
Initiation	First law (1991)	— Law No. 91-1381, known as the Bataille law, concerning research on the management of radioactive waste, passed on 30 December 1991 — Three complementary R&D[a] research areas: partitioning and transmutation of long lived elements; reversible disposal in deep geological formations; long term storage — In the case of the second research area, the Waste Act stipulated several formations to be studied in different geological formations by the creation and operation of underground laboratories — Andra in charge of the second and third research areas
Siting	Selecting sites for URLs (1993–1998)	— Call to potential candidates to apply to host the URL[b] facility. Thirty-five communities interested — Geological surveys on four sites approved by the Government for the construction of URLs to study the feasibility of deep disposal — Andra applied for three URLs, one in each geological formation — Meuse/Haute Marne site (clay formation) selected by the Government to host a URL
	URL works and studies. From district area to transposition zone (2000–2005)	— Construction of the Meuse/Haute Marne URL with a view to studying the properties and behaviour of a clay layer in situ — Submission of Dossier 2005 to the Government, a report through which Andra confirmed the feasibility and safety of deep disposal within a 250 km^2 area around the URL
	Public consultation (2005)	— Public consultation on the management of radioactive waste organized by the National Public Consultation Committee
	Second law (2006)	— Parliamentary debate and passing of Planning Law No. 2006.739 on 28 June 2006, which endorses reversible deep disposal as the reference solution for the long term management of HLW[c] and ILW-LL[d] and states that the results from the URL are valid inside a 250 km^2 transposition zone
	URL works and studies. From transposition zone to ZIRA[e] (2006–2009)	— Proposal made by Andra and approved by the Government for a 30 km^2 ZIRA to carry out investigations concerning the creation of the underground disposal facility
	Public consultation (2013)	— Public consultation on the Cigéo project organized by the National Public Consultation Committee
	Third law (2016)	— Law No. 2016-1015 of 25 July 2016, known as the reversibility law
	2016	— Submission of the safety options file to the safety authority based on the basic engineering design [I–17]
	2023	— Submission of construction licence application based on detailed engineering design [I–18]
	2025[f]	— Construction licence granted

TABLE I–4. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME FOR HLW AND ILW-LL IN FRANCE (cont.)

Phase	Activities	Sub-activities
Disposal	2028[f]	— Beginning of shaft construction
	2037[f]	— First canister in the repository

[a] R&D: research and development.
[b] URL: underground research laboratory.
[c] HLW: high level waste.
[d] ILW-LL: long lived intermediate level waste.
[e] ZIRA: special detailed survey zone (zone spéciale d'étude détaillée).
[f] Estimated timeline.

I–5. COUNTRY: GERMANY

I–5.1. Context

Germany has shut down 36 nuclear power plants and there are none operational any more. Spent nuclear fuel generated at the nuclear power plants is currently stored in on-site pools and dry interim storage facilities, and off-site dry central interim storage facilities. With respect to geological disposal, Germany has two repositories (Morsleben and Asse) currently in the closure phase of operations. These repositories were constructed and operated in salt domes for the disposal of LLW and ILW in the 1970s under earlier laws and are not further discussed in this summary. A further DGR for LLW and ILW, the Konrad Repository, is under construction in a former iron ore mine (Konrad) [I–19].

The siting phase for an HLW and spent nuclear fuel repository was restarted in September 2017.

In the course of the siting procedure, investigations of all types of host rock are underway (crystalline, argillaceous and salt formations are available). The procedures and responsibilities during the siting process are stipulated in the German Site Selection Act (Standortauswahlgesetz — StandAG) [I–20].

The operator, the Federal Company for Nuclear Waste Management (BGE), is responsible for data acquisition and evaluation and the performance of safety assessments, as well as checking compliance with siting criteria. At the end of each step of the siting procedure, BGE will prepare a compilation and evaluation of the results and issue proposals for the next steps. In 2020, BGE finished step 1 of phase I of the siting procedure and prepared a first report identifying potentially suitable subareas in all host rock types in Germany [I–21]. As the next step, areas for surface exploration have to be identified. The Federal Office for the Safety of Nuclear Waste Management (BASE) will evaluate BGE’s proposals and inform the Federal Government. The Federal Government will pass the information to the Federal Parliament (Bundestag) and the Federal Council (Bundesrat).

Furthermore, the public will be informed at the end of each siting step, as defined in the StandAG, through publication of the results, public statements and public hearings. Additionally, a national attendant board (Nationales Begleitgremium, or NBG) and regional boards will continuously observe site investigations and ask questions regarding BGE’s data and results.

I–5.2. Timeline for implementing the geological disposal programme

The timeline, decisions and milestones for the Konrad site and for the new spent fuel / HLW repository are shown in Tables I–5 and I–6.

TABLE I–5. ROADMAP FOR THE KONRAD GEOLOGICAL DISPOSAL PROGRAMME FOR LLW AND ILW IN GERMANY

Phase	Major decision/milestone	Principal activities (key issues)
Initiation	Governmental decision to investigate the former iron ore mine with regard to its suitability as a repository site for LLW[a] and ILW[b] (1976)	— Analysis and evaluation of existing geological and mining data from the former iron ore mine. Generic safety evaluation
Siting	Specific detailed site investigations to analyse suitability for LLW and ILW disposal (1976–1985)	— Development of a safety concept for operation and closure of an LLW/ILW repository at the Konrad site — Analysis of the geological structure of the iron ore deposits as well as the underlying and overburden formations and the regional surroundings (i.e. geophysics, geology, drillings) — Analysis and monitoring of seismic stability of the site — Investigations on hydrology, hydrogeology and hydrochemistry in the overburden, the host rock and the underlying formations (i.e. drillings, water wells and hydrological/ hydrogeological tests, monitoring programme) — Geological investigations of the host rock and the clay barrier formations relevant for retention of radionuclides (i.e. hydraulic, mechanical and geochemical/mineralogical properties through geophysics, drillings, exploration drifts) — Mechanical investigations of the host rock and the nearfield with regard to mining requirements (i.e. geophysics, drillings, exploration drifts, optimization of mining and ventilation technology) — EIA[c]
	Demonstration tests for technical feasibility (1980–1982), from 2002 continuous upgrade of technical planning to the current state of the art	— Design, construction, testing and qualification of technical components for transport and handling of waste packages, barriers, backfilling and corresponding procedures — Design and engineering of surface and underground facilities
	Safety assessment for the operational and post-closure periods	— Comprehensive data analysis of repository operation and for expected future evolution of the site. — Site descriptive model. Geoscientific long term prognosis — Development of adequate numerical models and tools — Safety analysis for repository operation (e.g. accident analysis) — Performance assessment for the barrier system for the post-closure period — Radiological consequence analysis

TABLE I–5. ROADMAP FOR THE KONRAD GEOLOGICAL DISPOSAL PROGRAMME FOR LLW AND ILW IN GERMANY (cont.)

Phase	Major decision/milestone	Principal activities (key issues)
Licensing	Licensing procedure (1982–2002) Final verification of licence by the Federal Court (2007)	— Publication of documents for licence application, discussion with public and stakeholders, public hearings, update of documents due to comments — Construction and operation licence initially granted (2002) — Stakeholder contentions adjudicated by the Federal Court and an executable licence for construction and operation of the Konrad repository issued (2007) — Upgrades of technology evaluated and verified by experts of the licensing authority (ongoing)
Construction	Construction of surface facilities at conventional site (Konrad 1) (2008–ongoing)	— Upgrade of hoisting tower (shaft 1) and shaft installations — Intake air fan installation — Construction of hoisting machine hall, repair/maintenance shops, stores, social and office buildings, supply installations
	Construction of surface facilities at nuclear site (Konrad 2) (2008–ongoing)	— Upgrade of hoisting tower (shaft 2) and shaft installations — Exhaust air fan installation — Waste acceptance and transfer hall, including buffer storage — Installations for radiological protection and monitoring, radiological laboratory — Hoisting machine hall, repair/maintenance shops, stores, social and office buildings, supply installations, security buildings/installations
	Construction of mine excavations (2008–ongoing)	— Excavation of drifts and chambers due to repository mine planning — Excavation and installations of underground infrastructure — Modifications of shaft landing at nuclear site (shaft 2). Adaption to long maintenance operation (e.g. robust, stable lining). Installations for waste package handling and transport underground — Excavation of disposal drifts
	Licensing procedures for equipment for repository operation	— Installations and vehicles for waste package handling and transport — Equipment for backfilling and sealing of disposal drifts
Commissioning	Completion of construction work expected by 2027	— Commissioning tests
Operation	Planned operational period: 40 years	

[a] LLW: low level waste.
[b] ILW: intermediate level waste.
[c] EIA: environmental impact assessment.

TABLE I–6. ROADMAP FOR A NEW GEOLOGICAL DISPOSAL PROGRAMME FOR HLW AND SPENT FUEL IN GERMANY

Phase	Major decision/milestone	Principal activities (key issues)
Initiation	Implementation of an expert group for Site Selection Procedure for a Repository for High Active Waste (AKEnd) (1999–2002)	— Scientific analysis and evaluation of the site selection procedure
	Governmental decision to restart the site selection process for a deep geological repository for high level radioactive waste (2013)	— Legislation for the Repository Site Selection Act (StandAG)
	Consultations by the Commission on the Storage of High-Level Radioactive Waste (2014–2016)	— Discussion on criteria and procedure for site selection. The commission involves experts and a broad spectrum of stakeholder groups. Results are proposals for a transparent and science based procedure for site selection
	Reorganization of the radioactive waste management system (2017)	— Implementation of new institutions and definition of their responsibilities — New regulations for radioactive waste management funding
	Amendment of the Repository Site Selection Act (StandAG) (2017)	— Amendment based on the results of the Commission on the Storage of High-Level Radioactive Waste
	Decrees of Ordinances for Repository Safety (EndlSiAnfV) [I–22] and Repository Safety Demonstration (EndlSiUntV) [I–23] (both 2020)	— Definition of principal safety issues for construction, operation and closure of a repository
Siting	First step of site selection procedure (phase 1) according to (§ 13 StandAG) (2017–2020)	— Identification of subareas with favourable geological properties by applying: exclusion criteria (§ 22 StandAG); minimum requirements (§ 23 StandAG); geoscientific weighting criteria (§ 24 StandAG) Database: existing exploration data from the regional geological offices — BGE[a] (2020) prepared a first siting report compiling the results of step 1 and identifying potentially suitable subareas [I–21]
	Second step of phase 1 of the site selection procedure (2020–ongoing) (§ 14 StandAG)	— Identification of siting regions for surface exploration by applying: representative PSAs[b] based on the results of step 1; evaluation of results of PSA with geoscientific weighting criteria; socioeconomic weighting criteria; development of an above ground exploration programme; proposal of regions for above ground exploration — The corresponding work of BGE is ongoing

TABLE I–6. ROADMAP FOR A NEW GEOLOGICAL DISPOSAL PROGRAMME FOR HLW AND SPENT FUEL IN GERMANY (cont.)

Phase	Major decision/milestone	Principal activities (key issues)
	Decision on regions for above ground exploration and corresponding exploration programmes (future step according to § 15 StandAG)	— BASE[c] will evaluate BGE's proposal — BASE will inform the Federal ministry of environment, nature conservation and nuclear safety (BMU[d]), which transfers the results to the Federal Parliament and the Federal Council — Based on BGE's proposals and BASE's evaluations, the regions for above ground exploration and the further procedure in the regions with insufficient data will be defined by a Federal Act. BASE will define the fundamentals of the exploration programme
	Above ground exploration and proposal for underground exploration (phase II)	— Above ground exploration of regions as defined in the Federal Act — Advanced preliminary safety assessments (based on above ground exploration results) — Development of exploration programmes and test criteria — Proposal of areas for underground exploration
	Decision on regions for underground exploration and corresponding exploration programmes (future step according to § 17 StandAG)	— Evaluation of BGE's proposal by BASE — BASE will inform the competent ministry (i.e. BMU) — Federal Government will inform the Federal Parliament and the Federal Council — The regions for underground exploration will be fixed in a Federal Act
	Underground exploration (future phase III according to § 18 StandAG)	— Underground exploration, as defined in the Federal Act — Comprehensive preliminary safety assessments (results from above ground and underground exploration) — EIA[e] — Definition and application of test criteria as well as application of criteria and requirements defined in § 23–25 StandAG — Identification and comparison of suitable sites — Proposal of the most suitable repository site, including comparison of suitable sites (at least two)
	Final comparison of suitable sites and site proposal (future step according to § 19 StandAG)	— BASE will evaluate BGE's proposal, including comparison of at least two sites — Based on BGE's results and considering the results of public involvement, BASE will identify the site with the highest safety — Documentation of site proposal and — after final completion of all court hearings and legally binding rejection of the complaints — submission to BMU

TABLE I–6. ROADMAP FOR A NEW GEOLOGICAL DISPOSAL PROGRAMME FOR HLW AND SPENT FUEL IN GERMANY (cont.)

Phase	Major decision/milestone	Principal activities (key issues)
	Site decision (final step according to § 20 StandAG) (envisaged 2031)	— The Government will submit the site proposal to the Federal Parliament (Bundestag) and the Federal Council (Bundesrat) as a Federal Act — The Federal Parliament will decide on the site proposal and fix the result in a Federal Act

[a] BGE: Federal Company for Radioactive Waste Disposal.
[b] PSA: preliminary safety assessment.
[c] BASE: Federal Office for the Safety of Nuclear Waste Management.
[d] BMU: Federal Ministry of Environment, Nature Conservation and Nuclear Safety.
[e] EIA: environmental impact assessment.

I–6. COUNTRY: JAPAN

I–6.1. Context

As of December 2021, 10 nuclear power plants are in operation in Japan, 7 units have been approved for instalment licence amendment, 10 units are under assessment for new regulatory requirements, 9 units have not applied for assessment and 24 units have been permanently shut down [I–24]. Nuclear power makes up approximately 46% of total electricity generation in Japan. Spent nuclear fuel is reprocessed and then vitrified. The radioactive waste management organization in charge of the geological disposal programme is the Nuclear Waste Management Organization of Japan (NUMO). NUMO was established in 2000 in accordance with the Specified Radioactive Waste Final Disposal Act and is responsible for a geological disposal programme for the long term management of high level radioactive waste (i.e. vitrified waste) and transuranium (TRU) waste.

At this stage the host rock options are crystalline or sedimentary formations including accretionary complexes; however, this will be identified as the site selection process proceeds.

In 2002, NUMO initiated an open solicitation for volunteer host municipalities to participate in its siting process. The site selection process comprises a literature survey stage, a preliminary investigation stage and a detailed investigation stage. However, no survey had been carried out because no volunteers had officially come forward. The Government of Japan, therefore, made a decision to take the initiative regarding Japan's site selection process for a geological disposal facility. The decision was intended to make a breakthrough in the siting activities in 2015.

The Government of Japan published Nationwide Map of Scientific Features for Geological Disposal, which divides all areas in Japan into four categories: (1) area assumed to be unfavourable from the viewpoint of long term stability of the deep geological environment; (2) area assumed to be unfavourable from the view point of the risk of future inadvertent human intrusion; (3) area assumed to be favourable; and (4) area assumed to also be preferable from the viewpoint of safe waste transportation.

In October 2020, two municipalities in Hokkaido prefecture announced acceptance for a literature survey, which is the first stage of site investigation to select the site for a DGR. NUMO's application to commence the literature survey was accepted by Ministry of Economy, Trade and Industry in November 2020.

Reference [I–25] describes the specific strategies and concepts devised by NUMO to facilitate progress towards implementation of a DGR, managing site selection, repository design and safety assessment. It also describes the geological investigation techniques used for the characterization of relevant sites and the development of the site descriptive models.

The timeline and activities for Japan's geological disposal programme are outlined in Table I–7.

TABLE I–7. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME FOR HIGH-LEVEL RADIOACTIVE WASTE AND TRANSURANIUM WASTE IN JAPAN

Phase	Activities
Initiation	— The Atomic Energy Commission of Japan initiates an HLW[a] management programme focusing on R&D[b] for geological disposal. In parallel with technical developments, the activities for enhancing public understanding are carried out (1976) — The Second Progress Report on R&D for the geological disposal of HLW (H12 report) is published after two decades of R&D activities and shows that disposal of HLW in Japan is feasible and can be implemented practically at sites that meet certain geological stability requirements (1999) — The Act on Final Disposal of Specified Radioactive Waste is enforced (2000) — NUMO[c] is established (2000)
Siting	— In 2002, open solicitation of volunteer host municipalities for exploring the feasibility of constructing a final repository was started (2002) — In 2007, the Final Disposal Act was revised to include radioactive waste containing TRU[d] radionuclides for geological disposal (2007) — In 2015, the proposal approach by the Government of Japan to local government was added in addition to the open solicitation approach, as stated in the revised Basic Policy on Final Disposal of Designated Radioactive Wastes (2015) — In 2017 the Government of Japan officially published the Nationwide Map of Scientific Features Relevant for Geological Disposal (2017) — A literature survey is started for areas for potential candidate sites are selected on a nationwide scale and the PIAs[e] are nominated mainly by area specific literature surveys from the viewpoint of the long term stability of the geological environment (2020) — Preliminary investigation stage: the DIAs[f] are then selected from the PIAs by surface based investigations (including boreholes) carried out to evaluate the characteristics of the geological environment — Detailed investigation stage: in the final step, detailed investigation in the DIAs will lead to selection of a final repository site. Investigations at this stage are conducted in an underground facility constructed at the DIAs
Construction	— Start of first repository operation according to the original Final Disposal Plan of Final Disposal of Specified Radioactive Waste, which was last updated in 2008 (2035)[g] — Updates to the final disposal plan, that were required every 10 years by the Final Disposal Act but have been suspended since the accident at Fukushima Daiichi NPP[h] in 2011

[a] HLW: high level waste.
[b] R&D: research and development.
[c] NUMO: Nuclear Waste Management Organization of Japan.
[d] TRU: transuranium
[e] PIA: preliminary investigation area.
[f] DIA: detailed investigation area.
[g] Estimated timeline.
[h] NPP: nuclear power plant.

I–7. COUNTRY: SWEDEN

I–7.1. Context

There are six nuclear reactors in operation in Sweden, distributed between three nuclear power plants: Forsmark, Oskarshamn and Ringhals. The Forsmark nuclear power plant has three reactors in operation, the Oskarshamn nuclear power plant shut down two of its three reactors in 2017 and the Ringhals nuclear power plant shut down one of its four reactors in 2019 and another one in 2020. The respective owners plan to operate the remaining six reactors until 2041–2045.

Seven reactors, including the closed Barsebäck nuclear power plant and the historic Ågesta plant, are accordingly in the decommissioning phase. Apart from the reactors in operation or undergoing decommissioning, there are a number of other nuclear installations in Sweden. They are used to manufacture nuclear fuel and store spent nuclear fuel and radioactive waste. The Swedish policy is to dispose of the spent fuel in crystalline bedrock without reprocessing [I–26].

The Swedish Nuclear Fuel and Waste Management Company (SKB) is owned by the nuclear power companies. According to Swedish law it is the owners of the nuclear power plants that have to pay for all the costs of dealing with spent nuclear fuel and its final disposal. They also have to pay the costs of decommissioning nuclear power plants and other nuclear installations. Since the mid-1970s the nuclear power companies have been allocating funds to cover these costs. These funds are administered by the Nuclear Waste Fund (controlled by the Government). The timeline, decisions and milestones for the Swedish geological disposal facility are shown in Table I–8.

TABLE I–8. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL IN SWEDEN

Phase	Major decision/milestone	Principal activities
Initiation	Stipulation Act (1977) New reactors could only be started if the reactor owner could demonstrate a completely safe method of disposing of the spent nuclear fuel, either by reprocessing or by direct disposal	— The reactor owners started the KBS-1 project [I–27], suggesting that the spent fuel should be reprocessed and then deposited in a geological repository. This, Sweden's first safety assessment, was sufficient as a basis to start the new reactors — The Swedish–American Cooperative (SAC) programme, 1977–1980. Evaluating the response of granite to elevated temperature in a simulated repository environment. Developing techniques for characterizing the hydrological and mechanical characteristics of naturally fractured granitic rock masses — Further geological surveys of bedrock at possible sites for a final repository (approved by authorities in 1979). In the updated safety assessment, KBS-2, it was suggested to go for direct disposal of the spent nuclear fuel and plans for reprocessing were omitted [I–28]
	The International Stripa Project (1980-1992)	— Final report published in 1993 [I–29]. Task forces on sealing materials and techniques. Fracture flow modelling — Participating countries: Canada, Finland, France (phases 1 and 2), Japan, Spain (phase 2), Sweden, Switzerland, UK (phases 2 and 3), USA — Managerial oversight by Joint Technical Committee (JTC) and Technical Subgroup (TSG)

TABLE I–8. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL IN SWEDEN (cont.)

Phase	Major decision/milestone	Principal activities
	KBS-3 was established as the design concept (1983)	— In 1983, the KBS-3 [I–30] method for final disposal of spent nuclear fuel in Sweden was elucidated in a report that then formed the basis for the applications to allow the most recently built nuclear reactors into operation — In 1984, the Swedish Government granted fuelling permits for the reactors, acknowledging the safety of the KBS-3 method [I–31]
	The Act on Nuclear Activities (1984) establishes that a party that holds a licence for nuclear activities shall be responsible for ensuring that all the necessary measures are taken for the safe management and disposal of nuclear waste generated by the operation or nuclear material derived from the operation that is not reused. It also states that a party that holds a licence to possess or operate a nuclear power reactor shall be responsible for all costs of the nuclear waste and decommissioning and shall establish a plan for the research and development required for safe final disposal. The plan shall be presented every three years and cover activities for the coming six years	— In September 1986, SKB[a] presented the first SKB RD&D[a] programme [I–31] according to the new Act on Nuclear Activities — One of the major highlights of the programme was the plan for construction of an underground research laboratory
Siting	Study areas (1977–1985) Siting of the underground research laboratory (1986–1990)	— Countrywide studies of type areas in Sweden — In 1988, after extensive site investigations, SKB decided to site the laboratory on the southern part of the Äspö island. Thus, the underground laboratory was named the Äspö Hard Rock Laboratory. The rock at the site is more than 1700 million years old granitoid rock with many types of fracture zones
	Construction of the Äspö Hard Rock Laboratory (1990–1995)	— A major issue for the work performed 1986–1995 was to verify the pre-investigation methods [I–32]. It aimed to show that investigations on the ground surface and in boreholes provide sufficient data on essential safety related properties of the rock at repository level. A strategy for achieving this goal was outlined. It included an iterative, integrated multidisciplinary approach to data collection and modelling. Predictions were tested by comparison with the data collected from the tunnel excavation
	Regional studies of Sweden	— In the early 1990s more studies and mapping were performed on possible feasible bedrock for the spent fuel repository

TABLE I–8. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL IN SWEDEN (cont.)

Phase	Major decision/milestone	Principal activities
	Feasibility studies (1993–2002)	— In 1992 SKB revised its siting plans and decided that siting should be based on a voluntary approach. Invitations to conduct 'feasibility studies' were sent to all Swedish municipalities. Eventually such studies, including surveys of geology and society, were conducted in eight potential municipalities. This phase ended with selection of municipalities for site investigations followed by decisions on their voluntary participation — In 1997, SKB presented the first updated safety assessment based on data from three different geological setting in Sweden (SR-97) [I–33]. Siting factors for the spent nuclear fuel repository were determined and presented to the authorities
	Site investigations (2002–2009)	— SKB presented it selection of investigation sites. The selection was later approved by Government and affected municipalities. Start of drillings, geological investigations, environmental studies and society surveys at two potential repository sites, Oskarshamn municipality (Laxemar site) and Östhammar municipality (Forsmark site) — In 2006, SKB presented an interim second safety assessment (SR-CAN). Based on this, SKB produced technical design requirements [I–34] to fulfil post-closure safety of the repository — In 2009, SKB presented Forsmark as the recommended repository site [I–35] based on extensive post-closure safety evaluations and the EIA[c]
Licensing	Licence application for construction and operation of the spent fuel repository in Forsmark and the encapsulation plant in Oskarshamn (2011)	— In 2010, SKB finalized the safety case (SR-site) and this and the environment impact assessment were extensively reviewed and completed [I–36] — In 2011, SKB finalized and submitted the KBS-3 licence applications to the Land and Environment Court and to the Swedish Radiation Safety Authority (SSM) — SKB also needs formal acceptance from the concerned municipalities Oskarshamn and Östhammar. Finally, the approval of the Swedish Government is needed — At the beginning of 2018, the Land and Environment Court issued its statement recommending that the Government require supplementary data on the long term safety of the copper canister with regard to corrosion aspects before potential approval — At the beginning of 2018, the Swedish Radiation Safety Authority approved SKB's applications — In June 2018, Oskarshamn municipality approved establishment of the encapsulation plant — In April 2019, SKB submitted supplementary information to the Ministry of the Environment regarding the canister's protective capacity

TABLE I–8. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME FOR SPENT NUCLEAR FUEL IN SWEDEN (cont.)

Phase	Major decision/milestone	Principal activities
		— In June 2020, the lawmaker (Riksdagen) decided on amendments to the law clarifying the State's responsibility for the final repository — In October 2020, Östhammar municipality approved establishment of the final repository for spent nuclear fuel — In January 2022, SKB received the Government's permission under the Nuclear Act to own, construct and operate a final repository and a facility for encapsulation of spent nuclear fuel in accordance with SKB's application. The Government also decided to allow the same activities according to the Environmental Code, which means, among other things, that the Government assesses that the impact on the environment can be accepted — In accordance with the Environmental Code, the Government has handed over the case to the Land and Environmental Court at Nacka District Court for a conditional hearing. The Government's decision according to the Nuclear Act has the condition that the SSM has to carry out a continued step by step examination, where future research and technology development will be part of the continued process
Disposal	PSAR[d] — to be submitted to SSM as a basis for obtaining a licence to start the underground excavation	— Coming step
	Start of underground construction and detailed design of the repository area	— Coming step
	Update to a SAR[e] that will form the basis for the operation of the repository	— Coming step

[a] SKB: Swedish Nuclear Fuel and Waste Management Company.
[b] RD&D: research, development and demonstration.
[c] EIA: environmental impact assessment.
[d] PSAR: preliminary safety analysis report.
[e] SAR: safety analysis report.

I–8. COUNTRY: SWITZERLAND

I–8.1. Context

As of 2021, four nuclear power reactors (three pressurized water reactors (PWRs), one boiling water reactor (BWR)) are in operation at three sites (Beznau, Gösgen, Leibstadt), totalling ~3015 MWe. The nuclear power plant at Mühleberg (BWR) ceased power operation permanently on 20 December 2019.

The producers of radioactive waste (i.e. the nuclear power plant operators and the Swiss Confederation (for the waste from medicine, industry and research)) have formed the National Cooperative for the Disposal of Radioactive Waste (Nagra), which is responsible for preparing and implementing solutions for the disposal of all radioactive waste categories.

The Swiss Federal Office of Energy (SFOE), within the Federal Department of the Environment, Transport, Energy and Communications (Eidgenössische Departement für Umwelt, Verkehr, Energie und Kommunikation — UVEK), participates in the organization and implementation of the various licensing procedures, and prepares decision making bases for the relevant federal department and the Federal Council. The SFOE also coordinates the site selection procedure and is responsible for the implementation of the Sectoral Plan for Deep Geological Repositories. The Swiss Federal Nuclear Safety Inspectorate (ENSI) supervises nuclear facilities with respect to radiation protection and nuclear safety at all stages of the life cycle.

Two repositories are proposed, one for low and intermediate level waste (LILW) and one for HLW and spent nuclear fuel (SNF). It is also possible to implement the two facilities at the same site. The site selection process has to follow a sectoral plan procedure within the framework of spatial planning legislation. The site selection process, according to the sectoral plan procedure for deep geological repositories, was started with the announcement of the Sectoral Plan for Deep Geological Repositories on 2 April 2008 by the Federal Council.

Site selection is based on scientific and technical criteria, with the main emphasis being placed on safety, but socioeconomic and environmental aspects also have to be addressed in the process. The site selection procedure is divided into three stages [I–37]. The timeline and activities for the Swiss geological programme are shown in Table I–9.

TABLE I–9. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME IN SWITZERLAND

Phase	Milestone	Principal activities
Initiation	Nagra[a] established in 1972 by the Swiss nuclear power plant operators and the Federal Government to implement permanent disposal of all types of radioactive waste generated in Switzerland A Government Ruling on the Atomic Act (1978) sets very specific requirements to demonstrate that safe disposal of radioactive waste in Switzerland is feasible, as a prerequisite to the construction of any new nuclear power plants. This provision is also included in the current nuclear energy legislation [I–38]	— Nagra prepared Projekt Gewaehr (Project Guarantee) and initiated programmes that established the foundation of the scientific and engineering basis for the radioactive waste management programme of Switzerland
Siting	The siting process consists of three stages Nagra submitted its proposals for suitable geological siting areas for the repositories for HLW[b] and LILW[c] to the SFOE[d] in October 2008 The Government approved all six potential siting regions 30 November 2011, concluding the first stage of the site selection process and initiating the second stage	— The aim of stage 1 was to determine geological siting regions that would potentially be suitable for deep geological repositories, based on safety relevant and geological criteria — The starting point was a ‘blank map’ of Switzerland, meaning that all of Switzerland’s potentially suitable regions and rock formations were considered. Nagra proposed potential siting regions in accordance with the safety and engineering feasibility criteria defined in the sectoral plan. — Public consultation was carried out in 2010 by the SFOE and comments were submitted to Government

TABLE I–9. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME IN SWITZERLAND (cont.)

Phase	Milestone	Principal activities
	At the end of stage 2, the Federal Council determined that the siting regions of Jura Ost (Canton Aargau), Nördlich Lägern (Cantons Aargau and Zürich) and Zürich Nordost (Cantons Thurgau and Zürich) would be investigated further, concluding the second stage of the site selection process and initiating the third stage (November 2018)	— In stage 2, the sectoral plan requests that waste producers prepare proposals for the design, layout and location of the required surface infrastructure in the various regions, in relation to potential sites for the underground facilities — Broad public consultation on stage 2 started on 23 November 2017 and lasted until 8 March 2018. Following this, the SFOE submitted a report to the Federal Council
	Nagra continues to investigate several candidate sites	— Nagra is investigating the three remaining siting regions in depth. The investigative programme includes previously conducted seismic measurements as well as quaternary boreholes and deep boreholes. The deep borehole investigations complete the already existing overall picture of the underground geological environment in the siting regions
	Nagra proposes Nördlich Lägern as the site for a repository (2022)	— Nagra is preparing the general licence applications based on this site
	Planned submission of licence application(s) for 2024	— By the end of 2024, the implementer, Nagra, will submit applications for a general licence (one for an HLW repository and one for an LILW repository or a single one in the case of a combined repository)
URFs	Switzerland hosts two operating underground research laboratories in two different host rocks: the Grimsel Test Site and the Mt Terri Project	— As of June 2013, 18 organizations and research institutes from 12 different countries, as well as the European Union, are participating in various projects at Grimsel — At Mt Terri, two well known experiments include the Full-Scale Emplacement experiment (FE) and the so called HG-A experiment investigating the gas path through host rock and around seals
Disposal[e]	The decision of the Federal Council is expected in 2029[e] and Parliament's decision concerning the Government's approval of the general licence for deep geological repositories is expected around 2030[e]. That decision is subject to an optional national referendum around 2031[e]	— Coming step

TABLE I–9. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME IN SWITZERLAND (cont.)

Phase	Milestone	Principal activities
	After the granting of the general licence, a licence for the construction and operation of an underground facility for geological investigations is required. After the underground investigations, applications for a construction licence and for an operating licence for each repository will follow; both will be granted by the relevant federal department. According to the current schedule, the LILW repository should be operational around 2050[e] and the HLW repository around 2060[e]	— Coming step

[a] Nagra: National Cooperative for the Disposal of Radioactive Waste.
[b] HLW: high level waste.
[c] LILW: low and intermediate level waste.
[d] SFOE: Swiss Federal Office of Energy.
[e] Estimated timeline.

I–9. COUNTRY: UKRAINE

I–9.1. Context

As of 2021, there are 4 nuclear power plants and 15 operating reactors in Ukraine. Nuclear power makes up more than 50% of total electricity generation in Ukraine.

A site for a centralized storage facility (CSF) for spent nuclear fuel has been selected within the Chornobyl Exclusion Zone (ChEZ) and construction of this facility started in May 2019 [I–39].

A decision on the DGR concept has not yet been made. Preliminary considerations include a combination of two mined disposal facilities: one at intermediate depth (for Chornobyl accidental waste and other ILW) and one at a greater depth (for HLW and, possibly, for SNF). The borehole disposal concept is also being considered as an option for SNF disposal. The radioactive waste management organization in charge of the geological disposal programme is the Central Enterprise for Radioactive Waste Management.

According to Ukrainian legislation, only the Ukrainian Parliament can make decisions about site selection and the design and construction of disposal facilities of national importance (including a DGR). The decisions should be approved in the form of a special law. The Ukrainian radioactive waste management organization (RWMO) should prepare associated documents that justify the decisions. The documents will include the results of siting and feasibility studies, general safety assessments, description of public consultancies and stakeholders' opinions [I–40].

According to preliminary evaluation of the National Academy of Sciences, the crystalline formations of the Chornobyl Exclusion Zone are considered the most promising formations and region for geological disposal in Ukraine.

I–9.2. Timeline for implementing the geological disposal programme

As of 2021, Ukraine is in the siting phase for a geological disposal programme. Currently, general site screening and conceptual study of the disposal system are underway. The overall siting stage consists of a DGR concept and planning stage, a regional investigation, site characterization and, finally, site confirmation. The ChEZ and adjacent territories can be considered to comprise the most promising region of Ukraine for high priority field investigations for the identification of sites for DGR placement. Within ChEZ there are three areas for high priority investigation: Novosilky, Zhovtneva and Veresnia [I–41].

A site specific underground research facility (URF) is considered to be necessary in the Ukrainian DGR programme. The site specific URF could be transformed into a pilot section of the DGR. It is intended that the site specific URF will be built at the site confirmation step.

I–10. COUNTRY: REPUBLIC OF KOREA

I–10.1. Context

As of May 2019, 26 units of NPP are in operation, 2 units are under construction, and 2 units have been permanently shut down. Nuclear power makes up approximately 23% of total electricity generation. Spent nuclear fuel arising from NPPs is temporally stored at on-site pools and a dry storage facility.

The government of the Republic of Korea publicly announced a national basic plan for HLW management in 2016, which focused on interim storage and subsequent deep geological disposal. The national basic plan is based on recommendations from the Public Engagement Commission on Spent Fuel Management (PECOS). The basic plan provides the timeline for implementing a deep geological disposal facility. The siting process is expected to be carried out for 12 years followed by construction and operations of a site specific URF. Underground characterization will be performed at the site specific URF to provide scientific and engineering basis for the safe and efficient disposal of HLW. In parallel to the siting process, the development of a generic URL is planned.

The radioactive waste management organization in charge of a geological disposal programme is the Korea Radioactive Waste Agency (KORAD).

I–10.2. Timeline for implementing the geological disposal programme

The timeline and activities for the Republic of Korea’s geological disposal programme are shown in Table I–10.

TABLE I–10. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME IN THE REPUBLIC OF KOREA

Phase	Milestone	Principal activities
Background	In 2009, KORAD[a] was created to meet the requirements of Radioactive Waste Management Act	— Management of all kinds of radioactive wastes including LILW[b], HLW[c] and even RI[d] waste in Korea
Initiation	Resolution of the 6th AEPC[e] (Atomic Energy Promotion Commission) (25 July 2016) [I–42]	— Basic Plan on Management of High-Level Radioactive Waste developed, based on PECOS[f] recommendations. The plan included the roadmap for HLW management to ensure the public safety

TABLE I–10. ROADMAP FOR THE GEOLOGICAL DISPOSAL PROGRAMME IN THE REPUBLIC OF KOREA (cont.)

Phase	Milestone	Principal activities
	Korean Government's Decision to Review the Basic Plan on HLW Management (July 2017)	— Review the basic plan on HLW management through Public Engagement Programs as President's Agenda No. 60
	Korean Government decided to review the basic plan on HLW management through Public Engagement Programs as President's Agenda No. 60 (2018)	— Preparation Group to collect opinions of stakeholders and experts. The group held 21 meetings to set a guideline for agendas and procedure of the new SNF[g] public engagement. Their recommendations were submitted to the government after six-month activity
	R&D[h] for DGR[i] (2021–2030)	— Develop a generic safety case for a deep geological disposal of HLW
Siting	Siting phase duration ~13 years	— Site selection process: literature review, preliminary investigations and detailed investigations. The Ministry of Trade, Industry and Energy (MOTIE) to oversee other decisions including initiation of siting, site selection, and the emplacement of waste into a disposal facility based on regulatory oversight
URFs	Site specific URF[j] duration ~14 years	— Two different types of URFs, generic URF and site-specific URF to be developed
Disposal	Repository and operation ~37 years	— Coming step
	Repository operations and post-closure monitoring (to be determined)	— Coming step

[a] KORAD: Korea Radioactive Waste Agency.
[b] LILW: low and intermediate level waste.
[c] HLW: high level waste.
[d] RI: radioisotope.
[e] AEPC: Atomic Energy Promotion Commission.
[f] PECOS: Public Engagement Commission on Spent Fuel Management.
[g] SNF: spent nuclear fuel.
[h] R&D: research and development.
[i] DGR: deep geological repository.
[j] URF: underground research facility.

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Annex II

WORK BREAKDOWN STRUCTURE FOR ACTIVITIES FOR FIVE MAJOR WORK ELEMENTS OF A GEOLOGICAL DISPOSAL PROGRAMME

Annex II is available as an on-line supplementary file on the publication's individual web page, https://doi.org/10.61092/iaea.80st-qaw7. It provides a series of matrices that illustrate the work breakdown structure for each phase of the roadmap.

ABBREVIATIONS

Andra	National Radioactive Waste Management Agency (France)
BGE	Federal Company for Nuclear Waste Management (Germany)
DGR	deep geological repository
EIA	environmental impact assessment
ENSI	Swiss Federal Nuclear Safety Inspectorate
FEPs	features, events and processes
HLW	high level waste
ILW	intermediate level waste
KORAD	Korea Radioactive Waste Agency (Republic of Korea)
LLW	low level waste
Nagra	National Cooperative for the Disposal of Radioactive Waste (Switzerland)
NWMO	Nuclear Waste Management Organization (Canada)
QA	quality assurance
R&D	research and development
RAWRA	Radioactive Waste Repository Authority (Czech Republic)
RD&D	research, development and demonstration
SBD	safeguards by design
SKB	Swedish Nuclear Fuel and Waste Management Company
STUK	Radiation and Nuclear Safety Authority (Strålsäkerhetscentralen), Sweden
URF	underground research facility
WAC	waste acceptance criteria
WBS	work breakdown structure
WIPP	Waste Isolation Pilot Plant (United States of America)
WMO	waste management organization

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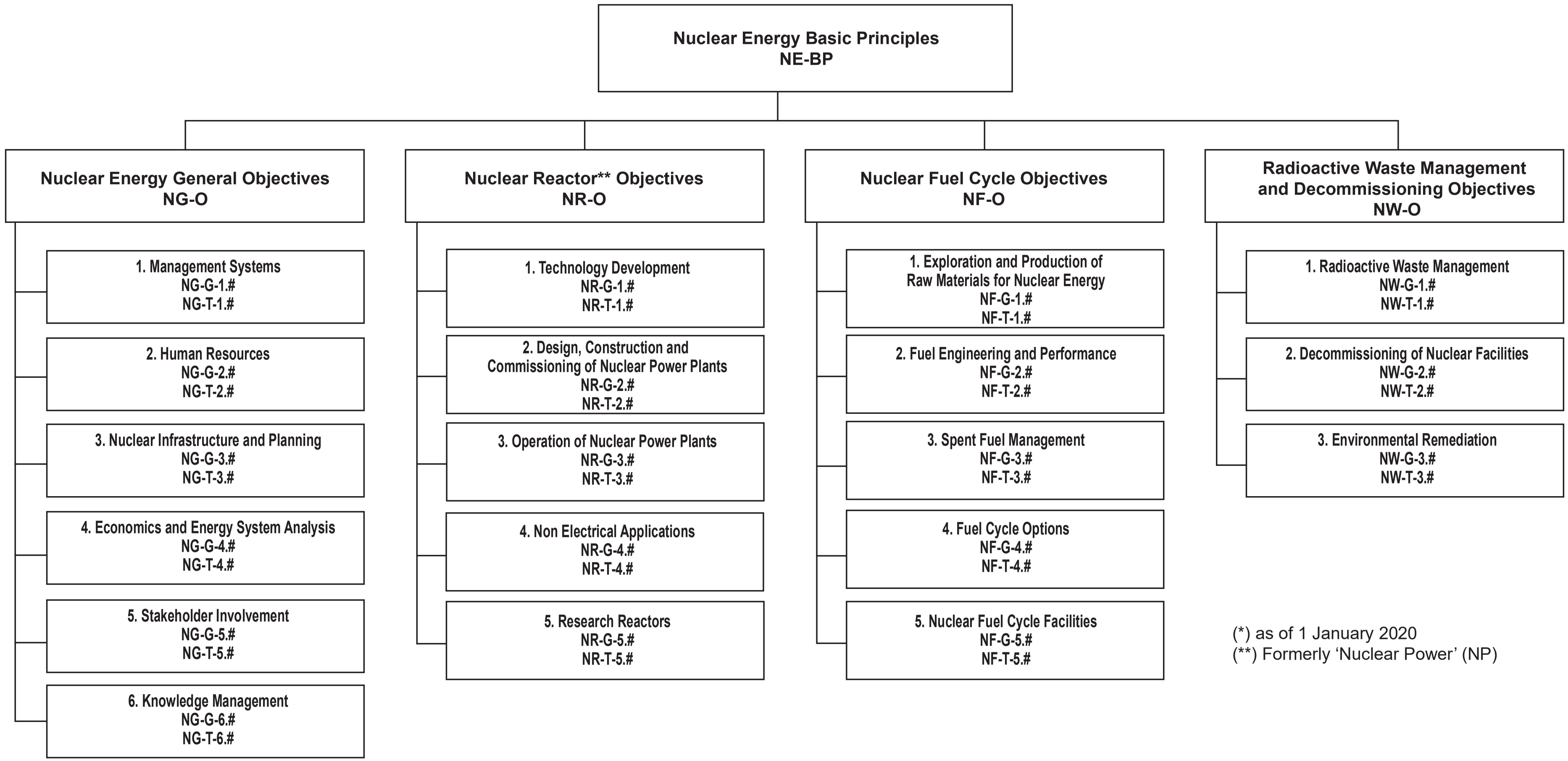

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