Deliverable 1.7: EURAD Roadmap, extended with Competence Matrix

Work Package 1

This project has received funding from the European Union's Horizon 2020 research and innovation programme 2014-2018 under grant agreement N°847593.

Document information

Project Acronym	**EURAD**
Project Title	**European Joint Programme on Radioactive Waste Management**
Project Type	**European Joint Programme (EJP)**
EC grant agreement No.	**847593**
Project starting / end date	**1st June 2019 – 30 May 2024**
Work Package No.	**1**
Work Package Title	**Programme Management Office**
Work Package Acronym	**PMO**
Deliverable No.	**1.7**
Deliverable Title	**EURAD Roadmap, extended with Competence Matrix**
Lead Beneficiary	**Andra**
Contractual Delivery Date	**M12**
Actual Delivery Date	**September 2021**
Type	**Report**
Dissemination level	**PU**
Authors	**Tara BEATTIE (TB Environmental), Johan ANDERSSON (Jabia AB), Christophe BRUGGEMAN (SCK-CEN), Neil CHAPMAN (Neil Chapman Consulting), Bernd GRAMBOW (CNRS), Tobias KNUUTI (BGE), Louise THEODON (Andra), Piet ZUIDEMA (Zuidema Consult GmbH)**

To be cited as:

(2021): EURAD Roadmap, extended with Competence Matrix. Final version as of 27.09.2021 deliverable D1.7 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

Disclaimer

Acknowledgement

This document is a deliverable of the European Joint Programme on Radioactive Waste Management (EURAD). EURAD has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 847593.

Status of deliverable		
	By	Date
Delivered (Lead Beneficiary)	Andra	16/08/2021
Verified (WP Leader)	Andra	16/08/2021
Reviewed (Reviewers)	BGE	24/08/2021
Revised (PMO)	Andra	26/08/2021
Approved[1]	Bureau	20/09/2021
Submitted to EC (Coordinator)	Andra (Coordinator)	28/09/2021

[1] This deliverable did not undergo a formal College review, but it has been approved by the Bureau members.

Executive Summary

A Roadmap, with clear objectives, linking EURAD activities (as listed in the strategic research agenda (SRA)) to milestones typical of different phases of a radioactive waste management (RWM) programme has been developed. It is based upon the IAEA phases for implementation of a deep geological repository [1]:

- Phase 1: Policy, framework and programme establishment;
- Phase 2: Site evaluation and site selection;
- Phase 3: Site characterisation;
- Phase 4: Facility construction;
- Phase 5: Facility operation and closure;

For each of the phases above, the EURAD Roadmap explains how aspects related to disposal facility design and safety case development (and supporting safety analyses) span across all phases, including Phase 1. The Roadmap elaborates further on the how the emphasis of work on each of these differs and changes through successive Phases.

The Roadmap is organised in a goals breakdown structure (GBS), to contextualise the scope of EURAD and its relevance to radioactive waste management and geological disposal programmes at different stages of maturity. The GBS effectively provides a framework upon which to organise the scientific priorities of the SRA, enabling users and programmes to 'click-in', and to access existing knowledge and active work or future plans. It also provides a framework for future periodic assessment of EURAD, and to evaluate future priorities and new work packages as new knowledge is acquired or as new needs are identified.

The Roadmap GBS will be used throughout EURAD as a tool to support the management of the SRA in reviewing progress, to support prioritisation of new scope suggestions (importance and urgency) and to communicate completed, ongoing and future work activities to those interested in our work.

This deliverable (D1.7) is a re-issue (Issue 2) of the EURAD Roadmap GBS, to capture developments since its previous publication at the start of EURAD. It also captures a summary of capability requirements extracted from Roadmap Theme Overview Documents, providing a perspective in time of capability needed in each Theme of the Roadmap.

Please note that contrary to the request by the EC for the SRA to be translated into a roadmap, with clear objectives, deliverables and high-level milestones for technical solutions per waste streams and waste types, we have intentionally avoided this. Rather we have utilised a work break down structure using domains and IAEA phases (focussed on geological disposal) that combines domains of RD&D relevant to many waste streams and technical solutions. Technical solutions need to be tailored and developed for the specific needs of a national waste management programme, particularly taking account of the waste characteristics and the options for siting. There is no one size fits all technical solution for each waste stream, choices on this remain the responsibility of the national waste management programme.

Table of content

Overview of the EURAD Roadmap GBS (Issue 2, September 2021)

This is issue 2 of the EURAD Roadmap goals breakdown structure (GBS). It comprises a hierarchy of generic radioactive waste management (RWM) programme goals and, in combination with the IAEA typical phases of implementing a deep geological repository programme[2] [1], is the framework upon which the EURAD Roadmap is organised. The GBS is the focus of this EURAD deliverable (D1.7). The intent is to use this GBS and roadmap structure as the basis for the developing EURAD Knowledge Management and Networking Programme [2]. A separate EURAD Roadmap Guide [3] is also available that provides a more in-depth view of how the roadmap has been used to capture experience and knowledge in each of the themes of the roadmap, see Roadmap Theme Overview Documents [4, 5, 6, 7, 8, 9, 10]. The guide also describes how the roadmap will continue to be populated with state-of-knowledge documents, guidance and training during the remainder of EURAD.

The intention of the EURAD roadmap is to provide information and guidance to three primary user groups:

- organisations that are developing or updating their national RWM programmes with the objective of moving towards deep geological disposal of some of their wastes and requiring information on the steps and the activities in which they are likely to become involved;
- organisations with advanced RWM and DGR programmes that require an informative training tool for new staff and a means of propagating knowledge across the groups involved in diverse activities;
- all organisations concerned with identifying potential future gaps in capabilities that could hinder implementation of their DGR programmes in decades to come.

The intended purpose of the EURAD Roadmap is to provide a high-level checklist of generic and typical RWM programme activities and signposts to existing knowledge, both based on learning from advanced programmes and people that have done it before. It should not be considered complete and should not be understood to mean that by using this roadmap, a national programme could be certain of meeting national or international RWM or DGR legal requirements. The extended roadmap competence matrix identifies capability needs in non-technical fields (for example, programme management, inventory management, legislation and regulation). However, it should be noted that EURAD activities are primarily focussed on scientific and technical domains identified in the EURAD roadmap.

The content of the roadmap is currently organised in documents (which possibly in the future will be migrated and integrated into a knowledge management system, e.g., a wiki). These documents are organised and scope is bound in a modular structure according to the EURAD Roadmap GBS. The GBS is worded in a directional style, i.e., do this, do that. Each goal is a 'call to action' with an implicit set of competence requirements associated. To supplement these generic goals and implicit competence requirements, a summary of programme capability needs is also supplied, extracting content from each Roadmap Theme Overview Document [4, 5, 6, 7, 8, 9, 10].

As the EURAD Roadmap evolves and more RWM experts contribute to its population, it may be subject to further iteration and changes. These changes will be captured and periodically reported via an update and re-issue of the Roadmap GBS via this document (D1.7).

Note: Tables 1-7 below contain the EURAD Roadmap GBS – these are printable on size A4. Table 8 contains the summary of theme capabilities and outlook – this is printable on size A3.

[2] Typical phases of implementing a deep geological repository programme: 1. Initiation: Policy, framework, and programme establishment; 2. Site(s) identification and selection; 3. Site characterisation; 4. Facility construction; 5. Facility operation and closure. Note that phases are not necessarily discrete but often overlap and are typically iterative (i.e., not simply sequential), and can differ from country to country.

Theme 1 Goals Breakdown Structure: National Programme Management (Level 1)	
1. Implement a national programme for the management of spent fuel and radioactive waste, covering all types of spent fuel and radioactive waste under its jurisdiction and all stages of spent fuel and radioactive waste management from generation to disposal (National Programme Mgt.)	
Sub-themes (Level 2)	**Domains (Level 3)**
1.1 Establish the national policy and plan for radioactive waste and spent fuel management activities, from generation to disposal (Programme Planning)	1.1.1 Establish and maintain a national plan for radioactive waste management, including a nuclear fuel cycle strategy (e.g., open or closed cycle) for those countries with, or intending to use, nuclear power (National RWM Policy).
	1.1.2 Develop and maintain broad timescales and schedule for implementing radioactive waste management activities using a stepwise decision-making process (Timetable for decision making)
	1.1.3 Ensure that public information on radioactive waste and spent fuel and a process for public participation are available (Public information and participation)
	1.1.4 Establish a process for progressive development and optimization of the plan (safety, security, use of resources)
1.2 Establish and maintain a national regulatory and organisational framework for the timely implementation of all steps of spent fuel and radioactive waste management, from generation to disposal (Programme Organisation)	1.2.1 Establish and maintain a competent and independent regulatory body and system for licensing (Licensing framework)
	1.2.2 Establish regulatory criteria for waste management facilities, based on international standards (Licensing criteria)
	1.2.3 Establish and maintain organizational structures or license holder(s) having overall clear responsibility for any activity or facility related to the management of spent fuel and radioactive waste (Allocate responsibilities)
	1.2.4 Implement a system of appropriate oversight, a management system, regulatory inspections, documentation, and reporting obligations for radioactive waste and spent fuel management activities (Waste management System)
	1.2.5 Establish and implement a research, development and demonstration strategy with activities clearly related to timeframes, concepts, plans, and milestones defined in the national programme (RD&D Strategy)
1.3 Ensure that adequate financial and human resources (core capability and supply chain support) are available, and can be adapted to the changing needs of the programme over many tens of years, from generation to disposal (Programme Resources)	1.3.1 Specify a funding mechanism to ensure that adequate financial resources are available when needed for the implementation of the national radioactive waste programme (Financing Scheme)
	1.3.2 Develop and maintain a technical and management skill base within the programme (core capability), meeting national regulatory competence requirements (Skills and Competence Management)
	1.3.3 Use the knowledge, technology and experience gained internationally and co-develop RD+D where possible to improve and consolidate confidence in the scientific and technical data base, to help reduce risks to successful programme implementation and to avoid unnecessary costs (International Cooperation)
	1.3.4 Work collaboratively with delivery and specialist organisations nationally and internationally to obtain value for money (Procurement & Supply Chain Arrangements)

1.4 Establish and maintain a national inventory of radioactive wastes (National inventory)	1.4.1 Develop and maintain an inventory of all spent fuel and radioactive wastes from all sources and activities, together with estimates for future quantities arising, including the characteristics, location, ownership (responsible organisation) and amounts, in accordance with an appropriate classification scheme (National radioactive waste inventory)
1.5 Identify and select appropriate disposal routes and concepts for the national radioactive waste inventory (Management Solutions)	1.5.1 Identify and evaluate potentially available concepts and technical solutions for spent fuel and radioactive waste management, taking account of national or local conditions, such as available predisposal and storage options, geological environments, national technical and economic resources and expertise etc. (Integrated waste management routes and strategic options)
	1.5.2 Perform iterative evaluation of options and concepts at each stage of programme development taking account of international technological advances (Options and Concept selection)

Theme 2 Goals Breakdown Structure: Pre-disposal (Level 1)	
2. In conjunction with waste generators, identify and deliver solutions to optimise the management of radioactive waste throughout the predisposal phases of the radioactive waste management programme (Predisposal)	
Sub-themes (Level 2)	**Domains (Level 3)**
2.1 Planning predisposal management of radioactive waste in close cooperation with waste generators (Planning)	2.1.1 Evaluate waste inventory from generators and existing storages, accounting for future waste generation and evolution (Inventory)
	2.1.2 Identify parameters and metrics for waste acceptance criteria through whole life cycle (Waste Acceptance Criteria)
	2.1.3 Assess potential technologies for the implementation phase, considering cost-benefit ratio and availability (Technology Selection)
	2.1.4 Evaluate options to apply the waste hierarchy to minimise waste volumes at higher impact inventory disposal levels (Waste Hierarchy)
2.2 Implementing predisposal management of radioactive waste to support key risk and hazard reduction, and to help reduce costs and save space at interim storage and disposal facilities (Implementation)	2.2.1 Sort, characterise, classify and quantify radioactive waste in accordance with requirements established or approved by the regulatory body (Characterisation)
	2.2.2 Minimise the quantity and volume of radioactive waste through pre-treatment and treatment (Treatment & Processing)
	2.2.3 Stabilise waste by conditioning prior to long-term storage (Conditioning)
	2.2.4 Package waste accounting for future transport and deposition, and maintain safe interim storage of packages (Storage)
	2.2.5 Transport radioactive wastes between facilities in accordance with regulatory requirements (Transport)
2.2 Enhancing predisposal operations through iteration with waste generators and repository operators, to develop and deliver safe and cost-effective solutions (Optimisation)	2.3.1 Implement quality system and management system to ensure accurate detailed records of waste and package characteristics over their lifetime, from production until deposition (Quality & Management Systems)
	2.3.2 Evaluate potential for improving and optimising implementation phases with new technologies, to improve costs and environmental impact while maintaining safety and accounting for potential accident scenarios (Optimisation)
	2.3.3 Manage secondary waste streams produced during initial processing, for lifecycle approach (Secondary Waste Management)

Theme 3 Goals Breakdown Structure: Engineered Barrier Systems (Level 1)	
3. Develop an engineered barrier system, tailored to the characteristics of the waste and compatible with the natural (geological) barrier, that performs its desired functions for the long-term disposal of radioactive waste (EBS)	
Sub-themes (Level 2)	**Domains (Level 3)**
3.1 Confirm wasteform compositions, properties and behaviour under storage and disposal conditions, including radionuclide immobilisation and impact on the disposal environment (Wasteforms)	3.1.1 Spent nuclear fuel (SNF)
	3.1.2 Vitrified HLW (HLW)
	3.1.3 Cemented LL-ILW (Cemented LL-ILW)
	3.1.4 Bituminized waste, ceramics, polymers (Other wasteforms)
3.2 Identify container materials and designs for each wasteform under storage and disposal conditions and confirm properties, behaviour and evolution under storage and disposal conditions (Waste packages, for disposal)	3.2.1 HLW and SF containers (HLW and SF Containers)
	3.2.2 LL-ILW containers (LL-ILW Containers)
	3.2.3 Containers using advanced materials (Novel Containers)
3.3 Identify appropriate buffer, backfill and seal/plug materials and designs, and confirm their properties, behaviour and evolution for the selected repository concept (Buffers, backfills, plugs and seals)	3.3.1 Buffer components under storage and disposal conditions (Buffers)
	3.3.2 Backfill components under storage and disposal conditions (Backfills)
	3.3.3 Plug and sealing components under storage and disposal conditions (Plugs and seals)
3.4 Confirm integrated EBS system understanding and identify compatible EBS designs and materials for facilities containing multiple wasteforms (EBS system integration)	3.4.1 Confirm complete and integrated EBS system understanding, including the design of an optimized interface EBS/repository and the understanding of the interaction with the repository nearfield environment (EBS system)
	3.4.2 Confirm that interactions between different EBS materials in disposal areas for different waste types do not compromise the performance of the disposal system (Co-disposal)

Theme 4 Goals Breakdown Structure: Geoscience (Level 1)	
4. Assemble geological information for site selection, facility design and demonstration of safety (Geoscience)	
Sub-themes (Level 2)	**Domains (Level 3)**
4.1 Provide, or confirm a description of the natural barrier and how it contributes to high level safety objectives (Site description)	4.1.1 Develop a model of the host rock and surrounding geological environment, including distributions of rock types, geometry and properties of structural features, geotechnical properties and the hydrogeological and hydrogeochemical environment (Site descriptive model)
	4.1.2 Describe bedrock transport properties (aqueous and gas transport, advection/dispersion, diffusion) including retention (sorption, matrix diffusion) of different geological materials
	4.1.3 Characterize or confirm surface ecosystem properties and their potential evolution in the future (Biosphere model, also part of 4.3)
4.2 Characterize the potential impact of disposal facility construction, operation and closure on the natural geological barrier (Perturbations)	4.2.1 Characterize or confirm the chemical, hydrogeological, geomechanical, thermal, geomicrobiological, gaseous and radiation-induced perturbations which may be caused by facility construction, operations or closure and their impacts on long-term disposal system evolution (Perturbations).
4.3 Provide, or confirm a description of the expected evolution of the geosphere (including the repository) in response to natural processes and future human actions (Long-term stability)	4.3.1 Assess the expected geological and tectonic evolution and the potential for natural disruptive events and their impacts on the stability of the natural barrier (Geological and tectonic evolution)
	4.3.2 Assess the nature of future climate change and landscape evolution and its potential impacts on THMC conditions in the repository host rock (including the repository) and surrounding formations (Climate change)
	4.3.3. Assess the effects of future human actions (human intrusion by exploration activities, exploitation of natural resources within, above and below the host rock)
4.4 Provide a geoscientific synthesis (Geosynthesis) with geoscientific key information with respect to long-term safety and repository concepts (layout and construction)	4.4.1 Provide commented tables with key data, key figures (conceptual models) and comments on the interrelationships of site characteristics, perturbations and long-term evolution (stability). This report should contain the so-called Geo-Datasets for long-term safety analyses and repository concepts (layout and construction) for each licensing phase.

Theme 5 Goals Breakdown Structure: Disposal Facility Design and Optimisation (Level 1)	
5. Design a facility that fulfils safety and security requirements and that can be practicably constructed, operated and closed (Disposal Facility Design and Optimisation)	
Sub-themes (Level 2)	**Domains (Level 3)**
5.1 Design and develop a disposal system for the national radioactive waste inventory (Design)	5.1.1 Based on regulatory requirements, safety criteria, and a high-level safety strategy, establish a transparent procedure finally leading to design requirements for the preferred concept option (Design requirements)
	5.1.2 Based on the design requirements, perform layout calculations to define detailed specifications for the design of the underground facilities (Design specifications, facility-scale)
	5.1.3 Based on the design requirements and safety assessments, define detailed specifications for the design of the geotechnical barrier system (Design specifications, component-scale)
	5.1.4 Develop and establish qualification procedures, especially with regard to manufacturing and testing requirements, as well as safety demonstration concepts to confirm that structures, systems and components will perform their allocated safety function(s) in all normal operational, fault and accident conditions identified in the safety case and for the duration of their operational lives (Design qualification)
5.2 Demonstrate and verify that facility components and barriers can be practically manufactured, constructed and installed in accordance with detailed design requirements and specifications (Constructability, demonstration and verification testing)	5.2.1 Develop, adapt and/or buy the technology and systems required to be able to construct and then commission the facility (Pilot-scale, full-scale testing, and active commissioning)
	5.2.2 Perform a continuous balancing exercise with requirements and technical solutions to balance the risks among the different barriers. Keeping in mind that there is no such endeavour with zero risk, determine which risks can be (reasonably) taken and which cannot be. Any balancing need to include a cost assessment (Optimisation)
	5.2.3 Establish reliable manufacturing routes to produce facility barriers and components, and inspections plans for how to test for unacceptable defects, and overall quality assurance against specified design tolerances and industry standards (Manufacture, inspection and testing)
	5.2.4 Utilise available robotics and remote handling technology - all reliably tested beforehand - to optimise facility construction and operations (Robotics)
	5.2.5 As a supplement to in-situ testing (cf. 5.2.1), consider simulating facility operations by using remote technologies and models to predict the most important variables of the disposal system implementation processes (Virtual Reality / Digital Twin)
5.3 Prevent theft of nuclear material or sabotage of	5.3.1 Establish arrangements to ensure that no nuclear material leaves the system and to ensure effective nuclear materials accountancy during transport, operations and closure of the facility, and that such information is suitable for transfer to a future facility operator (Safeguards).

nuclear facilities and protect sensitive technology, software and information (Security and safeguards)	5.3.2 Design and provide physical security measures to ensure compliance with regulatory security arrangements for transport and disposal of radioactive materials (Security and physical protection).
5.4 Develop and maintain operational safety case to demonstrate that the construction, operation and closure of the disposal facility will meet safety standards and be robust against potential faults such that the associated risks are restricted to levels that are as low as reasonably practicable (Operational safety)	5.4.1 Identify construction hazards or risks, and implement measures to eliminate these or provide a means of preventing the outcome, protecting those affected (Construction and Non-Radiological (Construction safety)
	5.4.2 Identify operational hazards or risks, and implement measures to eliminate these or provide a means of preventing the outcome, protecting those affected and reducing the consequences (Normal operations safety)
	5.4.3 Perform design basis accident analysis and optimise with mitigation options for risk reduction for identified faults (Accident safety)
	5.4.4 Demonstrate criticality safety during operations (Criticality safety)
5.5 Establish and implement an overall plan for meeting with national requirements for monitoring, and if required, reversibility and/or retrievability requirements. (Monitoring and Retrievability)	5.5.1 Establish plans and methods for implementing baseline environmental monitoring programme ready for the start of site characterisation (Baseline monitoring)
	5.5.2 Establish plans and methods for implementing a monitoring program to be performed during site investigation, construction and operational phases of the repository (Monitoring with regard to onsite investigation, construction and operations)
	5.5.3 Establish technical feasibility of waste reversal after emplacement and potential waste retrieval after operation and if required, demonstrate in full-scale representative conditions before the start of operations (Retrievability)

Theme 6 Goals Breakdown Structure: Siting and Licensing (Level 1)	
6. Demonstrate to regulators (and other stakeholders, incl. the public) that a properly sited disposal facility will protect people and the environment at the time of disposal and in the very long term, following closure (Siting and licensing)	
Sub-themes (Level 2)	**Domains (Level 3)**
6.1 Establish and implement an overall plan for the site selection process, and identify potential environments using available data (Establish site selection process and site screening)	6.1.1 Identify key decision points, and develop screening guidelines to enable a facility to be located to match national performance criteria and socio-economic, political, and environmental considerations (conceptual planning)
	6.1.2 Identify areas that may contain suitable sites by using the developed screening guidelines (area survey and site screening)
6.2 Investigate one of more sites to demonstrate that they would be suitable from the safety and other viewpoints (Site investigation and confirmation)	6.2.1 Initiate a site(s) investigation programme to obtain sufficient data to give strong assurance that the site(s) is/are likely to be suitable, based on a preliminary Safety assessment, and whether the final stage of site confirmation would be likely to result in a license application (site investigation)
	6.2.2 Undertake detailed site(s) investigation, confirmation of the site, through a complete safety assessment, and preparation of an environmental impact assessment to the level required for construction and operational license application submission (detailed site characterisation and site confirmation)
6.3 Obtain the necessary land use permits and nuclear licences to start implementation of the disposal facility (Permits and licensing)	6.3.1 Engage effectively with local government / regulators / consultative bodies / waste generators and the local population by providing open access to information to meet land use planning requirements (Local land use planning)
	6.3.2 Adhere to the licensing process set by national legislation and regulatory bodies (for nuclear installations) and meet the requirements relating to facility authorization (Regulatory licensing)

Theme 7 Goals Breakdown Structure: Safety Case (Level 1)	
7. Iteratively quantify and demonstrate, the safety of the disposal system and inform strategic design decisions (Safety Case)	
Sub-themes (Level 2)	**Domains (Level 3)**
7.1 Establish the safety fundamentals as a basis for the safety assessment (Safety strategy)	7.1.1 Establish the requirements that must be met to ensure the protection of people and the environment, both now and in the future (Safety requirements)
	7.1.2 Establish safety indicators to complement dose and risk, defined relative to overall safety requirements (Performance indicators)
7.2 Combine experimental and field data with scientific understanding and qualitative observations to construct models of the possible future behaviour of the disposal system (Integration of safety related information)	7.2.1 Maintain and develop a synthesis of all available information relevant to facility safety, required for regulatory compliance, and to guide forward disposal programme activities (Safety case production)
	7.2.2 Establish a system and adopt international good practice for information, data and knowledge management, modelling, transfer, and preservation (Information, Data, and Knowledge management)
7.3 Assess radiation risks and assure adequacy and quality of all the safety related work associated with the facility or activity (Safety Assessment and Tools)	7.3.1 Quantify how the facility and its components behave and evolve to provide continuing safety (Performance assessment and system models)
	7.3.2 Characterise uncertainties and determine their implications for the outcome of the safety assessment (Treatment of uncertainty)
	7.3.3 Evaluate post-closure features, events and processes relevant to safety to create plausible scenarios of disposal system behaviour (Scenario development and FEP analysis)

Table 8 EURAD Roadmap Competence Matrix: Capabilities and Outlook

During 2020/21, population of the extended EURAD roadmap has been initiated through the development of 'Theme Overview' documents. Each document has been authored and peer reviewed by a number of experts who provided their personal view of the current status and outlook for available capability in each theme. A summary of this is provided below (please refer to the individual Theme Overview documents, available on the EURAD roadmap webpages, for the full versions which describe the evolution of skill requirements as a function of the different phases of implementation). In combination with the competence definitions implicit in the goals breakdown structure, the expert views below provide a high-level perspective of competence that is needed and that is available to deliver the goals in each of the themes of the EURAD roadmap. It represents a snapshot in time and is based on the individual experience of the expert authors and reviewers.

Capabilities	**Programme Management (Theme 1)**	**Predisposal (Theme 2)**	**Engineered Barrier Systems (Theme 3)**	**Geoscience (Theme 4)**	**Disposal Facility Design and Optimisation (Theme 5)**	**Siting and Licensing (Theme 6)**	**Safety Case (Theme 7)**
Knowledge and understanding – focussing on competence that should be developed and maintained by national organisations responsible for implementation	The need to respond formally to Directive 2011/70/EURATOM places a responsibility on each Member State (MS) to have the basic elements of a programme in place and to continue with developing an effective RWM programme. All of the core capabilities for establishing a RWM programme exist across the EU and globally, however, some MS may not have all the capabilities required and might require assistance in evolving their programmes. European programmes on RWM began in earnest in the 1970s, almost fifty years ago. This period has seen two generations of experts come and go. It is evident that future DGR development projects, with newly involved experts, might tend to 'reinvent the wheel' if the decision-making deliberations of earlier work have not been adequately recorded. Efforts are required to maintain not only knowledge, but information on how knowledge has been used and how decisions have been made. While much of this critical decision-making involved technical choices (e.g., materials), there is also a need to record and pass on the basis and drivers for strategic decisions over programme options, and the mechanisms used to make them. This is likely to become increasingly demanding as DGR programmes enter routine, multi-decade operations and some of the skills involved in initially implementing them are no longer needed by the operators. As closure approaches, these skills and the thinking behind early decisions on design and post-closure safety will be needed again. Current knowledge management projects are addressing this problem and should be aimed not only at information management and transmission, but also at capturing strategic programme drivers and decision-making experience. This becomes particularly important when experts from outside the field of radioactive waste management are involved in programme development. As an example, economic analysts and advisers are a key component of programme optimisation as planning moves closer to implementation and major investment but they are likely to come from outside the nuclear sector. They need to work along with other experts within a multidisciplinary environment where the key decision, drivers and optimisation trade-offs (between costs, schedule, flexibility, practicality etc.) are widely understood. This requires the propagation of knowledge and past experience throughout a programme team. At present, there is no shortage of advice, experience or management expertise at a European level, although newer radioactive waste management programmes are likely to find gaps at a national level as they improve and integrate their pre-disposal activities and begin to implement disposal solutions. Mechanisms for such programmes to make best use of the available knowledge do, however, need to be developed or improved quite urgently.	Due to the extensive experience of many European Member States with industrial radioactive waste handling and Nuclear Power Plant (NPP) operations for many decades, there is high capability available for predisposal waste management to handle traditional types of wastes. There are experts who are practicing in public and private sector companies in this domain, with availability of new persons with relevant skills continuously entering the market. There is a wide range of guidance documentation available on predisposal methodology, best practices and technologies. The decision for a country or company to invest in their own predisposal management know-how is highly dependent on their inventory size and complexity. The decision to develop in-house (or in-country) technologies, infrastructure and competences for predisposal processing capacity should depend on the cost-benefit ratio.	At an early stage of a national programme, the key focus is mainly to demonstrate feasibility, since no repository is expected to be built for 50 years or more, at least regarding HLW/Spent fuel. It is still important to have an integrated team that can handle the issues of waste characterization, barrier design, transport processes and dose/risk estimates. There is a wealth of information available in these areas from other national programmes, but it is crucial to have domestic competence to be able to adapt local conditions, both when it comes to host rock and politics. At a later stage of a programme, when the focus is on licensing, it may be necessary to bring in competences in more scientific and technical areas into the national programme. At this point, barrier construction, quality control, industrialisation and installation becomes crucial and these areas need to be handled. There may also be a need go more into depth in certain specific areas regarding the long term performance of the barriers. When a programme moves into the construction and operation phase, a whole new set of capabilities will be needed. Science and long-term performance will still be important, but the focus of the programme will be on project management, construction and installation.	Step by step build-up of a core team with experienced individuals covering geology, hydrogeology, hydrogeochemistry and rock mechanics, with hands-on experience in deep geological disposal projects (including a basic understanding of perturbations caused by the repository). If such experience is not available nationally, a group of experienced people from one or more contractors or from sister waste management organisations (WMO) should be built up on the basis of long-term contracts. Different capabilities are needed: oversight and ability to make syntheses, specialists in detailed areas (tectonics/long-term evolution, sedimentology, hydrogeochemistry, field work (geophysics, drilling/sampling /testing), laboratory work etc.). For non-standard geoscientific work it is recommended to buildup and collaborate with so-called competence centres (groups of nationally/internationally recognized scientists with well-developed know-how, working on the basis of long-term contracts or letters of intent (so as to avoid loss of know-how)). A quality assurance system for all measurement, monitoring and characterisation work (including an internal data clearance system) is important. Step by step build-up of a permanent, preferably international, Geoscience Review Board from the beginning is recommended. It is important to point out that assembling geoscientific data and achieving a complete data set without important gaps is only one aspect of the geoscience work. This has to go hand in hand with development of an adequate understanding of all important processes in the geosphere and	At a very early stage, it is essential to get into contact with local and/or regional citizen stakeholders. The implementer should be the one demonstrating that he is honestly willing to communicate, be transparent and to take concerns of regional stakeholders into consideration. Designing the repository may be of regional interest since the design not only covers the underground facilities but also the access routes to the surface and the surface facilities. Communication to the public should be an in-house competence of the implementer since this is the basis for any trust. Development of design layouts of the underground facilities, especially the waste emplacement areas and the engineered barrier system should be an in-house competence of the implementer. Both are main issues with regard to safety demonstration and should be established as a core competence of the implementer. Keeping this as an in-house competence, necessary adaptations or optimizations can be done on a continuous knowledge base, without loss of time, and without any dependencies on third parties. It has to be noted that any changes may affect the long-term evolution. Thus, an update of the safety assessment is obligatory in that case. Thus, a core activity should be the concept development and the performance of large-scale demonstration and verification tests either in an Underground Research Facility (URF) or in designated test areas of the real repository or in a pilot repository.	For the establishment of the siting and licensing programme, special attention must be given to understanding of the special (additional) concerns that have to be addressed when undertaking the rock excavation work. The programme capability should include development of the appropriate safety culture and organisational structure to prepare for when the DGR programme management switches from prospective licensee (up to construction phase) to licensee (in the construction phase and the operational phase) when the programme and facility operations are formally subject to nuclear regulation. During the early phases of siting, when the scientific basis and safety case for the facility are being established, the programme is typically driven by an applied science methodology. Once the programme moves into an industrial phase, with a mature safety case and detailed site-adapted design, the programme becomes implementation driven, with execution aligned to standardized procedures and industrial processes. Site investigations require careful design and differ substantially from standardised geological prospecting activities. Due to the relatively large costs involved, programme management should not consider the investigation activities as "off the shelf" matters that can be requested from many deliveries strictly on a commercial basis. Critical technology capability is (i) data and information management; (ii) non-intrusive data acquisition tools and techniques and (iii) intrusive	For an early-stage national programme with limited resources, the priority is to develop an in-house understanding of all the factors, particularly those that have uncertainties, that could affect the long-term safety of a disposal facility. This understanding is best formulated in terms of the framework of FEPs and safety functions and their interactions. There is much international collaboration on generic methodologies and by gaining an understanding of these approaches, new staff can apply them to their national situation. A thorough understanding of what actually matters in terms of safety is essential for commissioning appropriate work to assist in developing the safety case. This can be summarised as "total system understanding". It often takes most of a career to develop the necessary level of understanding across the required breadth of disciplines to gain the knowledge to author and own a detailed safety case. It is important that younger staff have an appropriate career path to develop these technical skills and that acquiring this level of technical skill is appropriately valued in organisations. There seems to be an unfortunate trend for technical staff to be promoted into project management roles in order to achieve career progression, thus putting this critical "total system understanding" knowledge at risk.

				their interactions and dependencies.		data acquisition tools and techniques.	
Experts, Practical Skills, Infrastructure	- National nuclear legislation and regulation - Planning, implementation and cost estimation for major infrastructure projects - Community and partnership engagement - Professional services (project management, procurement, finance, information technology, human resources) - Radioactive waste inventory management - Value frameworks and strategic decision making at government or regional levels - Strategic overview of national nuclear infrastructure - Nuclear fuel and materials testing - Generic underground research facilities	- Radioactive waste facility management and planning - Waste characterisation - Waste processing - Waste storage and transport	- Waste form characterization - Inventory calculations - Heat transport modelling - Material science - Soil mechanics - Aqueous chemistry - Mineralogy, geochemistry - Microbiology	- Site descriptive modelling - Geology - Hydrogeology - Geochemistry - Groundwater and contaminant transport modelling - Biosphere modelling - Climate change modelling - Hazard assessment - Tectonics and volcanology - Natural earth science	- Design specification - Radiation protection systems and protection procedures for operational safety - Nuclear transport, construction and operational safety and criticality safety - Repository monitoring techniques and planning for monitoring - Large scale design and testing facilities for waste handling equipment - Cyber security - Artificial intelligence and data monitoring	- Nuclear licensing - Environmental permitting - Remote sensing - Surface-based geophysics - Surface mapping and walk-over surveys - Borehole drilling - Downhole geophysical logging - Hydrogeological testing - Groundwater pressure monitoring - Rock, water and gas sampling	- Uncertainty treatment - Scenario evaluation (FEP analysis relevant to the disposal system) -Requirements management (safety functions associated with relevant disposal system components and how they may evolve over time) - Long-term evolution evaluation - Modelling capacity (simplified, analytical “insight” modelling and performance assessment modelling) - Research management - Safety case writing, review and integration
Key capabilities that are accessible from the open market, via third parties, contractors or via technology transfer from other programmes include:	Owing to the advanced nature of a number of European RWM programmes there are established supply chains of competent organisations, both at national levels and internationally, with many contractors supporting programmes worldwide. A new and developing programme is encouraged to make use of its own national expertise (e.g., national surveys and the academic sector) where appropriate, assisted by the many opportunities for experience-building and guidance outlined above. A MS at the early stages of establishing an RWM programme can take advantage of the experience built up over decades in other MSs. While there are multiple opportunities for interacting in shared EU research projects, there is at present no central mechanism for sharing strategic knowledge and assisting programme development in less advanced MSs. This gap needs to be filled. Because all aspects of programme development discussed above are covered in detail in a range of IAEA publications, such a mechanism would form a key resource for less advanced RWM programmes.	Due to years of EU Member States' experience in NPP operation including predisposal waste management, there are numerous mature technologies and services available on the international market. Some countries and companies have been operating predisposal waste management facilities for decades, including interim storage and final disposal or even free release of wastes re-used by other industries. Companies that are offering predisposal waste management can be found by international trade registries, associations such as SNETP and World Nuclear Association, and via their participation at trade fairs on decommissioning and waste management. Within the market offering, it is acknowledged that there are some problematic waste streams, such as graphite materials from reactor decommissioning, which are still at the research and development stage for predisposal processing prior to disposal. The sorting, characterisation, processing and packaging of such types of waste is not market ready.	Universities, national and European research centres as well as scientific companies have expertise in the scientific areas needed for the assessment of the performance of the Engineered Barrier Systems (EBS). The issues of concern regarding the EBS in a DGR may be different than in other areas and the application of the expertise to a specific issue may, however, not always be straightforward. New experimental work, model development and training of staff are very often needed. This means that there needs to be a close cooperation between the national programme and the research entities to ensure that the capacity is available when it is needed. There are certain technical aspects that can easily be dealt with internationally and do not require strong national competence, if not desired for other reasons. This applies to most EBS components, but probably not to EBS concepts.	Expertise in DGR geosciences lies within WMOs, specialist contractors, national geological survey agencies, universities and dedicated RWM centres of excellence. Most of these organisations currently work together on common R&D projects and share ideas and methodologies. Several key skills are also used more widely than in RWM: in mining, environmental analysis, resource exploitation and civil engineering. They do not depend on RWM projects to sustain and advance them. Borehole drilling and logging, surface-based and airborne/satellite geophysical surveying and underground rock engineering are among these skills. At present, the 'peak activity' state of the most advanced DGR programmes combined with general commercial applications means that all the skills necessary for surface-based and underground geoscientific work are available at market level, both within Europe and worldwide.	In principle, the development of technical equipment can be outsourced but the development of the corresponding design requirements and design specifications should be kept in-house as they relate to the safety assessments. Technical equipment for excavation activities in the underground facilities can be taken from the open market of the mining industry. This is also valid for loading and transport equipment for routine mining activities. Technologies for ventilation and fire security are assumed to be mature enough and can thus be taken from the open market. Mine water management systems can be obtained from the open market of the mining industry. The connection to the radiation protection system, especially clearance measurements of mine water, has to be under the responsibility of the implementer.	A cross-functional team of human resources is needed to deliver the siting and licensing programme of a DGR. This can comprise a combination of generalist skills/capabilities on the market, combined with more specialist skills that may need to be developed and maintained by the scientific community to address specific issues where uncertainty exists. A good communication between the safety assessment and the scientific community should be based on a long-lasting cooperation. Procedures for construction and infrastructure can be applied through consultancy services by national and international companies. Close cooperation should be established with geo-technical, -scientific consultants with experience from deep underground investigations, and with experience from repository or research facility construction.	Key capabilities that are accessible from the open market include: Waste container design and manufacture; Design of engineered barriers, including buffer / backfill formulation; Construction and implementation technology; All research activities, including development of 'process' models, such as sorption and corrosion models; Development of databases for handling large and diverse data sets, including all relevant meta-data (provenance, quality assurance, limitations on use etc.); Development of regional-scale hydrogeological and radionuclide transport models; Aspects of safety case production – noting that overall authorship / ownership must reside with the developer.

References

[1] IAEA, Roadmap towards developing a DGR programme (*In-publication*, 2021)

[2] EURAD Knowledge Management and Networking Programme (*In-publication*, 2021)

[3] EURAD Roadmap Guide, Issue 2, 2021, https://www.ejp-eurad.eu/roadmap

[4] EURAD Roadmap Theme 1 Overview, Programme Management, 2021, https://www.ejp-eurad.eu/publications/theme-overview-ndeg1-programme-management

[5] EURAD Roadmap Theme 2 Overview, Predisposal, 2021, https://www.ejp-eurad.eu/publications/theme-overview-ndeg2-predisposal

[6] EURAD Roadmap Theme 3 Overview, Engineered Barrier Systems (*In-publication*, 2021)

[7] EURAD Roadmap Theme 4 Overview, Geoscience, 2021, https://www.ejp-eurad.eu/publications/theme-overview-ndeg4-geoscience

[8] EURAD Roadmap Theme 5 Overview, Facility Design and Optimisation, 2021, https://www.ejp-eurad.eu/publications/theme-overview-ndeg5-disposal-facility-design-and-optimisation

[9] EURAD Roadmap Theme 6 Overview, Siting and Licensing, (*In-publication*, 2021)

[10] EURAD Roadmap Theme 7 Overview, Safety Case, 2021, https://www.ejp-eurad.eu/publications/theme-overview-ndeg7-safety-case