Vision 2040

Strategic Research Agenda

September 2020

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Implementing Geological Disposal of radioactive waste Technology Platform (IGD-TP)

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Foreword

Initiated by the European Commission, the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) was launched on 12 November 2009 by ten waste management organisations and one governmental body. The IGD-TP is dedicated to initiating and carrying out collaborative strategic scientific and technical actions to facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste, and other long-lived radioactive waste. IGD-TP members share scientific and technological knowledge and work to solve new and remaining scientific, technological and societal challenges, and thereby support European waste management programmes. The platform aims to enhance confidence in the solutions and implementation of geological disposal, to reduce overlapping work, to produce savings in total costs of Research, Development and Demonstration (RD&D), and to make better use of existing competencies and research infrastructures.

Now solely funded by the 12 organisations that form the Executive Group, the IGD-TP has around 140 participating organisations endorsing our vision and comprising of stakeholders with a wide range of backgrounds, including waste management organisations (WMOs), Research Entities (REs), Regulatory Technical Support Organisations (TSOs), Waste Producers, academia, industry and civil society representatives. Participation is open to all interested parties endorsing the IGD-TP Vision and willing to contribute positively and constructively to build a common task force (based on scientific, technological, education and training excellence) to safely and efficiently implement geological disposal. The IGD-TP is implementer-driven where members of the Executive Group are organisations either responsible for implementing a waste management programme or are formally responsible for the RD&D programme needed to underpin safe and secure implementation.

At the time of its launch, the IGD-TP published its Vision 2025 Report, which detailed the vision that by 2025, the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste would be operating safely in Europe. Following this, in 2011 a Strategic Research Agenda (SRA) was published, which was dedicated to identifying the main RD&D issues that required a co-ordinated effort in order to achieve Vision 2025.

In the decade that has followed, geological disposal in Europe has progressed such that the aims of Vision 2025 are expected to be achieved: Posiva and SKB are on course to establish operational geological disposal facilities (GDFs) in Finland and Sweden, respectively, with Andra (France) not far behind. To reflect this progress, an updated vision, Vision 2040, was announced in 2019. The new vision was intended to reflect the different stages of the various IGD-TP member organisations with respect to implementation of geological disposal, and to include the Small Inventory Member States (SIMS) and those who may wish to pursue the possibility of shared repositories. Vision 2040 sets out details of the vision for the industrialisation of radioactive waste disposal in Europe by 2040, via three pillars: (1) safe operation of the first geological disposal facilities in Europe; (2) optimisation and industrialisation of planning, construction and disposal operations; and (3) development of tailored solutions for disposal of the diverse radioactive waste inventories in Europe.

Consequently, the 2011 SRA required updating to reflect progress made since its inception, and to reflect the new RD&D issues that require a co-ordinated effort in order to meet Vision 2040.

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Of particular interest are the issues for which enhanced co-operation within the IGD-TP is considered desirable and practically achievable. This document sets out the IGD-TP's Vision 2040 and the revised 2020 SRA.

Since the SRA identifies the key RD&D topics that have the greatest potential to support repository implementation through enhanced co-operation in Europe, it also provides valuable input to identifying topics for future calls for proposals issued by the EC Euratom Research and Training Programme. The SRA is well suited to this role as the Topics within the Key Topics are identified in relation to their priorities, which have been established collectively through discussions among many European waste management organisations and also because benefits are expected to flow to a broad range of participants. The SRA is also the instrument for creating synergies, co-operation and co-ordination, both internally between the IGD-TP participants and with external activities that take place within other international forums.

The SRA has been produced by an IGD-TP SRA Working Group with representatives from the IGD-TP's member WMOs. IGD-TP Executive Group members and non-member European WMOs were consulted and encouraged to contribute to the content of this revision of the SRA, by being given the opportunity to suggest research topics of high priority to their particular national context or organisation and to prioritise the research topics. In this way the 2020 SRA has been produced to identify RD&D topics that are of common need to the European WMOs.

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Acronyms

BIM	Building Information Modelling
D&D	Development and Demonstration
DBD	Deep Borehole Disposal
DFN	Discrete Fracture Network
DGR	Deep Geological Repository
EBS	Engineered Barrier System
EC	European Commission
EG	Executive Group
ERDO-WG	European Repository Development Organisation Working Group
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
GDF	Geological Disposal Facility
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
IGD-TP	Implementing Geological Disposal of Radioactive Waste Technology Platform
IGSC	Integration Group for the Safety Case
ILW	Intermediate-Level Waste
LLW	Low-Level Waste
MOX	Mixed Oxide
NEA	Nuclear Energy Agency
NHB	Non-Human Biota
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
RD&D	Research, Development and Demonstration

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RE	Research Entities
RTD	Research and Technological Development
RWM	Radioactive Waste Management
SIMS	Small Inventory Member States
SRA	Strategic Research Agenda
SRRF	Spent Research Reactor Fuel
SSD	Small-Scale Disposal solution
THMC	Thermal-Hydro-Mechanical-Chemical
TP	Technology Platform
TSO	Technical Support Organisation
URL	Underground Research Laboratory
WM	Waste Management
WMO	Waste Management Organisation
WP	Work Package

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1 Introduction

As of March 2020, there were 442 nuclear reactors in operation in the world, of which 181 (41%) were situated in Europe [1]. By the same date, there were 187 nuclear reactors in the world that had been permanently shut down, of which 113 (60%) were in Europe. The main source for nuclear waste in Europe is the operation of electricity-producing nuclear reactors and their eventual decommissioning and dismantling. In addition, countries which do not have nuclear power plants still produce smaller quantities of radioactive wastes from research and medical activities. Under the provisions of the International Atomic Energy Agency (IAEA) Joint Convention [2], acceded to by nearly all European Union (EU) Member States, each nation is responsible for managing the radioactive waste produced within its borders. These requirements are repeated in the 2011 European Commission (EC) Council Directive on the Safe Management of Spent Fuel and Radioactive Waste [3].

The EC Directive states that "it is broadly accepted at the technical level that, at this time, deep geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste and spent fuel considered as waste" [3, para.23]. In parallel, European citizens have a widespread wish for "a permanent and safe solution for managing radioactive waste" [4]. The majority of European countries with civil nuclear power plants have on-going waste management programmes, but the current status and the main challenges of those programmes vary. Despite the differences between the timing and the challenges in the different programmes, there is consensus that continued and strengthened co-operation on the scientific, technical, and societal challenges related to deep geological disposal is necessary for the safe, secure and timely implementation of geological disposal facilities.

Since 2002, the EC has been instrumental in establishing Technology Platforms (TPs) as forums to improve co-operation within European Research and Technological Development (RTD) sectors, especially where a more strategic approach is needed and industry needs to play a greater role in defining the needs and in driving the related RTD activities. A common aspect to all TPs is the development of a common vision and Strategic Research Agenda (SRA) with short- and medium-term objectives [5]. Based on the above-mentioned consensus and also the positive outcome from Euratom projects such as Net.Excel [6] and CARD [7], the vision for a TP on deep geological disposal was recognised. The "Implementing Geological Disposal of Radioactive Waste Technology Platform" (IGD-TP) was formally launched on 12 November 2009 and consisted of about 80 participating organisations. Publication of the IGD-TP Vision Report [8] in 2011 followed, which was prepared by a group of leading European waste management organisations (WMOs) and a governmental body in consultation with the wider community. The ambition of the IGD-TP was to bring together stakeholders with various backgrounds (e.g. industry, research institutes, academic community, regulatory bodies, public authorities, the financial world and civil society) who would develop a research and development strategy covering the priority research needed to realise the aims set out in the Vision Report (discussed below). At this time, the research needs of the advanced programmes were prioritised over those in their earlier stages, the rationale being that the greatest common benefit would be achieved via the acceptance of geological disposal facilities (GDFs) as the world-class solution for the disposal of radioactive waste in Europe.

The IGD-TP vision statement (Vision 2025) was that "by 2025, the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe". Its commitment was to:

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- Build confidence in the safety of geological disposal solutions among European citizens and decision-makers.
- Encourage the establishment of waste management programmes that integrate geological disposal as the accepted option for the safe long-term management of long-lived and/or high-level waste.
- Facilitate access to expertise and technology and maintain competences in the field of geological disposal for the benefit of Member States.

The strategic initiatives prepared by the IGD-TP were intended to contribute to the objectives expressed in the Specific Programme implementing the Seventh Framework Programme of the European Atomic Energy Community (EURATOM) for Nuclear Research and Training Activities (2007 to 2011) [9], namely *"a sound scientific and technical basis for demonstrating the technologies and safety of disposal of spent fuel and long-lived radioactive wastes in geological formations"*, and in addition the IGD-TP should *"underpin the development of a common European view on the main issues related to the management and disposal of waste"*. It was also envisaged that the IGD-TP would enhance European co-operation in the areas where work still remains, optimise the solutions and move results from laboratories and pilot-facilities to the industrial scale.

Since 2011, substantial progress has been made towards achieving Vision 2025 and the aims set out in the Vision Report. In Finland, Posiva was granted a construction licence in 2015 for a GDF in Olkiluoto for spent nuclear fuel [10]; SKB submitted a construction licence application for a GDF for spent fuel in Forsmark, Sweden in 2011, with further supplementary information supplied in 2019 [11]; and in France, Andra is preparing a licence application for Cigéo (the Industrial Centre for Geological Disposal) in Meuse/Haute-Marne departments for disposal of high-level and long-lived radioactive waste [12]. Progress has also been made across the spectrum of national waste management programmes. Early stage programmes have published policies in support of geological disposal as a preferred solution, and 'mid stage' programmes have developed and documented credible underpinning research programmes in line with the EURATOM spent fuel and radioactive waste directive that has been in force since 2011. Numerous small inventory programmes (e.g. those represented by the European Repository Development Organisation (ERDO)) have also expressed support for, or interest in, considering the option of shared European repositories [13; 14]. Based on the IGD-TP's 2011 SRA, the WMOs' research needs have helped define and direct numerous EURATOM research calls and projects such as CAST[1], MODERN[2], BELBAR[3], LUCOEX[4], CEBAMA[5], JOPRAD[6], to highlight only a few. To reflect this progress and set new, more appropriate aims to guide future Research, Development and Demonstration (RD&D), an updated IGD-TP vision was announced in November 2019 – Vision 2040 [15]. This is presented in Section 2.

As a result of the progress made over the last ten years, the IGD-TP SRA has also been reviewed and revised to identify the collaborative RD&D activities needed to achieve Vision 2040. The

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[1] CArbon-14 Source Term
[2] Monitoring Developments for Safe Repository Operation and Staged Closure
[3] Bentonite Erosion: effects on the Long-term performance of the engineered Barrier and Radionuclide transport
[4] Large Underground Concept Experiments
[5] Cement-based materials, properties, evolution, barrier functions
[6] JOint Programming on RADioactive waste disposal

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SRA is a document for communicating the shared priority WMO research needs and opportunities to stakeholders in the waste management community, and it is also an instrument for creating synergies, co-operation and co-ordination with activities taking place in other international co-operation fora. The rationale and framework for the revision of the SRA is presented in Section 3 whilst the identified research topics are presented in Section 4.

The IGD-TP is now solely funded by the 12 organisations that form the Executive Group. The IGD-TP aims to offer benefits to all of its members irrespective of the differences in timescales of national waste management programmes. For small waste management programmes and programmes in their early stages, the IGD-TP offers possibilities for knowledge transfer and experience build-up. The IGD-TP acts as a vehicle to facilitate and support collaboration between members to cost-effectively and efficiently deliver RD&D necessary for the implementation and operation of geological disposal facilities, without undue duplication, and to share knowledge and experience. The IGD-TP represents the common views and objectives of European waste management organisations. The IGD-TP's work and results, together with general information about the IGD-TP, are posted on the website (www.igdtp.eu).

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2 IGD-TP Vision 2040

Now, in 2020, the IGD-TP has around 140 participating organisations. In the past decade, RD&D surrounding geological disposal issues has advanced, and Finland (Posiva) is on track to meet the Vision 2025 target of achieving an operational GDF by 2025, with Sweden (SKB) and France (Andra) close behind. In light of the progress made, and to reflect the changing RD&D needs of the European waste management organisations as a result, a new vision, Vision 2040, was published in November 2019 [15] (Figure 2.1).

Vision 2040 considers the next steps that must be taken to achieve the industrialisation of radioactive waste disposal in Europe by 2040; its scope covers RD&D supporting progress towards achieving final geological disposal, as well as RD&D relating to pre-disposal issues such as waste acceptance criteria (WAC), waste characterisation and waste treatment in support of disposability.

The vision is to be achieved via "three pillars", which have been designed to promote research that is inclusive of WMOs at varying stages of geological disposal development and implementation, including pre-disposal activities.

(1) safe operation of the first geological disposal facilities in Europe;

(2) optimisation and industrialisation of the planning, construction and disposal operations needed to achieve this; and

development of tailored disposal solutions in order to meet the requirements of the diverse range of waste inventories in the various countries and programmes in Europe.

Figure 2.1: IGD-TP Vision 2040, showing the "three pillars" - Safely Operate, Optimise and Industrialise, and Tailor Solutions.

2.1 IGD-TP Objectives

As mentioned above, some waste management programmes have already submitted or are rapidly approaching the licensing stage. Considerable knowledge has been achieved, however old challenges still remain and new ones are emerging (in the context of optimisation) that relate

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to science and technology and their interfaces with society. To meet the overall vision of the IGD-TP in an efficient way, the activities to be performed within the IGD-TP are implementation-oriented. The platform provides:

- a forum for discussion of RD&D issues and priorities
- a means for sharing RD&D information and results, including information and experience on RD&D planning, methodology and management, and how to integrate these in decision making; and
- a mechanism for co-ordinating RD&D on topics of shared interest between programmes and groups of organisations.

The main objectives of the IGD-TP are to initiate and carry out European strategic initiatives to facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste, and other long-lived radioactive waste by solving the scientific, technological and societal challenges, and to support the waste management programmes of members. The IGD-TP constitutes a means to further build confidence in the solutions, to reduce overlapping work, to produce savings in total costs of research and implementation, and to make better use of existing competence and research infrastructures.

To meet its objectives the IGD-TP is active in:

- Pooling of critical European resources and preparing co-ordination of future projects. It is important to ensure and to foster a sustainable European "critical mass" of competent human resources that can handle all aspects of geological disposal such as site characterisation, nuclear engineering, repository construction, operation and monitoring, closure, and the overall safety case now and in the future. The pooling of resources can create and support the development and strengthening of strong networks or centres of competence excellence in Europe. These competence networks can also provide unbiased knowledge concerning the feasibility of safe geological disposal that decision-makers and citizens may consult.
- Mobilising public and private funds from the platform members and from other funding sources to finance implementation of the agreed strategic initiatives.
- Development, management and transfer of knowledge concerning geological disposal.
- Contributing to the availability and maintenance of critical masses of resources for RD&D of technology.
- Identifying areas in strategic knowledge or know-how that can be covered by concerted actions.
- Creating synergies with other international organisations and European initiatives.

2.2 Challenges

Extensive RD&D work has been carried out for decades demonstrating the feasibility of deep geological disposal. However, while a limited number of scientific and technical challenges still remain, the long duration of the programme also requires regular update in response to scientific and technological improvements and an evolving state-of-the-art. The primary

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objective of the technology platform connects to these remaining challenges, examples of which are described in the following:

- How to handle the remaining uncertainties in long-term safety is one of the **scientific challenges** and there is a common interest to reduce these uncertainties by using knowledge and data from laboratories and natural systems. Preparation and review of the overall safety case for a deep geological repository is a significant task; further development of methods to efficiently and clearly improve and communicate the safety case is desirable. Addressing both the scientific and the communication challenges is expected to benefit from international co-operation.
- How to transfer the studies and results of RD&D activities into proven and reliable industrial-scale technologies for the construction, operation and closure of a deep geological repository is one of the **technological challenges**. A major task relates to understanding when knowledge is sufficient for well-founded decision-making, and how to transfer from a research and development phase into an industrial-scale implementation phase. Improved knowledge on and experiences from practices in different WMOs are a key to such an understanding.

Another task during the implementation phase is to combine nuclear safety requirements with current practices and constraints for construction and operation of underground facilities. This task also entails education and training of the people involved in the implementation.

The remaining **societal and political challenges** can generate some activities within the platform even if these challenges are, to some extent, country-specific. Addressing these challenges is especially valuable for the members in the initial phase of their waste management programmes. However, it is a major challenge to devise a plan giving all stakeholders the possibility to influence the process without creating deadlocks and to maintain the support for geological disposal at both local and national levels during the many decades needed to site, construct, operate and close the repository. In this context it is essential to interact with the general public to share and enable participation in the extensive scientific and engineering work underpinning the conclusions that *"geological disposal is technically feasible"* and that the *"geological disposal system provides a unique level and duration of protection for high-activity, long-lived radioactive waste"* [16]. Development of mechanisms for sharing and transfer of experience on confidence-building from the forerunners of implementing deep geological disposal might therefore be one activity within the platform.

2.3 Benefits

Co-operation and focused RD&D, with openness about the results and clear explanations as to how conclusions have been drawn and decisions made, are important stepping stones for the implementation of deep geological disposal. This applies equally to advanced programmes and to small waste management programmes or programmes in their initial stages. Stakeholder confidence in Europe will be enhanced by a demonstration of a viable solution for managing spent fuel, high-level and/or long-lived radioactive wastes.

Competence building

RD&D on geological disposal has been carried out for many decades and a wealth of scientific information, technology, knowledge and experience exists. The IGD-TP's co-operative work aims to efficiently further build competence and to disseminate knowledge. Communication

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with all relevant stakeholders concerned with radioactive waste management, and with deep geological disposal in particular, is vital and leads to increased confidence. Openness and willingness to co-operate and build on previous experience is essential for co-ordination of waste management programmes in different countries and for developing a common view and understanding on chosen deep geological disposal systems and/or on their components.

Joint work and use of resources

The IGD-TP supports collaborative, or joint, work and use of existing facilities for research and demonstration projects, joint use and transfer of results and experience, and the development of robust repository designs through interdisciplinary and focussed research. The platform supports further analysis of the evolution of the repository system, development of technological solutions and sharing of knowledge and experience between members.

Joint work on strategies

All countries with waste management programmes independent of their timetable for implementation can benefit from research made on strategic issues such as retrievability, reversibility and final closure. Other topics include monitoring during the operational period, security and safeguards, and institutional control and record-keeping measures.

Knowledge transfer

The IGD-TP supports the development of unique strong competence networks, which facilitate efficient knowledge transfer between countries in an early stage in their waste management programme and those who are entering the licensing stage. A further benefit in creating a network of centres of competence is that Europe can provide expert technology advice to other countries exploring the nuclear option. Opportunities are also likely to evolve for technology providers regarding instruments, equipment, machinery and manufacturing.

2.4 Organisation and Participation

The organisational structure for the platform includes an Executive Group that is supported by a Secretariat and a forum for exchange of information and discussion on RD&D needs, as well as results, in relation to implementation of geological disposal.

Exchange Forum Participants

The Exchange Forum participants are all stakeholders in Europe (e.g. waste management organisations, industry, research organisations, research centres, academia, technical safety organisations, non-governmental organisations) endorsing the IGD-TP Vision and willing to contribute positively and constructively to the objectives and goals of the platform, such as implementing the Strategic Research Agenda (SRA). The participants' responsibilities include information exchange to and from the platform on the SRA and related RD&D needs, providing written recommendations to the Executive Group, and participation in collaborative RD&D activities.

Executive Group

The Executive Group (EG) is the decision and management forum of the platform. The IGD-TP is implementer-driven where members of the Executive Group are organisations either responsible for implementing a waste management programme or are formally responsible for

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the RD&D programme needed for implementation. The EG members' responsibilities are to take decisions and steer the different tasks of the platform; to prioritise activities and collaborative projects; to initiate, monitor, and evaluate activities; to fund the secretariat; to approve the SRA; to establish working groups; to encourage information exchange with other international groups; and to develop reports and to share information with participants.

Secretariat

The Executive Group appoints the Secretariat, whose responsibilities are to organise and co-ordinate the activities of the IGD-TP; to support the finalisation and publication of IGD-TP documents; to contribute to and ensure that the IGD-TP is organised in an appropriate manner to achieve the committed Vision and activities; to act as an information and communication centre about the activities of the IGD-TP and on developments in the waste management community. The Secretariat maintains a public website where information and documents about progress, future and past events are published (www.igdtp.eu); supports the exchange of information among the members and other exchange fora; and fosters consultation and co-operation on projects. The Secretariat reports to the Executive Group.

Working Groups

Working Groups are established within the working programme. These groups have specified mandates, such as development of the SRA. Co-operative projects and other forms of joint activities carried out in the Working Groups follow the Executive Group's decisions.

2.5 International Co-operation

Geological disposal has been studied since the 1970s as the reference option for the long-term management of high-level and/or long-lived radioactive waste. During this time, waste management organisations and research institutes have collaborated in order to generate improved knowledge aimed at implementing geological disposal solutions. Research needs are mostly defined by end-user WMOs with major inputs from research institutes, regulatory Technical Support Organisations (TSOs) and other organisations undertaking research. The quality of the work is checked through peer reviews, regulatory reviews and by cross-referencing programmes and results. One of the drivers for the progress in co-operation has always been the search for commonalities and explanation of differences among waste management programmes.

The continued increase of our knowledge through RD&D contributes to building confidence in the arguments that demonstrate the safety and feasibility of geological disposal. Although host rocks and GDF designs differ across the different waste management programmes, there are several areas of RD&D where co-operation is valuable and on-going, as discussed below.

International organisations such as the EC, the IAEA, the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), and the European Repository Development Organisation Working Group (ERDO-WG), and the mechanisms and forums set up by these organisations, already enable important co-operation amongst WMOs and governmental organisations.

The Treaty establishing the European Atomic Energy Community (EURATOM) was implemented to promote the peaceful uses of nuclear energy in Europe, and to support various

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aspects such as health protection, safeguards and fuel supply. The EURATOM Treaty also includes provisions for EU funding of research in nuclear science and technology, related knowledge management and support for infrastructure. Multi-annual EURATOM Framework Programmes for research and training activities are implemented by the European Commission with EU funding, and address the current technical issues and challenges posed by nuclear energy in Europe. This has led to important collaborative research projects in, amongst others, the field of geological disposal, involving different European waste management organisations, research institutes and universities.

This has been further supported by the 2011 EC Council Directive on the Safe Management of Spent Fuel and Radioactive Waste (the "waste directive") [3]. This requires, amongst other aspects, that EU countries have a national policy for spent fuel and radioactive waste management, that national programmes for management and disposal are developed and implemented, that public information and opportunities for engagement are available, and that a national status report is submitted every three years to the EC.

There has been an evolution in the focus of geological disposal research effort over the years. Early projects included the development of a catalogue of suitable host rocks in the 1970s [17] and detailed research topics on radioactive waste behaviour in repository conditions, migration of radionuclides in different barriers and thermo-hydro-mechanical behaviour of clay as a barrier in the 1980s and 1990s. Later, from about 2000 and onwards, the co-operation continued through large integrated projects, such as FUNMIG [18] and NF-PRO [19], and through large-scale demonstration projects such as ESDRED [20].

Most recently, the EC has implemented a step change in European collaboration towards safe radioactive waste management (RWM), including disposal, through the development of a robust and sustained science, technology and knowledge management programme that supports timely implementation of RWM activities and serves to foster mutual understanding and trust between Joint Programme participants – EURAD (www.ejp-eurad.eu). The aim is to implement a joint Strategic Programme of research and knowledge management activities at the European level, bringing together and complementing EU Member State programmes in order to ensure cutting-edge knowledge creation and preservation in view of delivering safe, sustainable and publicly acceptable solutions for the management of radioactive waste across Europe. The EURAD project gathers WMOs, TSOs and Research Entities (REs) and has developed its own SRA that identifies research interests common to all three entities [21]. The IGD-TP provides the function of the WMO College within EURAD, representing the WMO community involved in EURAD (including WMOs that are not currently members of the IGD-TP). The IGD-TP Executive Group acts as the co-ordination vehicle for the WMO College and facilitates the formation of a joint position of all WMOs participating in EURAD. This has led the IGD-TP to make a concerted effort to be as inclusive as possible to ensure the views and common research needs of all European WMOs involved in EURAD are represented. The IGD-TP SRA is intended to contribute to achieving this goal, as many of the identified research topics are typical of those that the WMOs would propose as possible international collaborative research projects, potentially within EURAD. Thus, this SRA is also expected to serve as an input to the EURAD SRA. However, not all of the WMO RD&D needs set out in this SRA will, or can, be addressed within EURAD. For example, some WMO RD&D needs may not be of common interest to the TSOs and REs also involved in EURAD; the research output may be required more urgently than can be delivered through such large projects; or the research need may have an applied focus rather than fundamental science and may therefore not meet

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relevant EURATOM funding requirements. Thus, the IGD-TP SRA identifies the common RD&D needs of European WMOs and acts as an input to the EURAD SRA, but its scope is broader in the sense that it is also has a strong focus on development, demonstration and decision-making related to programme elements with an RD&D component.

ERDO-WG is a multinational working group established to study the feasibility of establishing a Development Organisation (ERDO) that would implement one or more shared geological repositories in Europe. ERDO-WG members are typically national organisations from those countries with smaller nuclear power programmes or countries with no nuclear power (Small Inventory Member States; SIMS), but with small inventories of wastes that must be routed for geological disposal and whom are considering whether they will have to make independent provision for geological repositories. The disposal costs are high relative to the amounts of material involved and there are benefits of scale and economy in developing joint facilities, both for storage and disposal. The goal of the ERDO-WG is to investigate the feasibility of implementing shared solutions. Whether a geological repository is an independent facility for a single country or a shared facility used by multiple countries the scientific and technical challenges of safely managing the long-lived radioactive wastes are common to both. The ERDO-WG is chaired by the national waste agency of the Netherlands, COVRA, which is also a member of the IGD-TP, and the Arius Association (www.arius-world.org). Through COVRA, ERDO-WG member input has been sought during development of Vision 2040 and the SRA to ensure that the needs of SIMS are considered.

The IAEA's work has set the framework for cooperative efforts to build and strengthen an international safety and security regime. This framework includes advisory international standards, codes and guides; binding international conventions; international peer reviews to evaluate national operations, capabilities and infrastructures; and an international system of emergency preparedness and response. The IAEA also assists its members in scientific and technological aspects (e.g. development of strategies, and establishment and transfer of suitable technologies for radioactive waste management).

One of the goals of the NEA is to share information among OECD member countries on the management of radioactive waste and materials, focusing on the development of strategies for the safe, sustainable and broadly acceptable management of all types of radioactive waste, in particular long-lived waste and spent fuel. The main tasks are to exchange information and experience on waste management policies and practices, develop a common understanding of the basic issues involved, and to keep under review the state-of-the-art in the field of radioactive waste and materials management at the technical and scientific levels.

Besides joint research projects there has also for many years been bilateral (often through agreements) and multilateral (often through meetings) co-operation between various waste management organisations to share information and knowledge in science, engineering and methodology-related areas.

The most active and widespread co-operation on RD&D is of course between waste management programmes having similar host rock and/or disposal concepts (e.g. POSIVA – SKB: KBS-3 concept for the crystalline host rocks; ANDRA – NAGRA – ONDRAF/NIRAS: clay host rock). Nonetheless, co-operation between organisations with different host rocks also exists and helps to increase the level of knowledge and understanding in the general framework of long-term waste management, radioactive waste inventory, engineered barriers, etc.

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3 The IGD-TP Strategic Research Agenda: Rationale and Framework

3.1 Staged Implementation

Implementing geological disposal is achieved through a succession of research, siting and repository development stages as shown in Figure 3.1. These stages are broadly consistent across all current repository development programmes, even if the terminology used sometimes differs among the various programmes. A staged decision-making process is typically adopted, in order to provide assessment of the results of interim phases, the required regulatory reviews and societal inputs to the decisions made at each stage. The required number of the major stages (e.g. site selection, development and design, demonstration and construction, operation and closure) may be subject to a formal licensing process, although this varies from country to country.

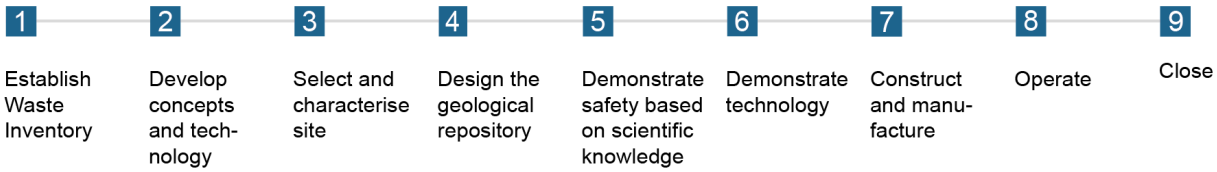

Figure 3.1: Main stages in the implementation of geological disposal. The number of the required main, and detailed sub-stages, may be subject to licensing according to the national legislation in question [22].

The first action, to prepare a national waste management programme, has often been a political decision to develop a strategy for implementation of geological disposal, and then later the transposition of this strategy into a legal, regulatory and organisational framework [23]. The strategy needs to include definitions of the roles, responsibilities and rights of the parties involved (implementer, regulatory body, civil society) and to define clear rules for securing sufficient funds to finance the implementation of geological disposal.

Site selection and site characterisation of a geological disposal facility for radioactive waste is a complex undertaking where legal, scientific, technological and societal factors are to be considered. The IAEA has therefore published guidance documents for siting geological repositories [24].

Many activities in the siting process need to be integrated and conducted in parallel and the sequencing may be country-specific. Typical time periods for siting are 20-30 years (although it is hoped that learning and transferable experience from advanced programmes may enable this phase is to be reduced for future programmes), at least five years for licensing, and 10 years of construction before first waste emplacement. Time before closure depends on the duration of the nuclear power programmes, but is at least several decades after the start of operation. In summary, the technical development and implementation of disposal projects demand decades to realise. Each siting process has to be adapted to the national situation, but there are certainly benefits in transferring experiences from processes in other countries.

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Geological disposal of spent fuel and high-level waste has been developed from a conceptual stage to the stage of implementation over a number of decades in those countries in the licensing process. Remaining challenges that are related to science, technology and their interfaces with society have to be solved. At the appropriate time periods and steps in the implementation of geological disposal, there is a need to address those challenges. Some of them might be similar in several countries but some others are country-specific.

3.2 National Waste Management RD&D Plans

The EC requires in its Council Directive [3] of July 2011 that all Member States present national programmes for the management of spent fuel and radioactive waste. Such programmes now exist in most European Member States, though in different forms owing to national regulations and internal programme needs, and are in some cases revised at regular intervals.

The RD&D plans at waste management programme level might differ significantly as they strongly depend on the national context (like national laws, stage of the programme, type of host rock considered, stakeholder interactions, funding arrangements, etc.). Each WMO focuses on carrying out RD&D that helps to deliver the input, answers and state-of-the-art needed for the next programme stage and beyond, based on the available information and knowledge within the geological disposal community.

In general terms, the development of RD&D plans by the different WMOs is based on similar types of elements, as schematically illustrated in Figure 3.2. Such RD&D plans extend beyond the licensing application as continued RD&D is required for all stages of geological disposal implementation and operation (see discussion in Section 3.3).

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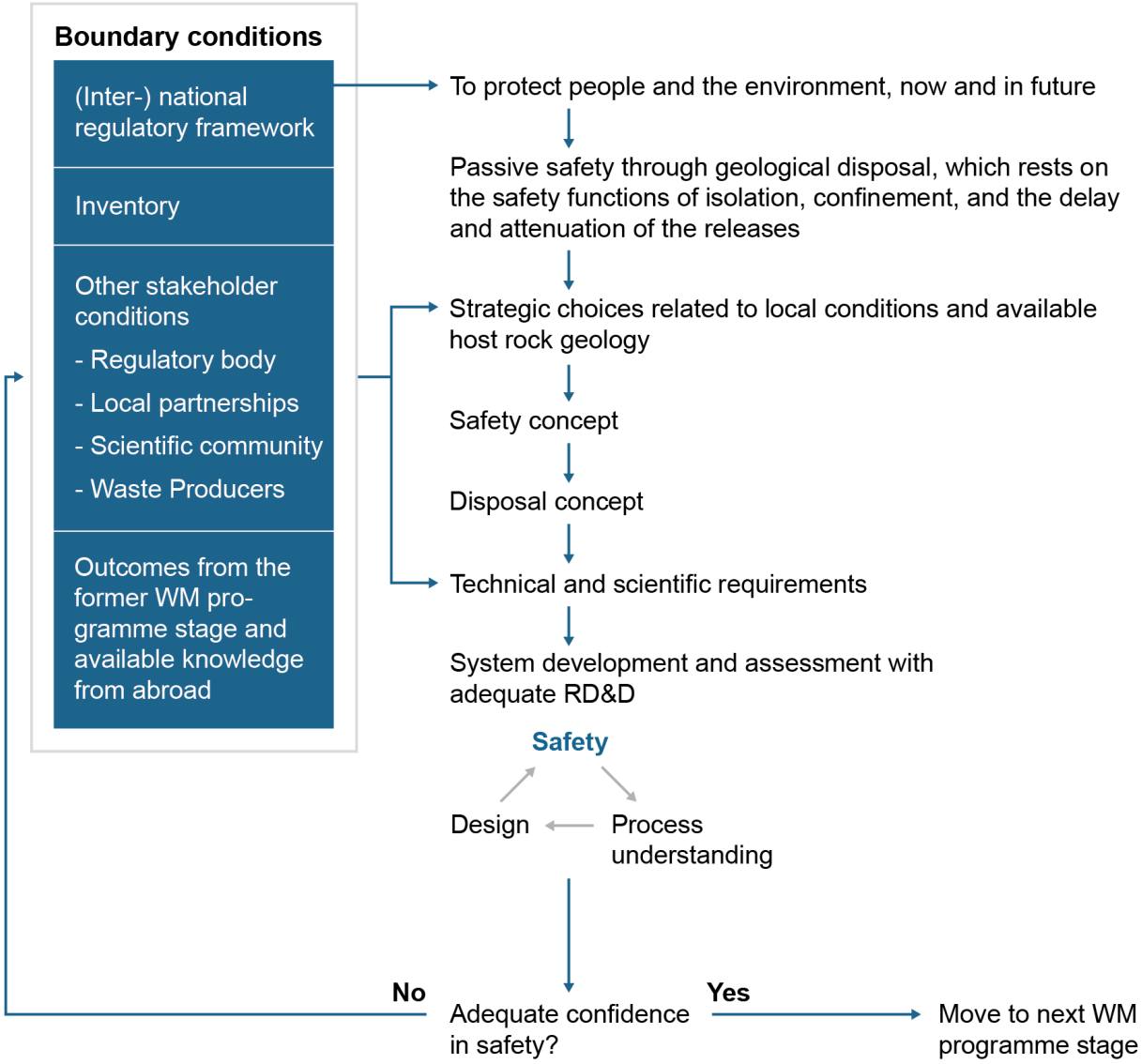

Figure 3.2: Schematic description of elements for developing RD&D plans for a waste management programme.

Based on the context (including available host rock geology), this is translated into technical and safety requirements for specific components. Here, other boundary conditions might also be relevant, for example specific questions from the regulator. The resulting evaluation then leads to an RD&D plan that is adequate to perform the system development and assessment needed for the next programme stage. Within this approach for developing RD&D plans and system evaluation, the necessary interaction between safety, design, process understanding and operating data is considered.

In accordance with (inter-) national guidance the aim of the long-term management of high-level and/or long-lived radioactive waste is *"to protect people and the environment from harmful effects of ionizing radiation"* [25]. At the international level, there is a consensus that the maximum level of passive safety can be obtained through geological disposal [26]. The disposal system consists of engineered and natural barriers between the wastes and the surface environment that are manufactured or selected in order to prevent radionuclides and other toxic

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species reaching the surface in such concentrations that they could present an unacceptable risk. The different components of the disposal system perform a number of functions relevant to long-term safety, called safety functions. In general, the safety functions relied on are *"to contain the radionuclides associated with the radioactive waste and to isolate them from the accessible biosphere"* [27].

The safety concept describes the conceptual understanding of why the disposal system is safe. The disposal system performs the broad safety functions via a range of features and associated processes that vary in their effectiveness and in the level of scientific and technical understanding that is available. This safety concept is the main starting point to define the technical and scientific requirements for the disposal system and its specific components. However, other boundary conditions might intervene, like for example specific questions from the regulator or other stakeholders (e.g. specific questions on reversibility and retrievability).

Safety concepts differ between national programmes, but all GDF safety concepts are based on a multi-barrier system. The strength of a multi-barrier system is that it comprises a range of independent effective and well-understood barriers that work together to ensure that the disposal system is safe (radioactive waste is isolated from people and the environment and is contained until it naturally decays to less harmful levels) and that safety can be demonstrated, even allowing for the various uncertainties and events and processes that might affect the system's evolution.

On this basis RD&D plans are developed that address the need for further scientific and technical knowledge that is required to carry out the performance and safety assessments, and the integrated safety case, before proceeding to the next programme stage. In practice, this involves iteration between design options, demonstrable performance and continued research into process understanding of the (chosen) disposal system. During such iterations, estimates of performance are made and an understanding is developed of which elements of the disposal system actually provide safety under various conditions, thus refining the disposal concept.

The output of this work plan on RD&D leads in principle to an important milestone for the programme, often accompanied by a safety case [28; 29]. If adequate confidence in safety is obtained, the programme is ready to move to the next stage. This leads to a new iteration in function of the next programme stage whilst taking into consideration changes in boundary conditions (e.g. specific questions addressed by stakeholders). If not, however, a re-iteration through the boundary conditions and safety concept is needed in order to update the RD&D plan as required.

3.3 Rationale for Developing the SRA

The scientific and technological knowledge base that has been acquired from more than 40 years of collaborative international geological disposal research is considerable. This knowledge is now considered to be sufficient and appropriately robust to facilitate licensing and construction of geological disposal facilities. However, it is of vital importance that this knowledge is maintained, enhanced and increased throughout the incremental development, operation and eventual closure of disposal facilities, which will be spread over many decades.

RD&D serves several purposes. It provides input to system design and optimisation and makes essential contributions to siting of repositories. Furthermore, it contributes to achieving a

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sufficient level of system understanding to allow an adequate evaluation of safety. The priorities of RD&D depend upon the national radioactive waste inventory, host rock geology, national context and/or legislation, and the stage of the programme's lifecycle - and these priorities change as the programme progresses. The current stage of advancement towards radioactive waste disposal facilities for selected European waste management organisations is depicted in Figure 3.3, along with a broad indication of their RD&D focus, which is closely related to their stage of advancement.

In the early generic/site-selection phases the emphasis is on the development of basic concepts, combined with an evaluation of safety and of technological feasibility, taking into account country-specific boundary conditions. This early phase is followed by a site-specific phase where the focus turns towards system optimisation, with an emphasis on post-closure safety and, correspondingly, on site-specific geology and design concepts. The system of engineered barriers is increasingly tailored to the specific geological conditions. In the later stages (i.e. construction phase onwards), when moving towards implementation, practical issues become increasingly important, such as construction procedures, operational safety and optimisation (including "industrialisation" of repository operation). RD&D does not however stop following the commencement of facility construction; it will need to continue throughout the construction, operational and closure phases.

RD&D effort is therefore necessary throughout the entire lifecycle of radioactive waste management and disposal programmes in order to ensure optimisation of management routes in general and of disposal solutions in particular, as well as to comply with Waste Directive obligations. RD&D must also continue in order to address evolving societal and regulatory concerns. This requirement for continued investment in RD&D may be considered in terms of four needs, as detailed below.

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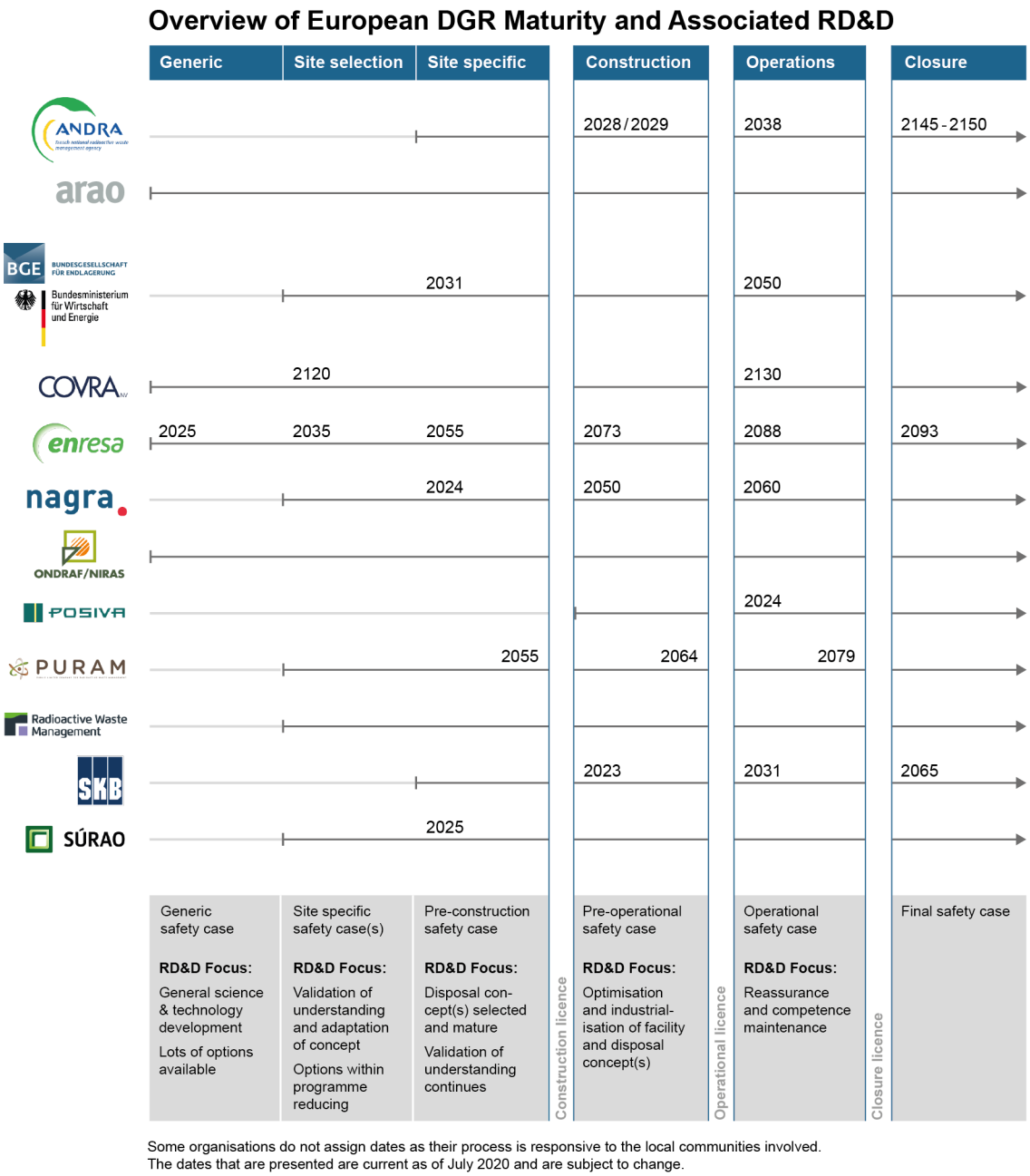

Figure 3.3: Deep geological repository milestone figure indicating the approximate current stage of facility implementation for selected European WMOs (the dates were current as of July 2020 but are subject to change). Some WMOs do not have dates listed in the figure as their process is responsive to the local communities involved. The stages in the figure are indicative and in reality there is likely to be a degree of overlap between activities in each stage, particularly for construction and operations (which will be undertaken in parallel).

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Underpinning knowledge base

In line with the Waste Directive 2011/70/Euratom, in order to provide responsible and safe radioactive waste management it is vital that the European community continues to develop underpinning knowledge that facilitates implementation of geological disposal and demonstrates the operational and long-term safety of disposal facilities. This is instrumental in building public and regulatory confidence, as well as in demonstrating the implementation of national policies.

Human resources and infrastructure

When establishing an RD&D programme, sufficient thought has to be given to the personnel and infrastructure necessary to undertake the work; for that purpose, it is highly beneficial to stimulate opportunities for co-operation with other waste management organisations in a bilateral or multilateral manner or within the framework of international projects and organisations. Specifically, the IGD-TP provides many opportunities for RD&D collaboration in a flexible manner, and also has a role in knowledge and technology transfer towards national programmes at earlier levels of advancement or European nations wishing to embark on a nuclear programme.

There is a high risk of shortage, at the European level and at short to medium timescales, of the skilled, multidisciplinary human resources needed to develop, assess, license and operate geological disposal facilities; this shortage may affect not only waste management organisations, but also authorities, research organisations, academia and supplier industries. Furthermore, this risk is relatively unique to the radioactive waste community/domain due to, for example, nuclear phase out in certain countries and the long duration of geological disposal projects through which continuity of knowledge must be maintained. Dedicated RD&D efforts have an additional benefit of helping bridge this shortage.

Flexibility to address arising stakeholder concerns

Stakeholders' concerns regarding the safety of geological disposal and protection of the environment must be addressed in a systematic way and the commitment of local communities that will host geological disposal facilities must be maintained over many years. Dedicated RD&D will likely help to address any arising future concerns.

Continuous improvement

The challenge of managing radioactive waste through geological disposal is no different to any other domain or challenge that necessitates a highly technological solution. Continued RD&D will be required throughout a stepwise implementation programme in order to be able to deliver continuous improvement and optimisation of geological disposal facilities (e.g. decreasing uncertainties and increasing safety margins, and optimising systems with respect to safety and cost). This need will remain even once the first European geological disposal facilities are constructed and safely operating. Indeed, given the long timespans of operation of geological facilities, optimisation in the light of evolving knowledge and technologies needs to be accounted for.

RD&D plays a major role in addressing these needs, and it is clear that a wide spectrum of RD&D is still needed. As representatives of the implementers of geological disposal in their respective nations, the IGD-TP Executive Group asserts that a sustained, co-ordinated and

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collaborative RD&D programme in the area of radioactive waste management and disposal is vital to ensure that all European countries, at various levels of advancement, continue to progress towards implementation of geological disposal. As discussed above, RD&D will not stop following successful implementation, but will continue during the construction and operational phases. The same level of RD&D effort will not be applied continuously; it will need to be adapted and re-prioritised as national programmes progress and needs evolve. In addition, the IGD-TP is acutely aware of the importance and significance that regulators and host communities (current, potential and future) often place upon involvement in international collaborative RD&D. RD&D efforts should therefore be maintained to help build and maintain societal confidence in geological disposal.

Vision 2040 can only be achieved through the progress of individual waste management programmes towards the implementation of geological disposal and during the development of the first repositories. However, whilst each country has its own research priorities and national RD&D plans, as discussed in the preceding sections, there are many areas where co-ordinated collaborative RD&D, between WMOs, but also including industry, research institutes, research centres, academia and civil society, is desirable. Such collaboration offers opportunities for sharing resources and cost savings, knowledge transfer and competence development. Indeed, applied research and education and training is often of greater importance in the earlier stage programmes than in those closer to licensing.

Therefore, this SRA has been produced to present the common research needs of the WMOs in order to support identification of future collaboration opportunities and priorities. The research topics presented are those where there are commonalities between several WMOs (but not necessarily all WMOs given their different research needs and stages of implementation) and where collaboration is desirable, uncertainties are highest, and/or important progress can be made. The SRA is a document for communicating the WMO research needs and opportunities to stakeholders in the waste management community, and it is also an instrument for creating synergies, co-operation and co-ordination with activities taking place in other international co-operation fora.

3.4 SRA Framework and Revision Process

The IGD-TP's Executive Group (EG) established a working group (see Appendix A) in February 2019 with the task of updating the 2011 SRA. The process of updating the 2011 SRA began with an initial review of the existing research topics, where each member of the IGD-TP EG indicated the views of their respective WMO on whether each topic should be kept, removed, or modified for inclusion in the updated SRA. Following this, the EG members were invited on behalf of their respective WMOs to suggest new topics for inclusion in the updated SRA that are of common interest to multiple WMOs. In order to be as representative and inclusive of the European WMOs as possible, the views and research priorities of other European WMOs who are not currently members of the IGD-TP EG were sought – this included all of the WMOs involved in the EC EURAD project and also SIMS via the ERDO-WG. Once a final list of research topics had been finalised, their descriptions were developed and reviewed by the European WMOs.

An important element of the staged approach to geological disposal is the determination of the appropriate level of understanding of the relevant research and technology issues needed for each stage. For the development of the 2011 SRA, the IGD-TP emphasised the issues that were

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relevant for achieving Vision 2025 - the vision of having a nuclear waste repository operational by 2025. However, even for programmes with later implementation dates, the nature of RD&D activities for any given stage, as well as the sequence of stages, is similar. Thus, the results achieved by the programmes close to licensing are of benefit to all other programmes. Consistent with the 2011 SRA, the revised 2020 SRA has aimed to identify the research required to achieve Vision 2040, with the identified research topics related to each of the three pillars: Safely Operate, Optimise and Industrialise, and Tailor Solutions.

Some of the RD&D issues that may be of key importance for the achievement of objectives in some individual programmes are of lower common interest to the participating WMOs if they are specific only to individual programmes. Typically, this is the case with site characterisation and the interpretation of its results, and therefore, even if highly important for geological disposal, this area has fewer research topics of common interest to WMOs in the SRA. For this reason, the SRA also does not discuss the detailed design, the licensing processes and the operational requirements that are specific to individual waste management programmes. However, in some cases, host-rock specific RD&D issues are of general importance with a strong added value to other geological disposal options as well.

The appropriate stages for developing geological repositories have been established over the last 40 years. Site selection strategies and site characterisation methodologies and techniques are well advanced. Further development of safe and efficient waste conditioning, handling, and transport is based on the specific needs and day-to-day practice. The testing of disposal techniques and components for geological disposal is part of some national and multi-national RD&D projects. The main focus of on-going research is on the safety strategy and methodology for the development of the safety case for geological repositories (see Figure 3.4). All this compromises the state-of-the-art, which provides a well-established scientific and technical basis for the content of the SRA.

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Stages of repository development

	Generic studies and concept development	Selection of host rock and site	Technology development and repository design	Technology development and repository construction	Industrial-scale manufacturing and repository operation
Safety strategy and methodology	Development of safety assessment methodology	Application of metho-dology in safety case and improvement of methods	Application of metho-dology in safety case and improvement of methods	Application of metho-dology in safety case	Application of metho-dology in safety case
Long-term safety: **Scientific and technical basis**	Broad-based research	Research narrowed to deal with host rock-specific aspects and specific aspects associated with the selected EBS	In situ experiments and improvement of data bases and understanding	Scientific work sharply focused on small number of residual issues, large-scale in situ experiments and component tests	Confirmation studies on components under site conditions incl. monitoring
Facility and component design	Concept variant studies	Repository design concepts adapted to specific rock type	Component design and layout design Operational safety studies	Full-scale prototypes constructed Industrial scheme developed	Full-scale production and operation
Site-related characteristics	Surveys of potential host rocks and their characteristics based on available information	Host rock characterization and site-specific studies	Detailed site characterization Excavation	Construction of main underground facilities Confirmation of rock properties for final design	Construction, confirmation, monitoring

Figure 3.4: Generic stages of repository development as derived from international experience. The given RD&D activities reflect today's state-of-the-art in geological disposal [22].

3.4.1 Different "Action" Categories of Research Topics

Within the SRA, the topics listed are those which are of interest to multiple WMOs and which still need some action. However, the form of these actions might differ significantly for the different topics. The SRA Working Group considered that three types of action may be needed, namely:

- **Networking.** For the topics that require networking, a lot of information is available at the different national WMOs. However, further improvements based, for example, on return-of-experience at different programme stages, or on progressing insight, or on the slow increase of new data, are always possible. Therefore, we assume that amongst WMOs we need to exchange information, clarify which methodologies and data are to be used, and within which specific context this is to be done. In this way, we try to optimise our knowledge and way of working. Furthermore, networking increases coherency between safety cases of the different national WMOs while still acknowledging the specific boundary conditions each WMO has to work with.
- **Research and Development (R&D).** For the topics that require research and development more detailed knowledge needs to be generated. This can be through quite innovative research as well as through clearly defined applied research and development work. For this category, WMOs often count on specialised third parties to support them in achieving the predefined objectives. For some topics, there might be a small contribution of R&D with a larger portion of networking. In that case R&D is often performed to gain knowledge on some very specific aspects or it is related to

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guaranteeing continuity of knowledge over decades with respect to a certain topic, or it is to further reduce uncertainties and increase safety margins.

- **Development and Demonstration (D&D).** For the topics that require development and demonstration it is assumed that the basic information is available but that additional large-scale experiments and / or one-to-one demonstrators are needed. This may involve large-scale surface mock-ups and/or in-situ experiments in underground research laboratories (URLs). In this case, WMOs regularly count on engineering firms and research organisations in order to achieve their goals.

Often a mix of actions might be appropriate, so for each topic described in the SRA the rough percentage of each action that is considered appropriate is indicated. Given the above descriptions of the different actions, we assume that topics that have a large portion of R&D assigned are the ones that are likely to be considered for action as part of larger international research projects (e.g. possibly via the EURAD European Joint Project on radioactive waste management, which is co-financed by the EC). However, while EURAD will address a range of important WMO RD&D needs, it will not address all of them. For example, the WMO R&D may not be of common interest to the TSO and RE Colleges involved, the need may be more urgent than can be met through such large projects, or the research need may have a greater applied element than the typical fundamental science requirement in EURATOM-funded research. Therefore, WMOs also collaborate with other international platforms and with each other to meet the research needs identified in the SRA. This is illustrated in Figure 3.5, which shows how the IGD-TP inputs to European RD&D programmes (both EURATOM and non-EURATOM funded activities), and how these relate to national WMO RD&D programmes. Recent examples of collaborative WMO-funded projects arranged via the IGD-TP include:

- KINA (Kiruna Natural Analogue), a project involving six WMOs that aims to investigate a smectite clay body that has been in contact with a magnetite ore body for hundreds of millions of years under repository like conditions.
- CCSC (Climate Change in the Safety Case), a networking project of six WMOs organised to make full use of synergies between the WMOs to ensure that arguments used in the scientific field of climate evolution/change are consistent, and to exchange methodologies, uncertainty estimations and results.
- PostCrit (Post-closure Criticality Safety), a networking project involving nine WMOs and their contractors, organised to share knowledge and approaches to demonstrating criticality safety, and exchange methodologies, knowledge gaps and results.

It is worth noting that the proportions of action types indicated for each topic are those that are considered applicable to the *common* interests of WMOs, not individual WMO research actions. For example, if a given topic is considered to consist entirely of networking activities, this does not mean that individual WMOs have no intention of undertaking R&D activities, but simply that there is not seen to be a common need to do so jointly.

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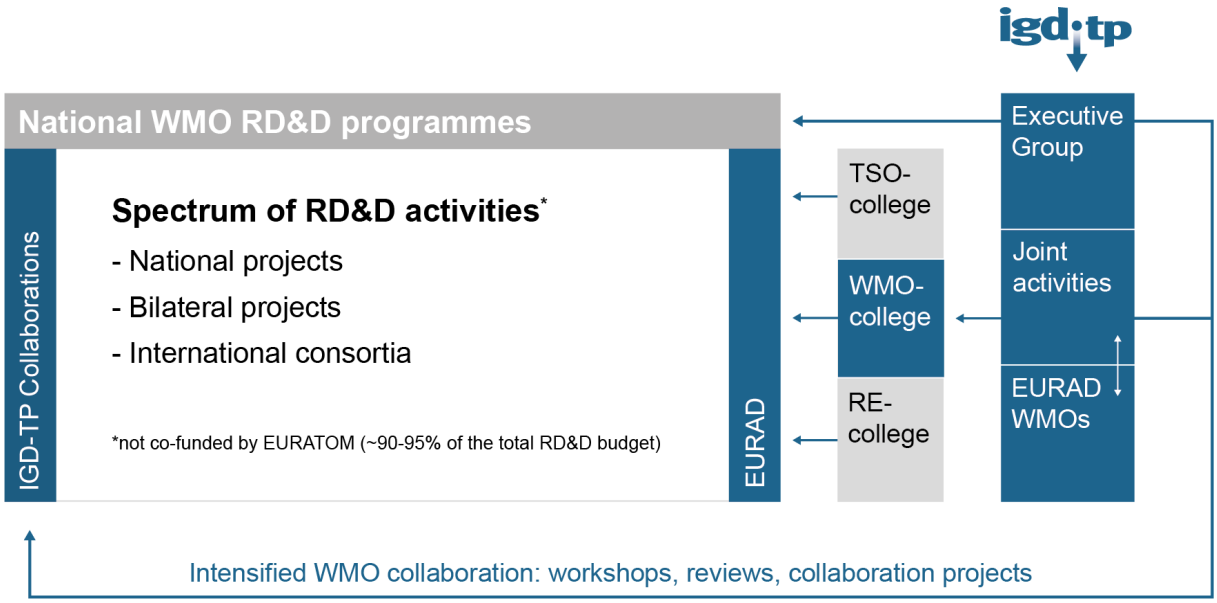

Figure 3.5: Illustration of how the IGD-TP inputs to European RD&D programmes (both EURATOM and non-EURATOM funded activities).

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4 Key Topics of the Strategic Research Agenda

The scientific reporting undertaken by WMOs reflecting their RD&D programmes is vast. Reporting generally takes the form of overview RD&D reports, produced at regular intervals, safety case reports that integrate the state-of-the-art, and a large number of more specific RD&D studies. Citing even the key reports produced by each WMO would quickly overload the text in this section, so in order to avoid this, in-text reference is made to key international projects, conferences and scientific journals only. Five key reports relating to WMO RD&D programmes, as well as the respective WMO websites (which generally provide access to a wider range of documents), are listed in Appendix B for the interested reader.

4.1 Key Topic 1: Post-closure Safety Case

4.1.1 Definition, scope and rationale

Definition – The purpose of the safety case is to gather all the scientific and technical arguments and evidence required to robustly support the safety claims of disposal facilities and systems. Safety is demonstrated by providing clear reasoning based on sound scientific and technological principles [30]. The safety case should be both robust and easily understandable. Moreover, the safety case sets out the arguments and evidence seeking approval of the licensing documentation for specific nuclear waste disposal facilities and must therefore comply with the various requirements set out by the relevant national authorities. Attention should also be devoted to recommendations suggested by international organisations such as the IAEA and the OECD/NEA.

The safety case must describe the evolution of the repository in such a way that it provides a reasonable representation of the events that might occur, and that also provides a clear indication of the uncertainties included in the description. This topic covers safety case and safety assessment issues related to the evaluation of the radiological impact of the whole repository on humans and the environment, and includes the evolution of the site over geological timescales (e.g. assessing the impact of processes such as erosion and climate change). The impact of the repository and its components are covered under Key Topic 3.

Objectives **–** The objectives of the Key Topic, all of which are related to the "Safely Operate" pillar of the IGD-TP's Vision 2040, are to:

a) Develop a broad view on the basis of the results of long-term safety assessments and enhance confidence in the concepts and the scenarios presented, thereby supporting development of the scope and content of subsequent safety cases for all IGD-TP participants.

b) Develop and refine the concepts and models applied to improve long-term safety assessments.

c) Improve the way in which sensitivities and uncertainties are addressed and communicated.

d) Further improve dialogue and engagement with the relevant authorities and other stakeholders.

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Rationale and benefits – The waste management community and its various stakeholders benefit from having safety cases that are consistent with respect to different waste management programmes and that are based on comparable regulatory objectives and assessment time frames. Review of safety cases, or parts of them, by other WMOs is good practice to ensure consistency (where appropriate), that the state-of-the art is implemented, and that there is critical evaluation of the cases presented to improve quality and clarity.

The first objective (a) is strongly related to the formulation of safety concepts and the definition of scenarios. With assessment periods of around one million years, the long-term evolution of the wider area of the geological repository needs to be taken into account. This is particularly important in relation to the occurrence of climate changes and climate-related processes where there is a need for collaboration in order to ensure that the methodologies and arguments used by WMOs with respect to climate scenarios are consistent with the evolving scientific understanding.

The second objective (b) concerns the development and validation of complex, interdisciplinary models in the disciplines of geology, hydrogeology, rock mechanics, geochemistry and solute transport. It is vital that future safety assessments are able to demonstrate that the models used in the creation of hydrogeological, thermal or geochemical models constitute true sub-sets of the corresponding geological models. The research effort required comprises both fundamental aspects, such as the understanding of processes, and applied aspects, such as the development of relevant modelling tools for safety assessment purposes. This objective concerning long-term performance of the repository and its components is covered in more detail by Key Topic 3.

The third objective (c) concerns improving the consideration of sensitivity and uncertainty that forms an important part of the regular work involved in the compilation of long-term safety assessments. Inclusive discussions on the communication of uncertainty management results constitutes a very important topic, particularly in siting regions.

The fourth objective (d) aims to improve the level of dialogue and engagement with the authorities and other stakeholders with respect to whom the safety case provides a key means of communication. Building good relationships with communities is essential. Communities should be considered shareholders in the programme, not just stakeholders, and building trust through professional competence and personal and organisational integrity is essential.

Concerning the authorities, it is of great benefit if the regulatory criteria are defined in advance of the compilation of safety case assessments. In practice, regulatory requirements become progressively more focused as the decision-making process (throughout the licensing process) advances. As a consequence, more focused RD&D in specific areas is required.

The safety case is based on state-of-the-art RD&D in all the relevant disciplines. The long-term performance of the repository depends on both the natural geological environment and the man-made engineered barriers. In order to optimise long-term performance, the man-made barriers should be appropriate for the geological environment via the application of the relevant engineering techniques and suitable materials. The safety case is closely linked to the environmental impact assessment and societal perception issues. Safety case reports should, therefore, be shaped so as to meet the requirements of regulators as well as other relevant stakeholders.

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The link between RD&D activities aimed at the demonstration and optimisation of technology, the construction of repositories and the long-term performance of the various repository components (Key Topic 3) and long-term safety should be included in the safety case. To a great extent, the site and host rock properties of the repository define its layout. These properties also define the requirements of the engineered barriers (often referred to as the engineered barrier system) and the disposal system components with respect to ensuring the safety of the repository during construction, operation and closure, as well as in terms of the long-term performance of the facility following closure. One of the most important links in this chain consists of the role of process models, including the investigation work that leads to the provision of the necessary data, as these provide the basis for the creation of abstracted safety assessment models and for determining component performance requirements.

4.1.2 Specific research topics

Topic 1.1: Increase confidence in, testing and further refinement of the tools (concepts, definition of scenarios and computer codes) used in safety assessments. This topic is strongly related to the formulation of safety concepts, the definitions of scenarios, and development of tools to evaluate the long-term evolution of all disposal facility components and safety assessments. In countries with very advanced programmes with licence applications already submitted there is already a sufficient knowledge of these tools, but the further refinement of the tools, particularly of THMC models, will help to optimise the disposal components, technical layout of the repository and to further refine the knowledge base. For countries with early-stage programmes the development of a set of performance and safety assessment tools will facilitate decisions on possible disposal sites and technical concepts. Relevant references include [31; 32; 33; 34]. [70% networking: 30% R&D]

Topic 1.2: Improve safety case engagement. One of the key conclusions of the NEA/OECD Integration Group for the Safety Case (IGSC) Symposium held in October 2018 in Rotterdam was that building good relationships with communities is essential, that communities should be considered shareholders in the programme, not just stakeholders, and that building trust through professional competence and personal and organisational integrity is essential. It is important for IGD-TP members, together with the IGSC, share experience and know-how on safety case development and communication with civil society representatives, as well as interaction with the regulators. The research activities in this field should focus on application of new communication technologies and knowledge management [35; 36; 37]. **[90% networking: 10% R&D]**

Topic 1.3: Increase confidence in and further refinement of methods to undertake sensitivity and uncertainty analyses, and address flexibility and adaptability of the repository and evolution of safety requirements and regulations. Management and treatment of uncertainties in safety analyses is a continuous activity. For advanced programmes the focus is on optimising the disposal components and understanding deviations in planned implementation scenarios and pre-closure disturbances, and their effects on performance assessment outputs. This includes the possible evolution of the radioactive waste inventory, safety requirements and regulations, and the need to ensure the flexibility and adaptability of the repository over several decades of operation. For early-stage programmes the focus is more on identifying the key input data of the complex system and identifying high priority research and development activities. High performance computing codes, already available for the simulation of important multi-physics couplings, also better enable refinement of sensitivity

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and uncertainty analyses. Uncertainty management and its communication is also one of the high importance topics of the IGSC. A further consideration is how to record and clearly communicate changes in the safety case over time – the safety case submitted during the licensing process is a snapshot at a point in time, but the assumptions, designs and lines of argument may evolve over time. [80% networking: 20% R&D]

Topic 1.4: Climate-related safety assessment issues. The impact of climate changes on the host rock and, consequently, on the water flow and chemistry are of high relevance [38]. Improving the understanding of glacial phenomena such as cryogenic cracks and subglacial channel formation is needed. The potential future scenarios need to contain information not only on climate, but also on other climate-related processes, such as ice sheet growth, permafrost development and sea level change. In this context, there is a need for collaboration in order to ensure that the methodologies and arguments used for the climate scenarios support and strengthen each other between organisations. [**70% networking: 30% R&D]**

Topic 1.5: Common approach to disposability assessments and records management. One of the problems facing early stage programmes and small inventory member states (SIMS) is that, without some concept of how the waste might eventually be disposed of, it is not possible to move forward with programmes for conditioning and packaging wastes. Consequently, wastes might today be being packaged only for storage, when they could already be packaged and conditioned for disposal (e.g. use of multi-purpose casks), thus saving additional costs and operator handling dose and risks. Using information (e.g. from EURAD Routes WP) on SIMS inventories and possible small-scale disposal solutions (SSDs), a common approach to 'disposability assessments' can be developed: a set of simple performance and safety assessments for each of the SSD options. The results will allow each of the SIMS to make decisions on possible storage and disposal routes and will assist with provision of waste packaging advice to small users and the development of waste acceptance criteria for the SSDs. A further aspect applicable to all programmes is management of records associated with packaged waste, in order to know what is, and is not, present in waste packages that have been produced in the past, or are being produced today, and which may not be disposed of for a further 50+ years (and possibly by a different organisation). [**100% networking]**

Topic 1.6: Long-term geological evolution and its potential impact on the repository. With assessment times of millions of years, the long-term geological evolution of the wider area around the geological repository needs to be taken into account. This can comprise erosion, crack formation, major earthquakes, etc. While the consequences of these are generally site-specific, the driving processes are similar and can be of interest to multiple WMOs. Furthermore, abstraction of (aspects of) long-term evolution scenarios can be useful, in order to identify common WMO interests and to progress understanding of long-term geological evolution. Collaboration and knowledge sharing between WMOs on seismic hazard assessment methodology would also be beneficial. [**50% networking: 50% R&D]**

Topic 1.7: Verification and validation of models for the simulation of the transport of radionuclides in the near-field of deep geological repositories. Several uncertainties exist concerning the transport of radionuclides from repositories to the flowing water in surrounding host rock, particularly in heterogeneous crystalline rocks. A benchmark study of various approaches and computer codes using advanced hydrological models and particle tracking methods to validate the results obtained against experimental data gathered from laboratory or in-situ experiments could help to reduce these uncertainties. [50% networking: 50% R&D]

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Topic 1.8: Behaviour of I-129, Cl-36 and U-progeny in various repository compartments. Most disposal concept safety assessments consider I-129 and Cl-36, and also U-progeny in some repositories and host rock environments, to constitute the most important radionuclides for the radiological impact of repositories on humans and the environment in the long term. However, very conservative data is used for some compartments (e.g. engineered barriers, geosphere, biosphere) in the safety assessments due to a lack of detailed knowledge regarding these radionuclides, which further emphasises their contribution to the effective dose. Identification of knowledge gaps, initiation of studies concerning issues that have not yet been adequately addressed, and collection of more information concerning the actual behaviour of I-129, Cl-36 and U-progeny (e.g. Ra-226, Po-210) in various repository compartments (including biosphere compartments), would contribute significantly to enhancing the credibility of repository safety assessments. [**80%R&D: 20% networking]**

Topic 1.9: Handling of non-human biota in safety assessments. A system for estimating dose to Non-human Biota (NHB) has been internationally developed over the last decade (i.e. the "Environmental Risk from Ionising Contaminants: Assessment and Management" (ERICA) approach [39]). However, few applications have considered geological disposal of radioactive waste. These few applications have shown that, if all exposure pathways are included, the dose to humans is considerably more critical than the ERICA screening value for NHB. It is suggested to compare several such studies and show that, generally, the regulatory requirements for geological disposal facilities are so strict for humans that NHB are not at risk. Such a conclusion could potentially relax very detailed requirements for NHB assessments, which could be helpful for future safety assessments. Relevant references include [40; 41; 42; 43; 44; 45; 46]. [**80% networking: 20% R&D]**

Topic 1.10: Development of inter-disciplinary DFN models. Discrete fracture network (DFN) models are of paramount importance when describing fractured media, specifically (sparsely) fractured crystalline rock, and when assessing the safety of such rocks for disposal of radioactive wastes. Future research efforts should focus on development of internally consistent DFN models within the disciplines of geology, rock mechanics, hydrogeology and solute transport. It is considered vital in future safety assessments to be able to demonstrate that DFN models used (e.g. in hydrogeological models) are true sub-sets of the corresponding geological DFN models. Furthermore, the coupling in DFN models between stress and properties affecting flow and transport, such as transmissivity and aperture, is a research priority. Each of the fractures in the discrete fracture network needs to be populated with properties describing its coupled hydro-mechanical behaviour. Despite relevant research efforts performed during the last few decades, outstanding questions remain and further research is needed to improve our knowledge about the relation between stress and fracture aperture and transmissivity. In addition, research and code development is needed to establish DFN models where genetic approaches to fracture generation are adopted. Such models mimic rock mechanical principles for fracture nucleation, growth and arrest, and as such reproduce termination patterns and fracture spatial arrangements not honoured by traditional methods based on statistical principles. Thus, the required research effort comprises both fundamental aspects, such as process understanding, and applied aspects, such as development of relevant modelling tools amenable to production runs in safety assessment applications. [**80% R&D: 20% networking]**

Topic 1.11: Development and testing of reactive transport modelling. Several uncertainties exist in the models for transport of solutes in highly-heterogeneous, crystalline rocks [47; 48;

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49]. To reduce such uncertainties, benchmark calculations will be performed using various computer codes followed by comparison of the results against either analytical equations or data from field measurements or laboratory experiments [50; 51; 52; 53; 54]. In this way, the ranges of validity of different conceptual models (e.g. DFN and equivalent continuous porous medium (ECPM)) will be explored. [**80% R&D: 20% networking]**

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4.2 Key Topic 2: Wasteforms and their Behaviour

4.2.1 Definition, scope and rationale

Definition – This Key Topic deals with understanding the behaviour of various wastes in geological repositories. All wastes that may require geological disposal are within the scope of this Key Topic, thus including the waste categories of spent uranium oxide (UO_2) and mixed oxide (MOX) fuels, vitrified high-level waste (HLW), long-lived intermediate level wastes (ILW) and some low-level wastes (LLW). Spent fuel from research reactors and legacy wastes are also considered. The wastes represent the potential source terms for release of radionuclides if and when waste containers are breached.

Objectives – The purpose of the research within this Key Topic is to understand safety-relevant processes, in particular the contribution of the wasteform to radionuclide retention in the repository. It is important to systematically define the physico-chemical properties of the waste materials, including their chemotoxic properties and presence of complexing agents, as well as the total inventory of various radionuclides – these properties together determine the time-dependent release of radionuclides. Methods for quantification of difficult-to-measure radionuclides are required here. This allows the formulation of mathematical models in order to assess radionuclide release from a repository. Spent nuclear fuel, when considered as the waste form for direct disposal, needs to be well characterised to address both pre-disposal and post-disposal issues. This characterisation is central for heat-output calculations and criticality safety analyses, which impact optimisation of repository plans and component requirements, and the definition of the initial state for the assessment of post-closure safety. Continued studies concerning how processes expected in the repository will affect the release rate of radionuclides from the spent fuel is required for both uranium oxide and MOX fuels. Understanding the waste source term directly relates to the first pillar of the IGD-TP's Vision 2040, to "safely operate" disposal facilities, and also to the ability to optimise the design and operation of the repository (the second pillar, "optimise and industrialise").

Rationale and benefits – The studies will better quantify the various processes controlling release of radionuclides, chemicals, and gas from wasteforms, thus contributing to the quality of models used in safety assessment and adequately defining the types and magnitudes of uncertainties associated with each process. This couples mainly to the first pillar of the IGD-TP Vision, to "safely operate". It is expected that, because experimental facilities and specialised equipment for work with highly radioactive materials are available in only a few countries, benefits for other countries could become available through use of these facilities in such studies under international co-operation arrangements. WMOs that are at an earlier stage of implementation in their programmes would benefit through participating at the appropriate stage and having access to information from the studies performed.

4.2.2 Specific research topics

Topic 2.1: Improved data for the rapid release fraction for spent uranium oxide fuel and improved understanding of its dissolution behaviour. The rapid release fraction for spent uranium oxide fuel was studied in the EC-funded project First Nuclides [55; 56]. Some, but not all, remaining issues are being investigated within the framework of the ongoing DisCo project [57]. There are aspects related to improved understanding of the distribution of the so-called instant release fraction in the fuel and the dissolution behaviour that are still uncertain. While

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significant improvements in understanding of the performance of spent fuel under repository conditions have taken place over the past 20 years [58; 59; 60; 61; 62; 63], the gradual increase in discharge burn-up as well as the use of new types of advanced fuel with additives, which may be used in some countries, means that the present spent fuel behaviour database should be extended. Licence applications need to be supported by data related to the use of modern fuels. Work in this area is ongoing in the DisCo project, but the impact on spent fuel properties of changes in operation of nuclear power plants needs improved understanding. [80% R&D: 20% networking]

Topic 2.2: Improved data and understanding of the release of radionuclides and chemical species from various long-lived ILW, including effects of organic materials with complexing ability. This topic includes detailed characterisation methods, the chemical form of waste materials and speciation of radionuclides, as well as their transport in the near- and far-field [64; 65]. Of particular importance are longer-lived radionuclides with anionic speciation that sorb poorly on cementitious materials, such as I-129, Cl-36, Se-79, Tc-99, and Mo-93 [66; 67], as well as C-14 [68; 69].

Transport of many radionuclides, primarily cations, is enhanced by formation of soluble complexes with organic ligands [70]. These organic complexing agents may form via degradation of various materials in the waste, such as cellulose which degrades into isosaccharinate, a strong complexing agent [71; 72]. Another waste material with complexing potential is polyacrylonitrile (PAN), used as a filter aid in water treatment in nuclear power plants [73]. PAN can degrade in the strongly alkaline repository environments. Studies should be undertaken to improve understanding of PAN reaction rates and degradation products under repository conditions, and their effect on the mobility and sorption of cations.

There is a general need for research on complexing agents. A more detailed understanding (e.g. via development of thermodynamic models for complexation with radionuclides under various conditions) would allow improved descriptions of how complexation affects radionuclide sorption and transport. **[80% R&D: 20% networking]**.

Topic 2.3: Improved data and understanding of the behaviour of spent MOX fuel. The rapid release fractions and dissolution behaviour of spent MOX fuel under repository conditions should be further studied to determine how the fuel structure influences dissolution. Quantities of such fuel are presently small and their disposal is likely to be deferred to allow cooling because of their high heat generation. MOX dissolution is studied in the ongoing DisCo project [57]. Good progress has been made but there are still areas to improve, such as how the incorporation of plutonium affects the electrochemistry of the spent fuel matrix and if this, in turn, affects the so-called hydrogen effect. This connects to the need to understand the impact of future changes (new fuel types in different countries, etc.). It needs to be confirmed that models describing the dissolution behaviour of standard UOX fuels may be applied also to MOX fuels and other advanced fuels. [**80% R&D: 20% networking]**

Topic 2.4: Further development of post-closure criticality safety analysis. Research needs for this topic are focused on two areas. Firstly, further development of burn-up credit methodology and its application for high-enriched fuels is necessary. A number of criticality safety evaluations have shown that canisters of spent fuel in a repository will remain sub-critical provided that a minimum average fuel assembly burn-up is reached. These studies need to be extended to different fuel types (including MOX fuel) as well as for higher-enriched fuels.

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Further development of burn-up credit methodology and compliance is also warranted. This is a broader issue than for high burn-up fuel, as a consistent methodology is needed to evaluate fuel over the entire burn-up range, including the assessment of major uncertainty components, like burn-up profiles, both axial and radial, and operating conditions during irradiation. The second aspect is that of post-closure criticality safety assessment of waste packages and the wasteform as they degrade, allowing the possibility of separation, relocation and accumulation of fissile nuclides (as well as the possible removal of absorbers from fissile material) [74, para.5.65]. Evolution of the geometry inside the waste package and the disposal cell over the long assessment timescales affects the conditions for the criticality calculations. Further studies are required for possible evolution and degradation scenarios to address their influence on reactivity in the long term. This should also include studies of the stability of the fission products in the fuel matrix if these are credited in the criticality safety analysis for spent fuel. **[70% networking: 30% R&D]**

Topic 2.5: Improved data and understanding of the performance of vitrified high-level waste. Over the years, this topic has been extensively studied and considerable data and information is available. Thus, models for dissolution and radionuclide release from vitrified waste have been developed and are being used. However, there are still some remaining uncertainties that can be reduced through further research efforts, such as the role of vapour in dissolution under unsaturated conditions, and the impact of radiation and/or the complex chemical environment on cement and corrosion products. For this topic, the focus of future efforts lies in efficient knowledge management and the need to maintain competence. **[20% R&D: 80% networking]**

Topic 2.6: Methods for determining the inventory of long-lived radionuclides and chemotoxic materials with high impact on the safety of final repositories for low and intermediate-level waste from nuclear power plants. This topic includes inventory determination via advanced analytical measurements and modelling. Long-lived radionuclides, such as I-129, Cl-36, Se-79, Tc-99, and Mo-93, as well as C-14, with poor sorption properties generally present a challenge for final repositories for low and intermediate level waste. These nuclides typically belong to the category of radionuclides that are seldom or never measured in the waste. By combining a limited number of measurements for samples from process systems at the power plants with modelling of activation, fuel failures and transport of radionuclides, a method for quantifying the inventory of difficult-to-measure radionuclides can be established. This could significantly improve the inventory estimates of many important long-lived radionuclides in low- and intermediate-level waste, improving the analyses of post-closure safety. **[60% networking: 40% R&D]**

Topic 2.7: Spent fuel matrix dissolution. The topic of spent fuel dissolution has been studied for many years and there is significant knowledge and experience available in this field [75; 76; 77; 78]. Still, there are issues that remain uncertain. One important issue is the mechanism behind the hydrogen effect (i.e. the activation of hydrogen to suppress fuel oxidation at the fuel surface), which is still under investigation (e.g. [79]). Improved knowledge regarding this mechanism is required if it is to be applied in spent fuel dissolution models. The catalytic effect of metallic particles has been found important; however, it is unclear whether these can be poisoned by, for example, sulphur, through the formation of sulphide. The decomposition of hydrogen peroxide has also been seen as an important aspect, but further experimental evidence is needed to understand how the reaction proceeds in the presence of hydrogen. **[70% networking: 30% R&D]**

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Topic 2.8: Common approach to physico-chemical classification. The understanding of non-radiological (i.e. physico-chemical) properties of radioactive wastes is essential to enable their proper treatment, storage and disposal. There are classifications for radioactive wastes that consider the radiological properties, but classifications based on physico-chemical properties, including chemotoxic properties, are not so well developed (e.g. compare with the EURAL-codes for conventional waste). There is also a lack of established, systematic methods for quantification of chemotoxic properties; these need to be developed as such properties can be significant for some low- and intermediate level wastes. A common, systematic approach to characterising and classifying waste based on physico-chemical properties would facilitate sharing and/or harmonisation of methodologies for conditioning, packaging and pre-disposal storage of waste streams with a small inventory. **[90% networking: 10% R&D]**

Topic 2.9: Spent fuel integrity. An improved description of the long-term stability of spent fuel during intermediate storage (e.g. [80; 81]), and a better understanding of the long-term behaviour of the spent-fuel cladding as a supporting basis for the optimisation of the design of the packaging facilities (particularly for handling and safety-related equipment), is required (e.g. [82]). As experiments with these materials bear a high cost, collaboration is necessary, including between pre-disposal and disposal research disciplines. A fuel matrix that has been in contact with water as a result of a breach in its cladding is affected with regards to its oxidation state and radionuclide content, first by the reactor environment and then the following environment in temporary storage. Better determination of the characteristics of this failed fuel is required to decide on appropriate further treatment in advance of emplacement in final storage/disposal containers. If the fuel is to be deposited as is, the radionuclide content and dissolution rate of oxidised parts need to be determined. The radionuclide release rates from these failed fuels in final repository environments need to be assessed. **[50% networking: 50% R&D]**

Topic 2.10: Spent fuel characterisation. This topic covers development of understanding, methods, codes and guidelines in order to have sufficient knowledge of relevant spent fuel parameters at all the steps in the back-end of the nuclear fuel cycle. The characteristics of spent fuel elements differ according to the composition of the fresh fuel element, impurities within the fuel, the composition of the cladding and the structural parts of the spent fuel elements, impurities within the cladding and the structure, and the burn-up of the spent fuel. It is not possible and, with respect to the requirements of a repository concept, not reasonable to individually describe each spent fuel element. Nevertheless, there are variations in the characteristics of the spent fuel elements that lead to uncertainties in the overall properties of the spent fuel inventory, and thus have an effect on the repository concept and the safety functions. Those variations have to be quantified in order to determine their effect on the repository layout and safety assessment. The characteristics of the spent fuel determine the properties that must be accounted for in the repository; some of the most important include: decay power (with an important link to thermal modelling); radiation levels (primarily gamma and neutron radiation); criticality safety; nuclide inventory; and fuel integrity. A number of activities are in progress on this, such as the Spent Fuel Characterisation Work Package (WP) in the EURAD joint programme [83], the IAEA process on Spent Fuel Characterisation including Consultancy Meetings, Technical Meetings and a probable Co-ordinated Research Project (CRP), SCIP IV (the NEA/OECD Studsvik Cladding Integrity Project), the ongoing DisCo project, the SKB – NEA/OECD blind test, and a number of other NEA activities on data libraries and prioritisation of determinations of nuclear data. These efforts address and reduce uncertainties in spent fuel properties in the pre-disposal phase. Improved data, methods and

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guidelines are essential both for the safe operation of the facilities and as input to the initial state of the post-closure safety assessment. There will be significant further needs in the coming period, which are important to synchronise with the other activities. **[50% networking: 50% R&D]**

Topic 2.11: Legacy waste (including graphite) characterisation for possible acceptance to a disposal facility. Nuclear activities performed in the past have generated a significant number of radioactive waste streams that have been treated and conditioned according to the rules in force at the time or simply stored pending a suitable management solution. These waste streams (conventionally called 'legacy waste') are often lacking sufficient physico-chemical-radiological characterisation data to determine suitable re-treatment/re-conditioning processes, and/or repository type (surface and/or deep disposal), in line with current regulatory requirements and compliance with Waste Acceptance Criteria of facilities for storage or disposal. Chemotoxic properties are also important here, since such materials are often present in legacy waste. The information exchange project LWC ('Legacy Waste Characterisation for possible acceptance to a disposal facility') aims to share this missing data or methodologies for waste characterisation. **[80% networking: 20% R&D]**

Topic 2.12: Disposal of spent research reactor fuel. Different small inventory programmes have, or had, research reactor facilities and consequently amounts of spent research reactor fuel (SRRF). Although many programmes benefited from fuel return programmes such as the US FRRSNF, not all SRRF has been or will be returned. The current development of repository systems addresses mostly the disposal of power reactor spent fuel and/or HLW rather than SRRF. For SIMS the small quantities of SRRF are difficult to manage and disposal options need to be developed. An understanding of the fuel and its likely post-closure performance is needed to determine if bespoke R&D is required and for which types of SRRF. **[60% R&D: 40% networking]**

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4.3 Key Topic 3: Technical Feasibility and Long-term Performance of Disposal and Repository Components

4.3.1 Definition, scope and rationale

Definition – This Key Topic involves RD&D activities for demonstrating and optimising technology and construction[7] of a repository and disposal components. This includes confirmation of a feasible and safe operational phase, as well as ensuring that the specified safety functions[8] will be provided over the required time frame after closure. Included are surface-based and underground works as well as construction technologies for waste containers (including waste encapsulation or overpacking facilities), buffer, backfill, plugs and seals. Also included is the demonstration of construction and operations of the repository and its components. It is noted that the requirements for the definitions of these materials and their associated properties are in many cases specific to the host rock and repository design concepts. Furthermore, this Key Topic addresses understanding of the repository components' long-term performance and the maintenance of their safety functions. While in the following paragraphs often reference is made to repositories, this section also includes technical feasibility and long-term performance for other concepts that might require RD&D.

Objectives – The first objective (a) for Key Topic 3 is to demonstrate, to the level typically required by national licensing approaches, that the technical design requirements based on safety of construction and operations, safety during the post-operational transient phase, and long-term safety after closure, can be met in practice by available construction technologies and related working procedures. This includes confirmation of repository components against pre-defined design specifications to determine their state before closure and extends to optimising operations and costs over the lifetime of a repository. As a consequence, this objective contributes strongly to the first and second pillars, "Safely Operate" and "Optimise and industrialise", of the 2040 Vision.

The second objective (b) consists of showing that the system demonstrated, according to objective (a), will provide all the safety functions needed for the system as a whole to fulfil the long-term safety criteria. This requires that the evolution of the engineered components and materials is sufficiently understood in the actual repository conditions over the specified timeframe. Because of the relationship between technical design requirements and long-term performance requirements these usually must be defined iteratively. In this context, robust design may be necessary to account for uncertainties. The second objective contributes mainly to the second pillar, "Optimise and industrialise", of the 2040 Vision, with some contributions also to the third pillar, "Tailor solutions".

Each component needs to fulfil the design criteria based on the specified safety functions of the repository and meet the qualifications defined in the regulations.

Rationale and benefits – The work performed for the first objective (a) will contribute to demonstrating that chosen construction and realisation technologies are available to meet the

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[7] Construction includes the manufacturing of components and their emplacement.

[8] The post-closure safety functions generally include containment of waste for a required period and limitation of groundwater and solute transport, including retention of radionuclides.

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performance targets and requirements set on the disposal facility. Depending on the national licensing requirements, the construction, manufacturing and installation of essential parts or components and machinery to be used have to be demonstrated to the degree required by the authorities to provide evidence of the safety of geological disposal in a stepwise manner. In general, this is required in anticipation of the construction licence. Programmes advancing beyond this stage will typically focus on further optimisation. The need for the demonstration is also derived from the review comments on on-going RD&D by some regulators.

Dealing with the second objective (b), in support of the requirement to demonstrate long-term performance of the repository and its components in meeting the safety functions, there is a need to adequately understand performance-relevant processes that relate to changes in the properties of the emplaced components and materials over the different time periods defined by the individual regulatory requirements. In general, for the various components and materials, design requirements are established that have to be met at the time of emplacement. The studies should also contribute to better quantifying the long-term performance-relevant processes that may modify properties of the waste containers, buffer, backfill and seals in repositories and help to confirm that licensing requirements will be met.

Waste disposal containers

The selection of waste container materials and associated design concepts[9] depends on the disposal environment, required container lifetime and operational handling requirements. For containers for HLW and/or spent fuel, container materials must be sufficiently corrosion resistant to provide complete containment for the required duration (this can vary from a few hundreds of years to several hundreds of thousands of years, depending on disposal system requirements). Sufficient structural strength is also necessary in order to withstand long-term structural loads and handling stresses during encapsulation and repository operations. For programmes close to repository implementation, it is necessary to demonstrate all aspects of waste container production and waste conditioning (including encapsulation technology) at the industrial scale. With several container concepts now being licensed, transferability to developing programmes is expected in the future. Based on the rapid progress in material science, new candidate container materials can be considered and tested for programmes in earlier stages of development or small programmes looking for specific solutions.

Concrete and steel containers for low and intermediate-level waste are widely used. RD&D related to new materials or components can further optimise safety-relevant properties, handling and costs during waste management stages (e.g. interim surface storage, repository operations and after disposal facility closure).

Buffer and backfill materials

The choice of buffer and backfill materials is largely dependent on the chosen disposal concept. Buffer and backfill have important safety functions in disposal concepts and shall therefore fulfil the requirements and specifications set for them. As these depend on the disposal concept

[9] Containment may rely on the waste container and/or any surrounding components, for example a disposal liner or an overpack if used.

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under consideration and that in turn is heavily influenced by the geological environment of the potential site their importance varies between the different waste management programmes.

For example, in fractured crystalline rock strong requirements on the bentonite buffer's safety functions as well as on the backfill are set for the disposal concepts close to implementation. Some of these requirements and regulatory review comments are related to the state directly after emplacement of the buffer and the waste container. Such materials have now been tested at full-scale with demonstrations at underground research facilities in advanced programmes, such that transfer to similar concepts in developing programmes becomes possible.

This work area also supports concept development activities, such as material selection, if the decisions relating to concept selection and detailed specifications have not yet been taken.

However, there are also requirements for their long-term safety function that must be fulfilled. The processes occurring during repository evolution are similar for many materials and repository environments (e.g. re-saturation, compaction, diagenesis, changes in hydraulic characteristics), which makes comparisons meaningful, even though the impacts on disposal system performance may be significantly different. Optimisation of disposal concepts can lead to adjustments of requirements on the materials and thus request further testing to enlarge their domain of performance.

The whole supply chain for the buffer and backfilling materials and especially for bentonite buffer materials has been developed by the most advanced programmes in preparation for their respective construction licences. Beyond this stage further optimisation for safety, robustness and cost is essential.

Other programmes continue their demonstration for their specific boundary conditions. There could also be advantages in defining quality assurance (QA), or acceptance, levels on a European level.

Plugging and sealing

The openings in the repository (tunnels, disposal caverns, boreholes, shafts, and access ramp) must be backfilled and sealed during the operational and closure phases. The plugging and sealing might or might not have a safety function, depending on the disposal concept and the host rock. In the case that the plugs and seals have a safety function they are typically designed to create a mechanical and hydraulic decoupling between the repository and its environment, hence avoiding any preferential flow pathways. Numerical modelling of the long-term performance of plugs and seals is therefore also needed.

The engineering (design and construction) of plugs and seals shall be based on the safety strategy of the repository while relying on engineering standards and compliance with the existing national legislation. Several examples have been developed by advanced programmes that also include full-scale demonstrations.

Different kinds of materials (cement-based, clay-based, salt-based, etc.) can be used in the construction of plugs and seals. Interaction (hydraulic, mechanical and chemical) and compatibility with other engineered and geotechnical barriers as well as with the geosphere needs to be assessed and ensured so that the safety functions of other components are maintained despite the interaction.

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As for other repository components, the design and construction of plugs and seals has to be tested and demonstrated at full-scale at repository depth to confirm feasibility and reliability, generally in preparation for a construction licence. Beyond this stage further optimisation for safety, robustness and cost is essential.

Tunnel and cavern construction

Depending on the safety strategy and the concepts chosen, various requirements need to be fulfilled from an operational and post-closure safety point of view for the construction of the tunnels and caverns. Next to the construction methods themselves, especially in lower-strength rocks, materials (steel, concrete, polymers, etc.) need to be selected for the tunnel and cavern reinforcements. It needs to be assessed if their long-term behaviour affects the repository evolution and the safety functions of components and barriers.

Other components

For small volumes of wastes in certain countries a mined repository is not envisaged. RD&D for components and techniques for realising innovative new concepts, beyond current practice, could be envisaged.

4.3.2 Specific research topics

Topic 3.1: Full-scale operational demonstration of HLW/SF disposal containers. This topic includes the industrial-scale fabrication, encapsulation, container handling and emplacement required for those programmes close to construction licensing. A generation of large-scale experiments in multiple URLs has been completed [84], and SF/HLW containers that meet regulatory requirements for site selection and repository construction stages have been demonstrated for some countries (e.g. Finland, Sweden). Optimisation of the technology and the operations for safety, cost and robustness is required for programmes in later stages. This includes the development of effective non-destructive quality control measurements on components. **[80% D&D: 20% networking]**

Topic 3.2: Industrial-scale operations for buffer and backfill. Industrial-scale operations for buffer and backfill have been demonstrated, including the entire production and emplacement chain in the repository by several programmes (Finland, France, Sweden). Transfer of knowledge and adjustment to specific concepts is required for programmes in earlier stages of development. Optimisation for operational safety and tailoring to specific in-situ conditions in a GDF are further areas of research. This includes the development of non-destructive quality control measurements on components. Swelling clay-based materials, and clay-based material in general, in European nuclear waste management concepts differ by composition, source, treatment and in-place characteristics (e.g. dry density); collaboration to increase the general understanding of differences between materials and programme-specific needs would be beneficial. Suggested objectives within this topic include: 1) to compare the properties of clay-based materials from different national programmes, including safety function and repository conditions; 2) to form common criteria that the materials should meet for use in waste disposal; 3) to evaluate quality control methods for consistent evaluation of (swelling) clay-based component safety functions. The materials would be characterised with suitable experimental methods and the differences evaluated. The results would be migrated to a common material data bank to be used by WMOs and regulators. **[80% D&D: 20% networking]**

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Topic 3.3: Repository layout design including operational safety studies. Repository layout design, including operational safety studies, requires work both at the conceptual level for early stage programmes (optimisation of decision-making tools) and at the detailed level in order to tailor and optimise the repository lay-out to the actual site-specific geology for programmes in the industrialisation stage. **[100% networking]**

Topic 3.4: Pilot demonstrations of repository operations. Pilot demonstrations of repository operations have been and/or are taking place in several programmes approaching construction/operational (e.g. Finland, Sweden). This can be (but is not necessarily) part of a pilot phase with cold or hot waste. With pilot phases, or operations of waste emplacement to take place in the next decade for those programmes that are most advanced, major return of experience and learning is anticipated for programmes at all stages of development. **[100% networking]**

Topic 3.5: Full-scale demonstrations of plugging and sealing. Major progress has been made in full-scale demonstrations of plugging and sealing, including construction and installation technologies for plugs and seals, such that all the established performance targets and requirements are met and comply with the safety strategy of the relevant disposal concept. This has been undertaken as part of EURATOM projects (e.g. DOPAS), but also via extensive activities in individual WMO programmes. With a solid basis now available, additional activities relate to enhancing knowledge through improved analysis methods for programmes in earlier stages, and through optimisation (safety, constructability, cost) for advanced programmes close to construction and optimisation. A further interest is in the final closure of the repository and exploring monitoring possibilities behind a sealed-off system. For borehole-based concepts, demonstration of emplacement according to requirements remains a topic of interest. [**80% D&D: 20% networking]**

Topic 3.6: Performance of seals and plugs. The evolution of seal and plug systems and modelling of their long-term behaviour, with assessment of the consequences on long-term safety, requires further attention. Although significant progress has been made in EURATOM projects (e.g. DOPAS) and multiple other studies, the complexity of processes involved over long timescales requires constant integration of the state-of-the-art, which is progressing fast. A focus should be on the impact of partly saturated/unsaturated conditions on other performance aspects, given that partly unsaturated conditions can prevail for a significant time and the resaturation regime and time of the repository (or the borehole disposal concept) needs to be understood. **[80% R&D: 20% networking]**

Topic 3.7: Interaction of cement-based sealing and construction materials with clay-based buffer and clay host rocks. The interaction of cement-based sealing and construction materials with clay-based buffer and seals has been targeted in many research activities in the last decade (e.g. CEBAMA) and a good conceptual understanding has been developed that allows the formulation of conservative assumptions. The process is complex and progress of the state-of-the-art needs to be integrated regularly. Use of low pH (and low curing temperature) cements to limit potential impacts on bentonite properties and to meet thermal criteria is now established as the reference in several programmes. Further activities relate to: obtaining very long-term data from URL experiment; the impact of cement-bentonite interactions under partly saturated conditions; improvement of the industrial workability with low pH cements during construction; and the longer-term chemical evolution of low-pH cements (particularly with respect to temperature), as the knowledge base compared to classical

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OPC (ordinary Portland cement) is less mature. An additional item is the study of potential replacement materials (e.g. geopolymers and future low-carbon cements). **[60% R&D: 40% networking]**

Topic 3.8: Long-term behaviour of salt backfill. This topic covers laboratory and modelling work on salt backfill to study its long-term behaviour (consolidation, healing, creep, interaction with the surrounding rock, influence of fluids, permeability and porosity). Major progress has been made in the last decades (Germany, USA). The current focus is on:

- Development of modelling tools to sufficiently describe long-term compaction, ductile and creep deformation up to low residual porosity (~1%).
- Development of adequate techniques for humidification of salt backfill, including studies on additive humidity carriers (e.g. salt grit/bentonite mix).
- Studies on the impact of moist salt material on pore reservoir volume of crushed stone (precipitates, creeping).
- Applicability of uniform, spotless contact surfaces[10], including up-scaling aspects (focus on in-situ testing).
- Studies on radionuclide sorption capacity of salt-clay mixtures and increasing the sorption capacity of salt backfill through addition of bentonite.

[50% R&D: 50% networking]

Topic 3.9: New materials for engineered components. The development of new materials (composition and technology) both for waste conditioning matrices and engineered components (e.g. the disposal container) is now mainly optimisation-driven to address increased robustness of safety demonstration (operating and post-closure) as well as technical-economic aspects. For advanced programmes, but also for programmes in development, this includes, for example, fibered concretes (without steel reinforcement), especially for support, inert materials such as ceramics for certain disposal containers, carbon composites for other components instead of steels, or geopolymers for reactive metals (i.e. electropositive metals). Programmes in earlier stages of development (e.g. site selection) can profit from the progress in material sciences as final selection of barrier materials still lies multiple years ahead and major choices in the engineered barrier system (EBS) concept are still open (e.g. bentonite, cement, innovative multi-layer concepts). **[80% R&D: 20% networking]**

Topic 3.10: Container materials and their long-term performance. Significant understanding has been developed to allow performance assessment of various steel, copper and copper-coated canisters. Corrosion processes have been studied and the conditions under which general corrosion can be assumed to occur has been bounded. Remaining work lies in the continuation of ongoing long-term corrosion experiments and further refined analysis on

[10] "Spotless contact surfaces" describes the contact between salt grid (the geotechnical barrier) and the top of the repository (e.g. in the storage area). After filling the storage area with salt grid, compaction produces a gap between the salt grid and the top of the storage area. The convergence movement of the salt gradually closes the gap. However, the main issue is to fill or to keep the gap as narrow as possible to reduce the time the salt convergence needs to close the gap to ensure a spotless (or complete) contact. As current techniques do not solve this problem either further development of existing techniques or development of new approaches is required.

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which specific conditions can trigger other corrosion mechanisms (e.g. pitting-corrosion, microbial-induced corrosion). The impact of corrosion at higher temperature ranges to accommodate higher thermal loads could become relevant; this might require additional experiments. The knowledge base of empiric and other studies on available container materials and their behaviour in order to support safety assessment needs to be regularly updated to account for developments in the state-of-the-art. Knowledge of new/alternative materials also needs to be integrated, as does improved understanding of performance at temperatures above 100°C. This topic is strongly linked to Topic 3.1 for full-scale operational demonstration of HLW/SF disposal containers. **[50% networking: 50% R&D]**

Topic 3.11: Repository-induced gas generation impacts and their mitigation. The anaerobic corrosion of steel can lead to substantial generation of mainly H_2 gas which, in the case of a "tight" host rock, can generate over-pressures and cause stresses that can affect rock barrier integrity. Gas generation and gas consumption rates still bear large uncertainties, while process understanding of gas transport in low permeability media could be further enhanced (although this aspect is now receiving attention as part of the EURAD GAS WP). This includes upscaling in space and time. The objective is to reduce over-conservatism in the current gas pressure assessments. Geological conditions and the safety margin with respect to the integrity of the host rock and overburden strongly determine the engineering measures needed and therefore this topic is strongly linked to Key Topic 1. **[60% R&D: 40% networking]**

Topic 3.12: Remaining issues on bentonite performance and properties. The knowledge base on the impact of hydrogeochemical evolution on the bentonite properties and long-term performance has progressed tremendously in the last decade thanks to a series of EURATOM projects (FEBEX, PEBS, Belbar, DOPAS, etc.) and intense work in multiple programmes over the last decades. The understanding of bentonites with various densities up to 100°C in various geochemical environments is now very mature with a few remaining issues such as:

1) The Fe-bentonite interaction topic, which will be able to make major progress with projects like EURAD ACED WP and IGD-TP KINA.
2) Sulphide sources, sinks and transport understanding in bentonite and at bentonite interfaces (sulphide is an important corrosion agent of container materials). For copper, it is the main cause for corrosion, but also iron-containing materials corrode by sulphide. The possibilities for formation of sulphide in, for example, a bentonite buffer, have been investigated, but also the extent of sinks, like precipitation (in the form of FeS), adsorption etc., should be investigated, as this could possibly provide more realistic assessments of post-closure safety.
3) Deeper understanding between the mineralogical composition of various bentonites and their properties (including microbial aspects) in order to develop alternative bentonite candidates and optimise production of bentonites for advanced programmes.
4) Improve the data support and the process understanding of bentonite performance in the range 100°C-200°C for thermal optimisation purposes. The ongoing EURAD HITEC WP is expected to progress knowledge and data within this topic area.
5) Further characterisation of the conditions under which bentonite erosion can occur.

[60% R&D: 40% networking]

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4.4 Key Topic 4: Implementation and/or Optimisation

4.4.1 Definition, scope and rationale

Definition – The future development of reactor, fuel cycle and waste management technologies and policies and the long duration of disposal development (several decades) will inevitably raise opportunities and needs for changes and adaptations in the design, implementation, construction and operation of geological repositories. Some of the future likely trends are already visible and may be reflected in adaptable and flexible designs and implementation schemes.

Construction of a repository will involve successive stages of construction operations with gradual implementation of the various technologies used for the disposal and surface facilities (including a pilot phase or pilot demonstrator(s)). This step-wise implementation allows continuous optimisation, flexibility and adaptation:

- *Optimisation* concerns technical and economic aspects, but also increases in the robustness of post-closure safety demonstration and/or operational safety.
- *Flexibility* concerns adapting the repository design and programme over time to address uncertainties that exist at the licensing application stage (e.g. if necessary, defining different design options to allow for inventory uncertainty). The need for flexibility particularly relates to possible variations in waste delivery, reception flows, packaging modes and processes, disposal modes for radioactive waste packages, waste inventory management of current nuclear power plant (increase of operating duration), etc.
- *Adaptability* concerns the ability of the repository design and programme to adapt over time, for example, to the disposal of waste not provided for in its inventory at the licensing application stage or to modification of requirements or design criteria.

Of course, the importance each WMO places on adaptability and flexibility in their disposal programme depends on their national context (e.g. national policy in terms of reprocessing of spent fuel or not, policies in terms of evolution of the current/future nuclear fleet, etc.) and associated radioactive waste inventory.

The design strategy has to be "optimised", taking into account the potential benefits of increased adaptability and flexibility versus management of uncertainties in the future, including assessment of the cost impacts of such adaptability and flexibility. This Key Topic deals with the integration of new developments during the lifetime of a geological repository (construction and the operation time up to closure). A licence would be issued for constructing and operating a geological repository on the basis of the available information at the time of the application. However, during the operational lifetime of a geological repository from its construction to its closure, new technologies, new scientific findings or improvements, and changes in the radioactive waste inventory, are likely to occur and can also be considered for the future closure, as well as for any reversibility and retrievability rationale [85].

Adaptation and flexibility will be ongoing throughout the lifetime of the repository from the reference layout, through design (including adaptation to the site), and during construction and operation. This supports the gradual development of a repository that may include a pilot phase or a pilot demonstrator in many design strategies.

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Objectives – The Key Topic aims to ensure that a higher level of safety, or at least the same level as that demonstrated for the initial licence (taking into account the entire waste lifecycle), is achieved through adaptation and flexibility, independent of the new developments or new inputs (such as change of radioactive waste inventory) related to the repository over time.

A geological repository should take account of new developments in order to adapt and to optimise its construction, operation and closure, particularly in concert with feedback from operation. Improving industrial conditions is expected to simplify the work and to improve quality and safety (both during operations and post-closure) and, at the same time, potentially reduce the costs. This holistic approach has to take into consideration the long timescale of repository development, particularly for cost assessment. Therefore, research with these objectives contributes to the second pillar, "Optimise and Industrialise", of the 2040 Vision.

Rationale and benefits – Development of a repository must be able to adapt and remain flexible to changing information and boundary conditions, by adjusting or modifying the design of the repository and thus its construction and operation conditions. This includes improving short-term as well as long-term safety, whilst also improving the industrial conditions of construction and operation.

Improving the safety conditions and their demonstration is beneficial to gain and maintain stakeholder confidence. A benefit from improving the industrial conditions could be a reduction in costs. Specific developments are also likely to occur in the fuel cycle (e.g. higher burn-ups, new reactors and fuels, new cycle options/policy), which may call for adaptation of the design, construction and operation conditions. In this case, adaptation might be induced by changes in boundary conditions.

Finally, at each milestone of the staged repository development, questions on the reversibility (defined as a governance principle over progressive development) and retrievability (as a tool of reversibility) will have to be managed, in the framework of the knowledge, repository situation (see link with Key Topic 6 on monitoring), and national boundary conditions (see above), and any decision to be taken.

Over the last ten years the methodology for developing strategies and approaches for adaptation, flexibility and optimisation has been developed in some countries as part of the licensing application (such as in France for the Cigéo project), or is included in the development of future licensing applications (such as in Switzerland). This methodology has the following steps:

- Identification of the different types of repository programme evolution.
- Indication of changes to expected boundary conditions for each type of programme evolution.
- Definition of initial repository design allowing flexibility and adaptability.
- Description of design adaptation to take account of possible programme evolutions.
- Preliminary assessment of the consequences of adaptations on the overall safety of the geological repository system, including all relevant sensitivity analyses.

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In addition, work has been undertaken on certain scientific and technical topics, for example:

- to increase the maximum temperature criterion in the host rock or EBS, particularly for clay media, or to better quantify margins about thermal damage of clay host rock, which could lead to a more compact repository;
- to develop new chemically inert materials (e.g. ceramics, geopolymers) for some EBS, such as the HLW over-pack, that could simplify the post-closure safety demonstration, or innovative materials that could increase operating safety margins and reduce cost, such as new liners for tunnel support in clay host rocks (see Key Topic 3).

4.4.2 Specific research topics

Topic 4.1: Improved methodologies for developing strategies and approaches for adaptation and optimisation. In order to proceed to the construction of a geological repository, licence applications need to specify how any adaptation and optimisation in design, construction and operations would be managed during the lifetime of the project. For example, it is important that strategies for considering system evolution are anticipated and clearly acknowledged from the initial licensing stage. In addition, interaction with safety authorities and their TSOs is needed in order to specify the type of requirements at the time of initial licence application that will allow further improvements. **[100% networking]**

Topic 4.2: Thermal dimensioning of the repository. Heat-emitting waste requires assessment of the thermal dimensioning of the repository. This involves issues ranging from estimation of the uncertainties and variability in the heat output of the spent fuel or HLW to canister loading, disposal package spacing and disposal cell spacing, up to estimation of the impact of the thermal pulse on the host rock and the definition of safety criteria. RD&D activities are needed to improve inventory characterisation, decision-making software for disposal canister loading, tool development to optimise repository lay-outs, and process understanding of heat transport and THM mechanical damage criteria in the host rock, particularly for clay rocks. The objective is to integrate the various elements that must be considered when optimising the repository thermal dimensioning. **[80% R&D: 20% networking]**

Topic 4.3: Building Information Modelling (BIM) and "digital twinning" of the as-built repository, coupled with numerical simulation of repository behaviour and data chain from monitoring. As observed in other industries (e.g. aeronautics), BIM coupled with numerical simulation and data chain management (High Performance Computing, Big-data, etc.) could be a major tool to support the development of a repository for both design and operations (including monitoring), which will also support flexibility, adaptability and optimisation. Such a system applied to a repository involves the need to aggregate R&D digitally in at least four areas: geosciences (new models); nuclear facilities; monitoring (see Key Topic 6); and numerical simulation. **[60% networking: 40% R&D]**

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4.5 Key Topic 5: Safety of Construction and Operations

4.5.1 Definition, scope and rationale

Definition – This Key Topic considers the protection of operators and members of the public that might be affected by construction and operations (including construction, normal emplacement and other operating modes, closure, monitoring and active control) in or nearby geological repositories.

Objectives – The purpose of this Key Topic on safety of construction and operations is to achieve consistency among WMOs in areas such as methodological approaches, strategies, procedures, and reference values. As a consequence, this objective contributes strongly to the first pillar, "Safely Operate", of the 2040 Vision. As the operational safety issues can have an impact on the final design and layout of a repository, this objective has also some links with the second pillar, "Optimise and Industrialise", of the 2040 Vision.

Rationale and benefits – Even though geological repository development is founded on the implementation of a strong safety culture, the practical issues of industrial/conventional safety will first be confronted at the construction stage, with the issues of radiation safety not confronted until the operational stage.

Adaptations in support of operational safety might affect the design of the repository system and should be evaluated with respect to their impact on long-term safety requirements, as well as their impact on operational safety in the shorter term. It is noted that geological disposal facilities are unique installations, where one needs to combine (amongst other aspects):

- Nuclear engineering practice and radiation protection.
- Classical industrial safety aspects.
- Geotechnical and rock engineering in underground works (including practical mining experience where applicable).

Although regulations for each of the safety aspects exist (or might exist as these can be dependent on national circumstances), there are not always clear integrated regulations available. Indeed, conflicting requirements might even exist among the different aspects as some regulations were developed for purposes other than geological repository construction.

Although design and concepts differ from one waste management programme to another, some operations and challenges of safety of construction and operation have similarities and there is considerable benefit in sharing experience and solutions.

4.5.2 Specific research topics

Topic 5.1: Improved methodology, approaches and documentation on safety of construction and operations. Building on studies undertaken in the past decades, which have been particularly focused on the long-term safety issues, the work should include:

- Improved methodologies for assessing the risk with respect to safe working conditions.
- The approach used for management of the risks during the construction and operational phase.

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- Further development of the documentation to be used to report on the safety of construction and operations.

Important progress on safety of construction and operations has been made in recent years at the international level. GEOSAF, an IAEA project on demonstration of the safety of geological disposal, has been ongoing for several years. The current phase, GEOSAF III, aims to clarify the concepts of As Built State (ABS), Design Target (DT) and Safety Envelope (SE), through discussions of practical examples found in actual safety cases from Member States with developed disposal programmes. GEOSAF III also validates the gap analysis performed in GEOSAF II, in order to prepare a document or documents that will form a basis for recommendation to the IAEA to develop guidance on operational safety. Also, this guidance document identifies and emphasises the influence of operational safety issues that may interact with long-term safety and therefore have an influence on the ABS and DT. IAEA TECDOC's are in preparation and continued support to finalise them is needed. Moreover, the practical consequences of these new TECDOC's and potential new guidelines deserves interaction between WMOs in order to exchange experience on approaches and common practices by the advanced programmes. **[100% networking]**

Topic 5.2: Strategies to evaluate the impacts of construction and operational issues on the disposal system. This topic covers developing strategies and evaluating the impact on long-term safety, design, complexity and cost of geological repositories for specific operational issues. For example, this includes strategies to evaluate operational issues such as emergency plans, volatile radionuclides and their impacts on workers and the environment during the operational phase. Explosive gases, air dust, ventilation and firefighting strategies are of interest to multiple WMOs.

A dedicated task of the operational safety task group (WG1) is carried out in GEOSAF III in order to identify – among all the operational safety issues – the most critical ones for long-term safety. This identification aims to integrate the concepts of ABS, DT and SE developed in GEOSAF II (illustrated and refined in GEOSAF III) to address this topic.

An operational incident occurred in the USA Waste Isolation Pilot Plant (WIPP) facility in 2014 and has strengthened the need for continued efforts on operational safety issues. Return of experience and continued evaluation of optimisation with respect to operational safety is a key driver within this topic. **[100% networking]**

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4.6 Key Topic 6: Monitoring

4.6.1 Definition, scope and rationale

Definition – Monitoring comprises strategic, governance, methodological and technical aspects of continuous or periodic observations and measurements of environmental (e.g. geological medium including host rock and biosphere), engineering, and radiological parameters. Monitoring helps to evaluate the behaviour of components of the waste disposal system, or of the impacts of the waste disposal system and its operation on the public and the environment, before construction (initial state) and during construction and operations, until the end of institutional control [86]. This Key Topic addresses both operational safety and post-closure safety. It includes regulatory oversight in concert with safety demonstration and assessment of impacts, in accordance with the operating licence.

Objectives – The scope of this Key Topic covers the development of:

- Practical monitoring strategies that do not negatively affect post-closure safety, including devices, techniques and methods of data treatment for implementation. This includes monitoring strategies for site characterisation, facility construction and operation, and contribution to the safety assessments.
- Monitoring strategies for current and future requirements for steps leading to closure of the facilities in an operational disposal system. It also considers requirements for monitoring dedicated to the post-closure phase of the geological disposal system and monitoring of progress in relevant scientific and technological areas.

Research with these objectives therefore contributes to the first pillar, "Safely Operate", of the 2040 Vision.

Rationale and benefits – Both the siting and environmental approvals included in a licence for construction, operation and/or closure of a geological disposal facility need data that partly originate from continuous or periodic observations and measurements.

It is acknowledged that many European Member States have included explicit or implicit repository monitoring requirements in their regulatory and guidance framework. Among these, performance confirmation monitoring stands out as a topic requiring further developments within the waste management community. Included in the strategies and programmes are also any development of tools in support of decision-making from the recorded monitoring data.

Monitoring would be carried out during each step of the development and operation of geological repositories. The purposes of the monitoring programme include providing baseline information for subsequent safety assessments, assurance of operational safety and operability of the facility, and confirmation that conditions are consistent with post-closure safety. In that context, monitoring has to be linked with the development of Building Information Modelling (BIM) and digital twinning of the as built repository, tools identified in Key Topic 5 that support the progressive development, operation and closure of the repository ("from cradle to grave").

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Due to the long timescales for repository development and its successive milestones, scientific monitoring activities include continuous:

- Development and adaptation of strategies for selecting and maintaining a list of components of the repository system, corresponding monitoring parameters and for responding to monitoring results, in concert with safety case assessment.
- R&D on monitoring technologies to improve the monitoring strategy, in particular to adapt this strategy to repository changes.
- R&D on methods of data treatment to improve assessment of repository system behaviour at all relevant time and space scales.
- Communication and engagement with stakeholders.

For over forty years, a large effort has been made on monitoring technologies for site characterisation and for the implementation of experiments in URLs. The European MoDeRn and Modern2020 projects [87; 88] have established a substantial basis for further development focused on the monitoring strategy and equipment for a repository, including the use of URLs as a test-bed before and/or during repository implementation. Results from these projects have contributed to the submission of licensing applications (Finland and Sweden) and the preparation of licensing applications (France).

A generic iterative workflow for developing and undertaking a repository monitoring programme has been developed in the MoDeRn and Modern2020 projects. Monitoring during the operational phase that contributes to building further confidence in the post-closure safety case requires greater consideration of, and integration of the repository monitoring programme in the safety case programme of work; such monitoring should be regarded as an integral part of the post-closure safety case. Analysis of the post-closure safety case can provide a set of possible processes to monitor based on, for example:

- Evaluation of safety functions.
- Evaluation of features, events and processes (FEPs).
- Evaluation of safety assessment parameters.
- Evaluation of thermal, hydraulic, mechanical and chemical (THMC) processes.

Based on the outcomes of the MoDeRn project, in the Modern2020 project, a method for selecting monitoring parameters was developed, which drew on consideration of the post-closure safety case and on information gathered from test cases focusing on European-specific programmes. The Modern2020 Screening Methodology is a generic process for developing and maintaining an appropriate and justified set of parameters to be monitored in an implementable and logical monitoring programme. It provides an overview of the steps that a WMO may take in identifying and managing a list of parameters, linked to processes, and repository monitoring strategies and technologies.

The Modern2020 project also developed a set of recommendations and guidance on planning for evaluating and responding to monitoring results. Most significantly, the work recognised that responding to monitoring results must be flexible in order to respond to unexpected repository evolutions, and, therefore, specific actions and response plans cannot be defined

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ahead of the acquisition of monitoring data. Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the entire dataset.

Technological work in the Modern2020 project made substantial advances in developing new, or adapting existing, technologies such that their readiness for use for monitoring in a repository context has been improved. These advances include wireless data transmission, long-term power supply, optical fibre sensors (OFS), new sensors (water chemistry using ion-selective electrodes, relative humidity using the dew point method, and temperature), and geophysical techniques (tomography algorithms, etc.).

Although technologies and methodologies exist to enable applications for repository construction licences (such as in Finland and Sweden, and shortly in France), and that account for the staged development of a repository over several decades, further research is still required to fully develop monitoring specifications, and to improve methods and technologies for practical use in an industrial setting.

4.6.2 Specific research topics

Topic 6.1: Monitoring strategy. The methodologies to define monitoring needs and translate these into monitoring programmes, as well as the development of overall monitoring strategies (including their evolution during the progress of a repository programme), has matured significantly as part of the EURATOM MoDeRn and Modern2020 projects. Several monitoring concepts have now been submitted as part of licence applications by advanced programmes. Exchanging experience of those with more developed monitoring strategies and adaptation to relevant national legal frameworks are important networking activities. **[100% networking]**

Topic 6.2: Specifications and methods. Specifications for monitoring sensors need to be fully developed based on strategic planning for monitoring programmes and on preliminary designs for monitoring systems. Methods of assessing the impact of monitoring sensors on post-closure performance need to be developed, improved and applied in order to demonstrate that monitoring of the EBS and near-field host rock can be undertaken without significantly affecting post-closure safety. **[80% R&D: 20% networking]**

Topic 6.3: Monitoring equipment. The energy efficiency of monitoring system components and long-term power supply requirements need to be further developed and improved (for example, by using interim energy storage solutions at sensor locations or thermoelectric generators). Existing sensors also require improvement; for example, wireless technologies, fibre-optic sensors (irradiation effects, lifetime) and geophysical methods (algorithms). New/innovative sensors also require further development, in particular for non-invasive techniques (muons, radar, ultrasonic) and direct chemical measurement (pH). The long-term reliability of sensors also requires improvement, for example for fibre-optic sensors, particularly for wireless data transmission solutions. There may be synergies with pre-disposal monitoring equipment and research. **[80% R&D: 20% networking]**

Topic 6.4: Data management. Development of new systems for gathering, filtering, managing and displaying huge amounts of data in link with operating and post-closure safety is needed. **[80% networking: 20% R&D]**

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4.7 Key Topic 7: Methodologies for Site Characterisation

4.7.1 Definition, scope and rationale

Definition – Site characterisation is essential for the selection of a suitable site and the design, planning and development of a repository. Furthermore, site characterisation is an important component for (long-term) safety analyses. The topic is linked to exploration and investigation programmes, site information, data management and syntheses for the purpose of iterative safety assessments.

Objectives – This key topic focuses on R&D activities that are essential for site characterisation to identify gaps and needs related to this topic. This embraces development and improvement of geological exploration methods for surface and sub-surface exploration, identification of critical information and data, and development of strategies and models to provide specific geological information about a considered site. In this context, transfer of knowledge and experience from completed site characterisations to early or intermediate stage programmes can help to reduce uncertainties and increase efficiency.

Rationale and benefits – The application of geological (and geophysical) exploration methods is essential for characterising any given site for constructing a repository for radioactive waste. A sound site characterisation is the key to a deep understanding of the geological situation (e.g. water-bearing features, deformation, fractures, fissures, rock mechanics, thermal properties and resource potential) and may reduce site-related uncertainties. Subsequently, the site characterisation contributes to the long-term safety of a repository for radioactive waste.

Site-related uncertainties, for example, the condition of host rocks and geological barriers, can be reduced by exploration and research activities.

Therefore, this key topic aims to contribute to the reduction of present and future uncertainties and therefore, strongly contributes to evaluations of long-term safety. The use of non-destructive exploration methods avoids disturbance of potential containment-zones and geological barriers. Therefore, this key topic aims to foster the research effort to improve exploration methods, particularly non-destructive techniques. Moreover, the analyses of natural analogues may be helpful to study long-term geological processes.

Another research focus includes acquiring data to assess the potential impacts of future climate change and long-term geological evolution on the repository. The development of suitable field methods to improve understanding of site evolution (e.g. erosion, tectonic evolution, potential for induced seismicity) can contribute data for the modelling topics discussed in Key Topic 1. The safety assessment models and safety case activities in Key Topic 1 also act to define the data required from site characterisation and the site selection criteria to be assessed.

Key Topic 7 also focuses on the determination and the development of approaches to handling heterogeneities. In this context, international exchange and co-operation, such as through collaborative development of databases for different host rock properties and the use of results gained in underground laboratories, are essential for progress to be achieved.

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4.7.2 Specific research topics

Topic 7.1: Exploration methods for site characterisation. Site characterisation strongly depends on the exploration methods used. For the safe disposal of radioactive waste, it is a pre-requisite to preserve the integrity of the containment zone and the geological barrier. Therefore, one focus of exploration-related R&D activities is the application of non-destructive and non-intrusive exploration techniques and measurement methods, and improvements to minimise the impact of destructive techniques (e.g. geophysics, drilling practices, fracture characterisation, sampling techniques, stress measurements, radiometric dating) [89]. Moreover, as drilling practices are a major part of site characterisation, R&D activities can help to develop site-related / host-rock-related drilling programmes containing information about, for example, the drilling technique, the borehole diameter and the logging methods. The combined analysis of geophysical and geological exploration results provides robust information on the geological situation [90] (e.g. stratigraphy, deformation, fracture characterisation, fissures, rock mechanics, thermal properties and permeability) and thus improves the understanding of the potential containment zone and geological barriers. Knowledge and experience transfer should be incorporated in this topic, so that early stage programmes can take advantage of the results from completed site characterisation programmes and benefit from specific host-rock information and possible exploration programmes. **[60% networking: 40% R&D]**

Topic 7.2: Confirmation of rock properties. Confirmation of rock properties for final detailed design is required for the construction of the main underground facilities. Driven by the operational and post-closure safety case, good practice has been demonstrated for several types of host rocks (crystalline, clay, salt) where URLs and first facilities have been constructed [91; 92; 93]. The methodologies can be further refined in optimisation cycles (safety, robustness, cost) and the technology applied can be further developed by taking stock of experience in other industries. **[80% D&D: 20% networking]**

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4.8 Key Topic 8: Strategy for Repository Project Development

4.8.1 Definition, scope and rationale

Definition – This Key Topic involves RD&D and networking activities that contribute to the 2040 Vision second pillar, "Optimise and Industrialise", and/or the third pillar, "Tailor Solutions". More specifically, the Key Topic covers how to move from a disposal concept, to an established project, through to facility siting and operation, both in national and multi-national projects. Although the steps are almost identical in both cases, the multi-national dimension adds further complications.

Objectives – The objectives are to:

a) identify the various aspects of the transitions from one project step to another;

b) identify the decision-making processes for each project step;

c) identify the underpinning knowledge and technologies needed in each step; and

d) additionally, consider the above objectives from the viewpoint of shared (multi-national) solutions.

Rationale and benefits – Establishment of the strategies and procedures for transitions between project steps at an early stage accelerates the decision-making process and helps to avoid mistakes. It also benefits the decision-making process if consistency across WMOs in the steps and procedures applied is achieved.

The transition from surface-based site characterisation for the site selection process to exploring the sub-surface at the selected site is complex and, depending on the regulatory framework, may require a separate licensing step. It does require a major shift in planning to include sub-surface exploration, monitoring (see Key Topic 6) and performance confirmation, and it requires specifying aspects of the design of the future repository. One possible strategic decision during the course of repository planning is retrievability/reversibility (e.g. whether it is a national requirement and how long reversibility should be possible for). Another consideration is that of facility security and international safeguards requirements, both technical and political (the latter aspect is being considered by the IGSC). Also, during the different stages of the project, cost estimation is an important part of project management and needs to take into account the long durations and complex nature of geological disposal projects.

The current development of repository systems addresses mostly the disposal of power reactor spent fuel and/or HLW rather than spent research reactor fuel (SRRF), which is relevant to some SIMS programmes. For SIMS, the small quantities of SRRF are particularly difficult to manage and disposal options need to be developed. One disposal option, for small inventories and specific types of waste, could be Deep Borehole Disposal (DBD).

About half of the EU Member States are considering shared RWM disposal solutions. A core issue with shared RWM solutions is how to move from one project step to another. Using one or more practical case studies it can be shown how participating Member States can work together to establish how a route can be found through these steps. Progress of the EURAD ROUTES WP, including the recently proposed second wave extension to the project which addresses some issues relevant to SIMS, will be followed carefully to avoid duplicate work.

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4.8.2 Specific research topics

Topic 8.1: Transition from surface-based site characterisation to going underground. The full detailed design of the repository will not be available when transitioning from surface-based to sub-surface exploration and uncertainties regarding the sub-surface geology might still be large. This can include planning the construction of a site-specific URL and the experiments therein, if required. The objective of this topic is to identify the various aspects of this transition, the decision-making process and the identification of technologies needed to make this happen. **[90% networking: 10% D&D]**

Topic 8.2: Routes to facility implementation. Some EU Member States are considering shared RWM disposal solutions. A core issue with shared RWM solutions is how to move from concept, to project establishment, and through to facility siting and operation. Although the steps are almost identical for any two national facilities, complications arise when considering the comparability of multi-national approaches. **[80% networking: 20% D&D]**

Topic 8.3: Deep borehole disposal. For small inventories and small amounts of clearly specified types of wastes, Deep Borehole Disposal (DBD) could be a solution. Deep (several kilometres) boreholes could handle all or most of the higher-activity and longer-lived wastes in one or more actual national inventories of SIMS/ERDO countries. Development of potential borehole disposal solutions and proposals of concrete technical solutions, including use of existing borehole technology, the need to develop new methods, waste packaging options for borehole disposal, depth of the borehole for the different types and packaging of the wastes, costs etc. need to be investigated. **[90% networking: 10% D&D]**

Topic 8.4: Reversibility and retrievability. Retrievability, or the wider term of reversibility, and the conditions under which this needs to be foreseen is generally fixed in the legal framework of individual countries. In earlier stages of the programme, a conceptual design is sufficient. Advanced programmes, as part of the construction licence application, have conducted demonstration experiments (e.g. in Sweden and France); this knowledge can be transferred to programmes at an earlier stage. Monitoring strategies to assess the conditions under which retrieval might be triggered need to be developed (see Key Topic 6). Adaptation of the design of the disposal concept to support retrieval, balancing between ease of retrieval and impacts on long-term safety, needs to be considered. While each country needs to develop its own approach and technical solutions, methodologies and general decision frameworks can be developed jointly. **[90% networking: 10% D&D]**

Topic 8.5: Costing. Quantifying the costs of radioactive waste management, and especially of disposal, and estimating how these may arise over long periods of time (many decades) is a complex issue. Some major national waste management programmes carry out and publish comprehensive cost estimates at regular intervals (e.g. Sweden, Switzerland and France). These estimates can, however, be difficult to compare since the methodology applied, including the itemisation of costs and the assessment of risk factors, are often different. The scope of costs estimated also differs between countries, as some countries include only waste disposal costs, whereas others also include decommissioning costs (including management of decommissioning waste). It is equally important for both large and small radioactive waste management programmes that their estimated costs are justified, transparent, affordable and regularly updated. For the case of proposed multi-national repositories, detailed and transparent disposal cost estimates are important since potential users of such a facility will be directly

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interested in comparing these costs with the funds required for implementing a national solution. **[100% networking]**

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4.9 Key Topic 9: Knowledge Management

4.9.1 Definition, scope and rationale

Definition – This Key Topic involves networking activities that contribute to all three pillars of the 2040 Vision, as maintaining knowledge, competencies, skills and infrastructure are vital to safely and efficiently implement, operate and close radioactive waste disposal facilities. The Knowledge Management (KM) Key Topic encompasses all knowledge that supports a geological disposal facility, which is broader than just the science and technology that underpins the safety case – it includes the reasons for why systems have been designed and implemented as they have, why decisions have or have not been taken, and why options are selected or not. It is as important to identify and treat obsolete, superseded knowledge as it is to gather and share new knowledge, in order to avoid repeating previous work. KM also covers competence maintenance, education, and training, as well as information/data management.

Objectives – The objectives are to:

- Develop a common WMO KM strategy in order to make effective use of common expertise, knowledge and systems.
- Facilitate knowledge transfer between more advanced programmes and early stage programmes (e.g. through training, face-to-face knowledge transfer, forging close links and ensuring collaboration between WMOs, and by making reports open-access where possible).
- Preserve capability (competencies, skills, infrastructure, etc) and ensure its transfer between generations over the long timescales of geological disposal.
- Avoid unnecessary duplication of work by mapping the information that has been acquired and research progress that has been achieved thus far across different programmes (this also helps facilitation of knowledge transfer between advanced and early stage programmes).
- Identify the areas that are considered to be sufficiently mature and where additional RD&D would no longer contribute to significant reduction of safety-relevant aspects, and also identify the priority knowledge gaps that need addressing in order to further reduce significant uncertainties.

Rationale and benefits – Knowledge is the nuclear industry's most valuable resource, without which the industry cannot operate safely and economically, and is vital for all stages of a nuclear facility's life cycle: research and development, design and engineering, construction, commissioning, operations, maintenance, refurbishment and closure. Such knowledge is also complex, expensive to acquire and maintain, and can be easily lost. Key challenges to KM in the nuclear industry, and for geological disposal in particular, include:

- The nuclear industry has an ageing workforce and significant, tangible and intangible, knowledge is at risk due to personnel retirements.
- In countries with stagnating nuclear energy programmes and/or a policy for nuclear phase out, or countries that do not have a nuclear energy programme, it is challenging to secure sufficient human resources, but to also obtain sufficient funding to continue to maintain infrastructure, experimental facilities and research.

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- Geological disposal is a large-scale infrastructure project with an unusually long timescale, both during the RD&D phase prior to licensing and then during the long construction, operational phase and monitoring phase. A challenge unique to geological disposal is that knowledge must be maintained without real activity for some decades.

Multiple approaches to KM are in use, including amongst IGD-TP member organisations. The many approaches applied are all valid, but there is a need to have a common WMO KM strategy in order to make effective use of common expertise, knowledge and systems. The IGD-TP can be a continuous link for consistency and KM across all WMOs, acting as a vehicle to manage the combined WMO KM needs.

There are many existing initiatives, with both the IAEA and NEA having undertaken work in this area for a number of years. It is important to complement existing initiatives, not to duplicate them (i.e. identify where there are gaps). There are many aspects to KM that must be maintained by WMOs, including the reasons for the strategies implemented and management decisions made, in addition to fundamental scientific and technological knowledge. Many international projects tend to concentrate on scientific and technological KM only. Currently ongoing activities include:

- an NEA initiative on information, data and knowledge management (IDKM);
- IAEA knowledge management activities;
- EDRAM Knowledge Management Working Group;
- EURAD Knowledge Management Work Packages; and
- KM activities within each WMO.

An important aspect to note is that writing documents is only one part of KM; there is also a need for continuity of knowledge held within the working community. In some areas sufficient information to underpin geological disposal has already been obtained and so limited further research is being undertaken, which means staff knowledge is not being maintained and has the potential to be lost when the last expert in that area retires. However, expertise on such topics needs to be maintained for several decades so questions can be answered and the impact of new research findings assessed. Collaboration between WMOs to finance such expertise maintenance without unnecessary duplication is an option to be considered further.

Another area in which WMOs are considering their ability to collaborate to cost-effectively maintain knowledge is with regard to the maintenance and retention of specialist infrastructure, such as laboratories (including hot cells) and underground research facilities. Whilst such facilities need to be maintained, no need is seen for each WMO to fund such in every member country; pragmatic rationalisation would be sensible. Equally, and particularly with respect to countries that have taken the decision to phase out nuclear energy and/or small inventory member states, there is a danger that unique facilities and expertise may be lost as national funding may be reduced or withdrawn; it is possible that unique at-risk infrastructure could be collaboratively funded by WMOs to ensure its continued existence and that of the experts using them. This would effectively create an international pool of experts who could be called on by all WMOs as the need arises.

A number of the WMOs who are owned by commercial organisations (i.e. waste producers), rather than national governments, have established business models (or commercial arms) that

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provide expertise in radioactive waste management and disposal. These form another vehicle by which knowledge can be maintained and passed on. Some early stage and small inventory members have found the services of these commercial organisations useful because they can be contracted to provide specific support as and when needed (e.g. to support development of work plans and to help interpret data in the context of the specific situation). As a number of IGD-TP WMOs are funded directly by national governments, the IGD-TP does not officially endorse a business model approach to KM, but it does recognise that this is one route to maintain and share knowledge.

4.9.2 Specific research topics

Topic 9.1: Develop a common WMO KM strategy. WMOs support and actively participate in the numerous existing KM initiatives, including the recently commenced EURAD KM Work Packages. Many of these activities have developed detailed tools and methodologies for ensuring KM, as well as documenting knowledge on particular topics. Therefore, whilst there is no desire to duplicate these actions, there is benefit in WMOs identifying how best to pool their finite resources to maintain and share knowledge in a collaborative fashion. **[100% networking]**

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5 Way Forward

Section 4 indicates the topics that have commonalities and shared priority between the WMOs and are therefore good candidates for future research effort and funds. However, it is important to note that this is not an exhaustive list of RD&D topics requiring attention from WMOs, as each WMO will undoubtedly have additional research topics of national importance. Nonetheless, the list remains rather long, and consequently it was considered useful to sort the topic list by their relative priorities.

To inform the process of identifying the highest-priority topics, a prioritisation exercise was carried out to gather feedback from WMOs. In this exercise, WMOs were asked to identify the importance and urgency of each research topic listed in this SRA to their national waste disposal programme by assigning each topic a score using the following scales:

- Urgency: <5 years, <10 years and <20 years.
- Importance: 1 to 5, where 1 indicates the greatest importance and 5 the least.

Further explanation about these scales is given below.

Urgency

Urgency was recorded in three categories: <5 years, <10 years and <20 years. These categories relate to the length of time until a particular WMO needs the results of the research on that topic to support their own national programme - progress of individual waste management programmes towards the implementation of geological disposal supports achievement of Vision 2040.

It is recognised that each WMO is at a different stage in their implementation of geological disposal and, therefore, a given research topic may be considered more or less urgent by a WMO with a more advanced programme. For example, the same research topic, while important, may not be required for some decades by a WMO at an earlier implementation stage (see Figure 3.3).

Importance

The importance score is used to reflect how significant a given research topic is to the achievement of each WMO's programme. This is distinguished from the Urgency score in that a research topic may be key to successful delivery of a disposal programme, but the research may not be urgent if the programme is at an early stage.

Importance is recorded on a scale of 1 to 5, where 1 indicates the greatest importance and 5 the least. For example, a score of 1 would indicate a research issue that is fundamental to a key safety case argument, whereas a score of 5 would be assigned to a research topic that is irrelevant to the WMO (e.g. research specific to salt environments when the WMO does not have such an environment).

It is important to note that some research topics may now be of less importance to advanced programmes because they have judged, for their programme, that they have sufficient information to make a safety case. Therefore, it is no longer regarded as important as previously to implementation, but improvements in the field would still be monitored.

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Results of prioritisation

Analysis of the results of the prioritisation exercise allowed the identification of topics that were consistently voted most urgent and/or important, and gave a preliminary indication of the relative priorities of topics in relation to one another. This information was used to support the review at the IGD-TP Executive Group meeting in February 2020, where the indicative prioritisation order was presented and discussed. Amongst the topics with the highest priorities, three groups were identified:

- Topics with the highest priority, which had been voted the most important and the most urgent:

Topic	Description	"Action" category
Topic 1.3	Increase confidence in and further refinement of methods to undertake sensitivity and uncertainty analyses, and address flexibility and adaptability of the repository and evolution of safety requirements and regulations.	20% R&D 80% networking
Topic 2.6	Methods for determining the inventory of long-lived radionuclides and chemotoxic materials with high impact on the safety of final repositories for low and intermediate-level waste from nuclear power plants.	40% R&D 60% networking
Topic 3.3	Repository layout design including operational safety studies.	100% networking
Topic 3.6	Performance of seals and plugs.	80% R&D 20% networking
Topic 3.11	Repository-induced gas generation impacts and their mitigation.	60% R&D 40% networking
Topic 6.4	Data management.	20% R&D 80% networking
Topic 8.4	Retrievability and reversibility.	10% D&D 90% networking

- Topics outside the "highest priority" category, but which were still considered of high importance by most WMOs:

Topic	Description	"Action" category
Topic 1.7	Verification and validation of models for the simulation of the transport of radionuclides in the near-field of deep geological repositories.	50% R&D 50% networking
Topic 3.2	Industrial-scale operations for buffer and backfill.	80% D&D 20% networking
Topic 3.10	Container materials and their long-term performance.	50% R&D 50% networking
Topic 3.12	Remaining issues on bentonite performance and properties	60% R&D 40% networking

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- A second group of topics which did not have the highest priority, but still scored highly:

Topic	Description	"Action" category
Topic 1.1	Increase confidence in, and testing and further refinement of the tools (concepts, definition of scenarios and computer codes) used in safety assessments.	30% R&D 70% networking
Topic 1.6	Long-term geological evolution and its potential impact on the repository.	50% R&D 50% networking
Topic 2.2	Improved data and understanding of the release of radionuclides and chemical species from various long-lived ILW, including effects of organic materials with complexing ability.	80% R&D 20% networking
Topic 3.5	Full-scale demonstrations of plugging and sealing.	80% D&D 20% networking
Topic 4.1	Improved methodologies for developing strategies and approaches for adaptation and optimisation.	100% networking
Topic 4.2	Thermal dimensioning of the repository.	80% R&D 20% networking
Topic 6.1	Monitoring strategy.	100% networking
Topic 7.1	Exploration methods for site characterisation.	40% R&D 60% networking
Topic 7.2	Confirmation of rock properties.	80% D&D 20% networking
Topic 8.5	Costing.	100% networking

Implications for the future

To make use of the results from the prioritisation exercise, it may be useful to note the "action" categories (namely R&D, D&D and networking, as described in Section 3.4.1) assigned to the topics in the highest priority lists. Topics that have a large portion of R&D are typical of those that the IGD-TP would propose as possible international collaborative research projects (e.g. within the European Joint Programme EURAD). Those topics with a high D&D proportion are likely to be suited to projects involving testing in underground laboratories or full-scale demonstrators. Finally, the topics that are more orientated towards networking are typical of those that will be further developed and addressed by the IGD-TP WMO members through meetings, workshops and exchange of information.

It is important to note that the range of high-priority topics covers all three pillars of the 2040 Vision (discussed previously in Section 2). As a result, continued progress in the research areas outlined in this SRA will act in support of WMOs at all different stages of development, which individually emphasise different elements of the 2040 Vision.

Finally, it should be noted that this prioritisation exercise reveals a snapshot at the time of writing of the priorities of the European WMOs. Continued national and international RD&D work and the evolution of WMOs towards different stages of GDF implementation can strongly influence the results of such a prioritisation exercise. Therefore, the prioritised list of topics

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presented in this document provides a broad picture of the topics that should be prioritised in the short-term, but it should not be considered a fixed list for the longer-term (i.e. the next 10 years).

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6 Conclusions

In the decade since its inception, the IGD-TP has become a well-established voice for the common RD&D needs of the member WMOs. The achievements that have contributed to being on course for achieving Vision 2025 and the development of the subsequent Vision 2040 as set out in this document, in tandem with the updated review of research needs across European WMOs, demonstrates how the RD&D programmes of WMOs at all stages of GDF implementation have matured and progressed over this time.

The IGD-TP has striven for greater inclusivity of all national waste management implementing organisations in its Vision 2040 and updated SRA; it is hoped that this will encourage a balanced allocation of resources and promote collaboration and knowledge transfer within the geological disposal community. This has been pursued in a number of ways. The scope of Vision 2040 has been widened to be more inclusive of WMOs at varying stages of GDF implementation, encompassing advanced and early-stage programmes, and those in between. The needs of ERDO-WG/SIMS are also represented in the updated SRA, which now contains several research topics brought forward by them. WMOs involved in EURAD have also been consulted during development of the SRA to be as representative as possible of all European WMOs, irrespective of whether they are currently members of the IGD-TP. Additionally, whilst the IGD-TP has historically had a strong focus on Europe, it now supports international collaboration beyond these boundaries, in recent years having welcomed participants from Canada and the USA.

The IGD-TP is a key instrument in ensuring continuity throughout the long timescales over which development, operation and closure of a GDF takes place, in terms of scientific and technological advancements and knowledge transfer of good practice and lessons learned within the community. The IGD-TP recognises that in a changing nuclear landscape it needs a strong focus to achieve this, and to ensure that expertise and facilities are state-of-the-art.

The challenging nuclear landscape, including an ageing workforce and stagnating or slowly-developing nuclear energy programmes and/or nuclear phase-out policies, means that the back-end of the nuclear energy production system needs to be managed in a way which takes advantage of the knowledge and resources currently available, but without judgement or expectation of what the nuclear landscape will look like in the future. Therefore, the IGD-TP provides a strong implementer voice and collaborative action to ensure necessary expertise and facilities are maintained and are state-of-the-art.

Vision 2040 and this update of the SRA are intended to guide the focus of activities and resource allocation over the next decade by highlighting the research areas that are of common interest to multiple European WMOs. The IGD-TP has a strong implementer focus with RD&D activities undertaken on a needs-driven basis. As such, the IGD-TP, and its member WMOs, carefully ensure that any RD&D undertaken contributes to the implementation of waste management solutions, that resources are mobilised only where needed and that those resources are efficiently applied. As such, the IGD-TP looks to ensure the most appropriate vehicles are used to achieve the identified research activities. The IGD-TP is committed to supporting EURAD and recognises its potential as an instrument to help realise Vision 2040 and identified R&D needs. The IGD-TP also monitors the activities of and collaborates with many other platforms, including the NEA (Salt/Clay/Crystalline Clubs, IGSC), IAEA, ERDO and Nugenia, to name but a few, to avoid duplication and identify synergies. In addition, the IGD-TP

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facilitates collaboration between WMO members to ensure that all other R&D, D&D and networking/information exchange needs are met.

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Appendix A
SRA Working Group

This SRA has been produced by the following SRA Working Group, with representatives from some of the IGD-TP's member WMOs:

ANDRA, France:	Frédéric Plas
BGE, Germany:	Astrid Göbel
COVRA, The Netherlands:	Marja Vuorio
Nagra, Switzerland:	Irina Gaus
ONDRAF/NIRAS, Belgium:	Maarten van Geet
SURAO, Czech Republic:	Antonín Vokál
SKB, Sweden:	Ella Ekeroth and Patrik Vidstrand
Secretariat:	Tamara Baldwin and Sally Scourfield (Galson Sciences Ltd), and Lawrence Johnson (L.H. Johnson Consulting)

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Appendix B
Key WMO Publications

There has been considerable progress achieved since publication of the last SRA in 2011. This appendix provides a short list, organised by WMO, of key publications delivered over the last 5-10 years, including the latest safety cases and RD&D plans. The most recent information can be found on the dedicated WMO websites listed in each sub-section.

B.1 Andra (France)

Website: international.andra.fr

Andra. (2015). *Dossier d'options de sûreté - Partie exploitation (DOS-Expl).* Note technique n° CG-TE-D-NTE-AMOA SR1-0000-15-0060. Cigéo safety options file.

Andra. (2015). *Dossier d'options de sûreté - Partie après fermeture (DOS-AFl).* Note technique n° CG-TE-D-NTE-AMOA-SR2-0000-15-0062. Cigéo safety options file.

Andra (2016). *Agence Internationale de l'Énergie Atomique - Revue Internationale par les pairs sur le Dossier d'Options de Sûreté du projet de stockage de déchets radioactifs en couche géologique profonde : Cigéo*. Rapport de la revue par les pairs, Novembre 2016. Cigéo safety options file - IAEA international peer review.

ASN (2018). *Avis n° 2018-AV-0300 de l'ASN du 11 janvier 2018 relatif au dossier d'options de sûreté présenté par l'Andra pour le projet Cigéo de stockage de déchets radioactifs en couche géologique profonde.* Cigéo safety options file - opinion of French Safety Authority.

ANDRA (2014). *Dossier D'Options Techniques de Récupérabilité (DORec)*, ANDRA Report CG-TE-D-NTE-AMOA-RV0-0000-15-0059-A DOREC, 8 April 2016.

B.2 ARAO (Slovenia)

Website: www.arao.si

ARAO (2005). *Overview of Geological Data for Deep Repository for Radioactive Waste in Argillaceous Formations in Slovenia*. GeoZS – Geological Survey of Slovenia, Ljubljana, 2005.

ARAO (2007). *Geological data and the preliminary catalogue of argillaceous formations for geological disposal of radioactive waste*. GeoZS – Geological Survey of Slovenia, Ljubljana, 2007.

ARAO (2009). *Preliminary Stage of Performance and Safety Assessment of the Reference Scenario of Geological Disposal in Hard Rock.* Internal report for the ARAO, GeoZS, ZAG, 2009.

ARAO (2012). *Criticality safety analysis of the NPP Krško spent fuel in the disposal facility at nominal conditions.* IJS, IJS-DP-10839, 2012.

ARAO (2019). *Reference Scenario for Geological Disposal Facility in Hard Rock with Cost Estimation for its Implementation.* IBE February 2019.

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B.3 BGE/BMWi (Germany)

Website: www.bge.de and www.bmwi.de

N. Semioshkina, Ch. Staudt, Ch. Kaiser, G. Pröhl, Ch. Fahrenholz, U. Noseck (2012). *Consideration of Climate Changes in Biosphere Modelling for Performance Assessment.* (BMWi FKZ 02 E 10548), Bericht GRS-299, GRS Braunschweig, 2012.

J. Krone, W. Bollingerfehr, W. Filbert, S. Keller, A. Lommerzheim, J. Mönig, S. Mrugalla, N. Müller-Hoeppe, J. Weber and J. Wolf (2013). *Status of the safety concept and safety demonstration for an HLW repository in salt.* Summary Report, DBE TECHNOLOGY GmbH, BGR, GRS.

W. Bollingerfehr, N. Bertrams, D. Buhmann, R. Eickemeier, S. Fahland, W. Filbert, J. Hammer, J. Kindlein, M. Knauth, T. Kühnlenz, W. Liu, W. Minkley, J. Mönig, T. Popp, S. Prignitz, K. Reinhold, E. Simo, E. Volkner and J. Wolf (2018). *Concept developments for a generic repository for heat-generating waste in bedded salt formations in Germany*. Projekt KOSINA, Synthesis Report. BGE Technology GmbH, FKZ 02E11405A, FKZ 02E11405B, FKZ 02E11405C, FKZ 02E11395, Peine.

U. Noseck, V. Brendler, S. Britz, M. Stockmann, J. Fricke, C. Richter, M. Lampe, A. Gehrke, J. Flügge (2018). *Smart Kd-concept for long-term safety assessments. Ex-tension towards more complex applications*. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, FKZ 02 E 11102 (BMWi), GRS-500.

U. Noseck, D. Becker, Th. Brasser, D. Buhmann, Ch. Fahrenholz, J. Flügge, K-P. Kröhn, A. Meleshyn, J. Mönig, H. Moog, A. Rübel, S. Spießl and J. Wolf (2018). *Scientific Basis for a Safety Case of Deep Geological Repositories.* Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, FKZ 02 E 11102 (BMWi), GRS-501, Braunschweig 2018.

B.4 Chornobyl R&D Institute (Ukraine)

Website: www.chornobyl.institute

B.5 COVRA (Netherlands)

Website: www.covra.nl

The Netherlands Ministry for Infrastructure and the Environment (2016). *The national programme for the management of radioactive waste and spent fuel*. June 2016.

J. Hart, J. Prij, T. J. Schröder, G.-J. Vis, D.-A. Becker, J. Wolf, U. Noseck and D. Buhmann (2015). *OPERA Evaluation of current knowledge for building the Safety Case for salt-based repositories* (OPERA-PU-NRG221B).

E. Verhoef, E. Neeft, N. Chapman & C. McCombie (2017). *OPERA Safety Case*. Nieuwdorp: COVRA N.V.

E. V. Verhoef, E. A. C. Neeft, J. Bartol, M. Vuorio, C. Scholten, A. Buitenhuis, G. van der Veen, N. A. Chapman and C. McCombie (2020, to be published). *Long-term research programme for geological disposal of radioactive waste*. Nieuwdorp: COVRA N.V.

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B.6 DEKOM (Denmark)

Website: www.dekom.dk

B.7 EEAE (Greece)

Website: www.eeae.gr

B.8 ENEA (Italy)

Website: www.enea.it/en

B.9 ENRESA (Spain)

Website: www.enresa.es

J. Cobos, N. Rodríaguez-Villagra, L.J. Bonales, J.M. Elorrieta, L. Gutiérrez, J. Nieto, S. Fernández, J.M. Cobo, L. Serrano, S. Duran, S. Royuela, A. Cazaña and J. Alcaide (2017). *Informe final de proyecto del anexo XXXVIII al acuerdo marco CIEMAT-ENRESA "Aplicación de técnicas de caracterización en el estudio de la estabilidad del combustible nuclear irradiado en condiciones de almacenamiento (ACESCO)*". Código: DFN/RA-11/IF-17 rev. 0. 17-dic.-2017, 121pp.

Enresa (2020). *Diseño e ingeniería del Almacenamiento Geológico Profundo (AGP) Arcilla, Actualización.* Informe de Enresa. In revision.

Enresa (2020). *Evaluación del Comportamiento del Almacenamiento Geológico Profundo (AGP) Arcilla, Actualización.* Informe de Enresa. In preparation.

B.10 Fond-NEK (Croatia)

Website: www.fond-nek.hr/en

B.11 IAE (Lithuania)

Website: www.iae.lt

B.12 IST (Portugal)

Website: www.ctn.tecnico.ulisboa.pt

B.13 Nagra (Switzerland)

Website: www.nagra.ch/en

Nagra (2014). *SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. Sicherheitstechnischer Bericht zu SGT Etappe 2. Sicherheitstechnischer Vergleich und Vorschlag der in Etappe 3 weiter zu untersuchenden geologischen Standortgebiete.* Technischer Bericht NTB 14-01.

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Nagra (2015). *Implementation of the Full-scale Emplacement Experiment at Mont Terri: Design, Construction and Preliminary Results.* Technical Report NTB 15-02.

Nagra (2016). *Production, consumption and transport of gases in deep geological repositories according to the Swiss disposal concept.* Technical Report NTB 16-03.

Nagra (2016). *The Nagra Research, Development and Demonstration (RD&D) Plan for the Disposal of Radioactive Waste in Switzerland.* Technical Report NTB 16-02.

Nagra (2016). *Entsorgungsprogramm 2016 der Entsorgungspflichtigen.* Technischer Bericht NTB 16-01.

B.14 NES (Austria)

Website: **www.nes.at**

B.15 NFJ (Slovakia)

Website: **www.njf.sk**

B.16 NND and IFE (Norway)

Website: **www.norskdekommisjonering.no** and **ife.no/en**

A. Ikonen, J. Engelhardt, T. Fischer, A. Gardemeister, S. Karvonen, P. Keto, K. Rasilainen, T. Saanio and T. Wanne (2020). *Technical Report: Concept Description for Norwegian National Disposal Facility for Radioactive Waste*, AINS Group on behalf of NND, 22 June 2020. https://www.norskdekommisjonering.no/wp-content/uploads/2020/06/Technical-report-Concept-Description-for-Norwegian-National-Disposal-Facility-for-Radioactive-Waste.pdf

H. Loukusa and H. Nordman (2020). *Technical Report: Feasibility of KBS-3 spent fuel disposal concept for Norwegian fuel*, AINS Group on behalf of NND, 25 May 2020. https://www.norskdekommisjonering.no/wp-content/uploads/2020/06/Technical-report-Feasability-of-KBS-3-spent-fuel-disposal-concept-for-Norwegian-fuel-20200615.pdf

NND (2020). *Begrenset konseptvalgutredning om behandling av norsk brukt reaktorbrensel*, NND. https://www.norskdekommisjonering.no/wp-content/uploads/2020/06/Begrenset-konseptvalgutredning-om-behandling-av-norsk-brukt-reaktorbrensel.pdf (Conceptual study on pre-disposal treatment options for Norwegian spent fuel, in Norwegian).

B.17 ONDRAF/NIRAS (Belgium)

Website: **www.ondraf.be**

ONDRAF/NIRAS (2013). *Research, Development and Demonstration Plan for the geological disposal of high-level and/or long-lived radioactive waste including irradiated spent fuel if considered as waste.* Technical report NIROND-TR 2013-12E.

A. Dizier, G. Chen, X.L. Li and J. Rypens (2017). *The PRACLAY Heater Test After Two Years of the Stationary Phase.* EURIDICE Report EUR-17-043.

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