European Joint Programme
on Radioactive Waste Management

ROADMAP GUIDE

ISSUE 2, 2021

A generic roadmap for implementing radioactive waste management, leading to geological disposal.

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“The EURAD Roadmap is essentially a representation of a generic Radioactive Waste Management (RWM) Programme, leading to geological disposal, enabling users and programmes to ‘click-in’, and to access existing knowledge, ongoing work and future plans. The content is focused on what knowledge, and competencies (including infrastructure) is considered most critical for implementation of RWM, aligned to the EURAD Vision.

If done correctly, our Roadmap will clearly communicate why different activities are supported and prioritized by different programmes according to their phase of implementation, radioactive waste inventory, geology, disposal concept, and national requirements. A key part of this narrative is signposting to existing knowledge, guidance and training – both existing within our EURAD community and elsewhere.

The Roadmap allows one to identify gaps in knowledge and competencies needed individually by each of the member states to take action accordingly. This gap analysis will also support the future orientation of joint activities.

This User Guide (Issue 2, 2021) describes the structure of the EURAD Roadmap and the variety of ways we are currently using it to support our work.

The greatest asset of EURAD is the many decades of RWM experience, talent and knowledge held within our community. Operating now as a Joint Programme, we are able to better harvest this shared knowledge to help orientate our future research and training priorities, and to structure the transfer of knowledge between programmes and to the future generations. “

Piet Zuidema

EURAD Chief Scientific Officer

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GLOSSARY

The following are common terms used in the context of the EURAD Roadmap:

Goals Breakdown Structure (GBS)

The EURAD goals breakdown structure is a thematic breakdown of knowledge and generic activities essential for radioactive waste management. It comprises Themes (Level 1), Sub-themes (Level 2) and Domains (Level 3), each formulated as goals. Although hierarchical and numbered, the knowledge and activities presented across the GBS should be considered collectively with no weighting to order of importance. Rather it is emphasised that there are many inter-dependencies and linked data across the GBS, where knowledge and activities can be centred in different ways, depending on the end user role and precise boundary conditions of the RWM programme to which the roadmap is applied.

Capability

The capacity to be used, treated, or developed for a specific purpose. Often it refers to a talent or ability that has potential for development or use.

Communities of practice (CoP)

A voluntary group of peer practitioners who share lessons learned, methods, and best practices in a given discipline or for specialized work. The term also refers to a network of people who work on similar processes or in similar disciplines, and who come together to develop and share their knowledge in that field for the benefit of both themselves and their and other organization(s).

Competency mapping

A mapping process to create a set of required competencies for successfully delivering a radioactive waste management and disposal programme within the different phases of implementation.

Competency

Generic task or a function. The ability to put skills, knowledge and attitudes into practice in order to perform activities or a job in an effective and efficient manner within an occupation or job position to identified standards. This may also involve crucial infrastructure needed for a specific task.

Contaminant

A general term used within the EURAD Roadmap to refer to contaminants originating from radioactive waste, which may include radionuclides, chemotoxic substances, or hazardous chemicals.

Domain

An area of activity, interest, or knowledge, especially one that a person, organization, etc. deals with.

End user

A person or organisation who uses the EURAD roadmap to support their work.

EURAD

The European Joint Programme on Radioactive Waste Management (EURAD). Also referred to as the ‘Joint Programme’.

Expert

Someone widely recognized as a reliable source of knowledge, technique or skill whose faculty for judging or deciding rightly, justly, or wisely is accorded authority and status by their peers or the public in a specific well-distinguished domain.

Knowledge

Knowledge: A mix of experiences, values, contextual information and expert insight for acquiring, understanding and interpreting information. Together with attitudes and skills, it forms a capacity for effective actions.

Knowledge base

1. The knowledge available to an organization
2. The knowledge available in a specific knowledge domain
3. A technology used to store complex structured and unstructured information used by a computer system.

Knowledge Management

Knowledge Management coordinates and integrates systemic practices and activities which enable and promote effective knowledge processes and ensure adequate knowledge assets as needed to achieve organizational goals.

Methodological Guidance

Activities consisting of developing a comprehensive suite of instructional guidance documents that can be used by Member-States with RWM programmes.

Roadmap

A high-level overview of a programme's goals, typical activities and knowledge needed to implement a RWM programme, leading to geological disposal.

State of Knowledge (SoK)

Experts' view of the most relevant knowledge and associated uncertainties in a specific domain applied in the context of a radioactive waste management programme.

State of The Art (SoTA)

Scientific facts underpinning the knowledge base.

Strategic Research Agenda (SRA)

Describes the scientific and technical domains and knowledge management needs of common interest between EURAD participant organisations.

Themes

Themes are large groups of related Knowledge Domains typical in Radioactive Waste Management and are the highest level of the EURAD Roadmap goals breakdown structure.

Training and Mobility

Activities consisting of developing a diverse portfolio of tailored basic and specialised training courses taking stock of and building upon already existing initiatives and creating new initiatives to bridge the identified gaps.

Work Package

A work package is a group of related tasks established within EURAD.

WHAT IS THE EURAD ROADMAP?

All EU Member States generate radioactive waste, with national inventories ranging from a few tens, up to hundreds of thousands, of cubic metres. Some Member States have extensive nuclear power programmes, generating large amounts of spent nuclear fuel or reprocessing wastes – others generate only small amounts of medical or research wastes. All of them vary in terms of national requirements and priorities for RWM implementation, but all require access to deep geological disposal for some wastes, unless they can return or export their small inventories.

The range of national strategies, priorities and current focus means that there is no "one size fits all" programme for RWM. Each Member State must develop its own programme, inevitably with scope common and complementary to what others have done or have planned.

Likewise, near-surface disposal facilities for lower activity wastes are operational in many Member States. The remaining key challenge, especially for larger inventory programmes, is to implement one or several deep geological repositories (DGR) for those categories of waste that require this solution. Hence within the EURAD roadmap, the focus is on how to achieve this endpoint, whilst also showing how its development must begin with, and be integrated into, a comprehensive national RWM programme.

Generalities or typical activities common across RWM programmes leading to geological disposal are the basis of the EURAD Roadmap – organised in a matrix of Phases (the time perspective) and a Thematic Goals Breakdown Structure (GBS) of RWM Themes > Sub-themes > Domains. The EURAD roadmap has several 'tiers' with content in each organised in a systematic way according to the GBS.

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. Because of its generic nature, the EURAD roadmap is populated with content that is common to all programmes, providing greater resolution to technical aspects of implementing a DGR. National programme specific activities, such as overall predisposal management and strategies for stakeholder and community interactions, are recognised as critical and significant, but are covered in less detail compared with DGR technical activities. However, technical aspects of the need for interaction between predisposal activities and the road to a DGR are covered.

Its development is a significant advancement since its origins during the establishment of EURAD, when it was initiated exclusively for mapping RD&D needs. Since this time, the GBS of the roadmap has been re-developed through a broader lens of all activities needed to successfully implement a RWM programme, leading to geological disposal. This provides a framework within which to look inside and see whether sufficient information and knowledge exists (knowledge management), or whether additional RD&D is needed (strategic research agenda).

PATHWAYS THROUGH THE EURAD ROADMAP

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 roadmap has been developed from the experiences of the more advanced EU programmes that have already been involved in many of the activities described, have made advanced plans for DGR implementation and have already taken some of the early steps in these plans. Because these programmes have developed over more than 40 years and have adopted different technical and strategic approaches to DGR development, the roadmap has been structured to capture largely generic best practice in its presentation of Themes and programme Phasing.

However, it is important for the user to recognise that there is not a unique route through the roadmap – like any roadmap, it can be used to stimulate consideration of alternative options. This is best illustrated by considering the alternative approaches that have been, and might be taken to DGR siting, construction and operation. Examples are discussed below:

- **Phasing:** the roadmap uses a simple model of Phasing involving five distinct stages of DGR development, from RWM programme initiation through to DGR closure, and the roadmap Themes describe activities within each phase. The roadmap Phases should be regarded as a convenient way of organising the main elements of a programme rather than a rigorous breakdown of all the activities involved.
- **Site Characterisation:** in a similar way to the definition of programme Phases, national programmes have adopted a range of approaches to site characterisation (especially geoscience) activities. Examples of the factors that can vary include:
    - whether there is a policy obligation to investigate more than one geological environment or host rock type before selection of a preferred site;
    - the level of detail of site characterisation required before a preferred site is chosen and the extent of site characterisation required.
- **Pilot and demonstration stages:** some programmes are required to include some form of pilot disposal stage into the operational Phase, which will provide data that could affect subsequent operational decisions: others move directly to operations. Many programmes plan to carry out testing of factors that will affect the final design during the construction Phase. In addition, some programmes plan to demonstrate certain activities or systems before deployment.
- **Underground Research Facility (URF) / Rock Characterisation Facility (RCF):** a considerable amount of geoscience RD&D in the most mature national programmes has taken place in ‘generic’ underground research facilities that are not located at a DGR site. Owing to the considerable knowledge gained, there is a diminishing requirement for such facilities and a new programme might, alternatively, include one in its planning (e.g., for training purposes). Or it may decide that it does not require one, or access a URF in another country, and / or perform any necessary RD&D work in a dedicated rock characterisation facility at the eventually selected DGR site. The range of options and approaches is potentially wide and will depend

on the geological environment and the size, design and inventory of the DGR being considered.

For a new or developing programme, decisions on all of the above points will be influenced by a variable mix of policy requirements, the scale and nature of the DGR programme being planned, access to knowledge and expertise both nationally and from other programmes, and available resources.

Typical Phases of a Deep Geological Repository Programme (x-axis)

Structured according to phases of implementation, the roadmap can be used by all programmes in Europe, irrespective of level of advancement.

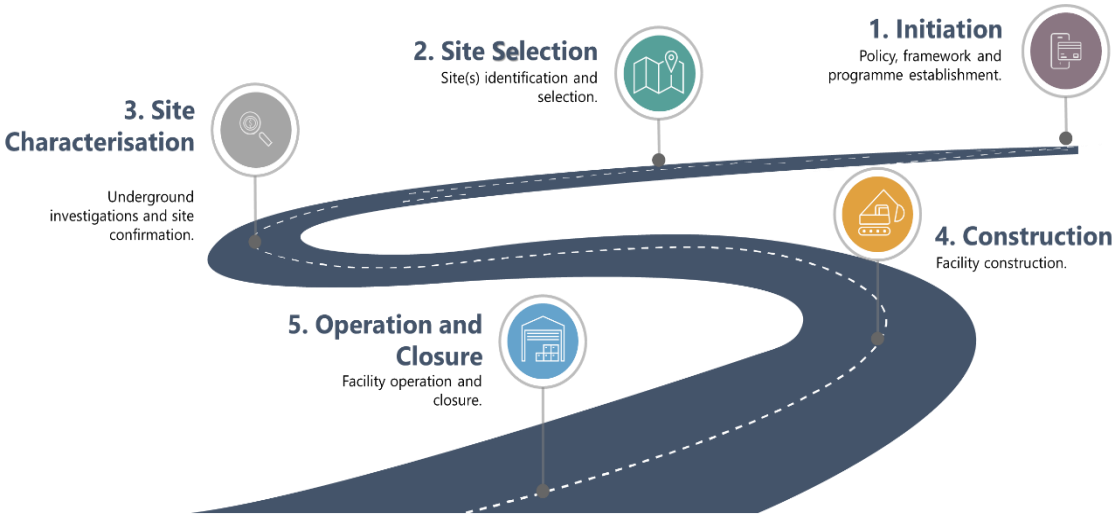


Figure 1: Phases of implementing a deep geological repository programme, adapted from the IAEA DGR Roadmap (IAEA, 2021). Note: Phases are not necessarily discrete but often overlap and are typically iterative (i.e., not simply sequential), and can differ from country to country.

1. Initiation: Policy, framework and programme establishment
2. Site Selection: Site(s) identification and selection
3. Site characterisation: Underground investigations and site confirmation
4. Construction: Facility construction
5. Operations and Closure: Facility operation and closure

For each phase, the Roadmap explains how activities and existing knowledge are used to fulfil generic safety and implementation goals common across RWM programmes (See, p19). The Roadmap elaborates further on how the emphasis of work on each of these differs and changes throughout successive Phases.

Thematic Goals Breakdown Structure (y-axis)

The roadmap describes typical programme goals, activities and capabilities needed against 7 themes, which are each further broken down into sub-themes and domains in what we can call the Goals Breakdown Structure (GBS). This matrix of phases vs thematic goals provides a tiered and common framework allowing users to 'click in' and access existing knowledge. It is goals oriented to knowledge and competencies most critical for implementation, aligned to the EURAD Vision.

Each theme is described below. Top level goals of the extended EURAD roadmap GBS are further elaborated on page 8.

1. National Programme Management

Goal: 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.

Context: Geological disposal is the preferred solution for some of the radioactive wastes (RW) in almost every national inventory, with all EU Member States eventually requiring access to some form of deep geological repository (DGR). Implementing a DGR is thus the endpoint of many national programmes and is also the most complex and difficult activity that they will have to undertake. Getting to an safe effective solution has to be done within the framework of a broadly-based and comprehensive national programme that addresses all aspects of radioactive waste management (RWM) for all of the wastes in the national inventory and all of the RWM facilities that will be needed. This Theme looks at how such a broad, supporting programme, leading to eventual geological disposal, can be established. It focuses on some of the practical experiences of more advanced programmes as they move through the phases of work that lead to a DGR. A national RWM programme requires a strong foundation of national policy that defines overall objectives, a schedule and the legal framework for implementing waste management, transport, storage and disposal solutions. The legal framework should include provisions stipulating the responsibilities of waste producers, waste owners and the national regulatory authorities. It should identify the mechanisms for funding the national RWM programme. The national RWM programme should operate inside a strong infrastructure of effective organisations with sound management systems and clear interaction procedures. There should be a clear policy of involving relevant external stakeholders in decision-making processes. In the early phase of establishing national policy or developing a RWM programme there is documentary and advisory support available from the IAEA, along with decades of experience encapsulated in EU-wide good practice.

2. Pre-disposal

Goal: In conjunction with waste producers, identify and deliver solutions to optimise the management of radioactive waste throughout the predisposal phases of the radioactive waste management programme.

Context: All EU Member States (MS) produce radioactive waste (RW) resulting from not just operation and decommissioning of nuclear facilities but also from the use of radionuclides in medicine, industry, agriculture and research as well as processing of raw materials containing naturally occurring radionuclides. The ultimate requirement is for all wastes that cannot be freely released to then be permanently disposed within a geological repository, including radioactivity from very low to high level wastes. Yet before disposal, there are typically predisposal activities done to improve the safety, efficiency, and environmental impact of the waste's final disposal. The waste characterisation and processing phases within the predisposal activities are primary focuses, where physical actions are implemented for waste reduction, treatment and packaging. These actions are taken to support the waste hierarchy of minimising the disposal volumes of higher activity material. There are a variety of complimentary actions associated with storage, transport and planning associated with the waste lifetime that also factor into the holistic predisposal management. Predisposal activities can be implemented at many phases during the waste transfer between the producers, waste owner and the final waste disposal facility owner/operator, thus iterative communication and documentation is a factor of success. A national radioactive waste management (RWM) program should establish the policies associated with predisposal waste management, in the same way as for final disposal, as described within Theme 1 Programme Management. Through all phases and predisposal activities, there are also continuous planning activities associated with evaluating the waste inventory evolution, technology availability and economics, as also noted within Theme 1 Programme Management.

3. EBS

Goal: 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.

Context: Repositories for the disposal of radioactive waste generally rely on a multi-barrier system to isolate the waste from the biosphere. This multi-barrier system typically comprises the natural geological barrier provided by the repository host rock and its surroundings and an engineered barrier system (EBS). This multi-barrier principle creates an overall robustness of the system that enhances confidence that the waste will be successfully contained, as the natural barrier provides a stable environment that allows the EBS to function for hundreds to many thousands of years, depending on the disposal concept. The EBS represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill and seals. The waste form component of the EBS, depending on the waste type and definition specified by the national programme, may be specifically processed, and conditioned for disposal (e.g., by incorporating it in a cement matrix). Other waste forms cannot be significantly processed or conditioned for disposal (e.g., direct disposal of spent fuel or non-conditioned bulky items) and are thus not engineered for disposal, as no technical design requirements can be specified for them, although their properties (e.g., corrosion resistance) can contribute significantly to overall safety.

For a given national programme there will be a number of different waste forms including vitrified high-level waste and spent fuel, intermediate level reprocessing, operation and decommissioning waste, low level waste of different types, legacy waste and more. The waste may be pre-packaged in concrete, steel or bituminized waste packages. A given national programme may also have the possibility to select host rocks of different characteristics for the repository. Since the EBS should be tailored to the characteristics of the waste and be compatible with the natural (geological) barrier, there will be a significant number of different options and combinations of engineered barriers.

4. Geoscience

Goal: Assemble geological information for site selection, facility design and demonstration of safety.

Context: Geoscience is of key importance for geological disposal of long-lived radioactive waste of higher activity. It is linked with all (EURAD) safety functions, i.e., isolation of waste from people and accessible biosphere, containment, retention and retardation of contaminants, minimized water flow and long-term geological stability. A broad stakeholder community ranging from interested laymen to highly specialized geoscientists will follow the role of and the work done in geoscience with great interest through all the phases of a deep geological disposal project as described in the EURAD Roadmap. A permanent, clear and transparent communication is therefore a prerequisite for gaining broad acceptance of a deep geological disposal project.

5. Design and Optimisation

Goal: Design a facility that fulfils safety and security requirements and that can be practicably constructed, operated and closed.

Context: Disposal facility design covers early conceptual design during early programme phases, right through to detailed design for construction, operation and closure. In particular, facility design covers the layout of the underground facilities with regard to the host rock and the types and amount of the radioactive waste. In addition, the design covers the specifications for the geotechnical barriers including the selection of appropriate material.

Safe operation and closure activities need to be prepared by demonstrating that waste handling, transport, emplacement, and retrieval (if applicable) is a safe operation and radiation protection is guaranteed. Post closure safety will as well rely on a suitable repository design and a corresponding safety assessment. Underground research laboratories and/or rock characterisation facilities provide suitable opportunities to perform demonstration tests at a representative scale and active conditions. A final repository is a nuclear facility and its operation has to consider nuclear material safeguards. This is a

system of inspection and verification by the International Atomic Energy Agency designed to detect the misuse of nuclear material or technology.

When it comes to optimization, revisiting technical design requirements and technical solutions may be a driver. In addition, monitoring activities may play a significant role. On the one hand, monitoring activities are useful for checking whether technical aspects of facility construction and operation are suited for their purpose and provide information for potential optimization. On the other hand, monitoring may provide useful information about the evolution of the engineered barrier system. This information may be a sound basis for design optimization of individual engineered barrier components as well as engineered barrier emplacement techniques prior to final closure of the repository.

6. Siting and Licensing

Goal: Demonstrate to regulators (and other stakeholders, including 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.

Context: The repository site must be fit for the purpose of the construction and operation of a waste repository which is safe for time periods of up to one million years. The site must also be accepted both nationally and locally as being suitable. Three requirements must be fulfilled:

1. the constructed waste repository must be safe;
2. the stakeholders must agree to the location; and
3. it must be possible to construct and operate the repository without undue difficulty.

Siting has the goal to find and confirm the suitability of the site(s). The siting process starts with collecting existing information about potentially suitable sites broadly (on a national scale, e.g., national geological screening). Gradually the process leads to only one or a few sites to be investigated leading to a site licence when more information has been collected and evaluated and the licensing process has been successfully terminated. Licensing has also the goal to obtain the acceptance by relevant stakeholders. The site licence may also include the construction licence based on a repository concept with all the needed details for the formal decision to construct and operate the repository.

7. Safety Case

Goal: Iteratively quantify and demonstrate, the safety of the disposal system and inform strategic design decisions.

Context: The safety case is a critical tool for guiding programme development, integrating and synthesising information to build understanding to inform decisions at each stage of the repository development programme and to guide and prioritise R&D activities. The safety case is a synthesis of the evidence, arguments and methods that demonstrate that a disposal facility will be safe: safe to construct, safe to operate and safe for people and the environment with no further maintenance once it has been sealed and closed. The safety case addresses the suitability of the site and facility design, the assessment of radiation risks and assurance of the adequacy and quality of all safety related work associated with the disposal facility. A formal definition of the safety case is given in IAEA safety standards. It is important when considering the strategy for developing the post-closure safety case to recognise that it is not necessary to predict the detailed evolution of the disposal facility, rather the aim is to build confidence that all credible evolutions of the facility will be safe. A safety case should provide robust arguments, including multiple lines of reasoning, to demonstrate the completeness of the evolutions considered and their safety. Safety is defined by the national regulatory framework, which typically reflects international guidelines, such as those set by the IAEA.

Extended GBS (Issue 2, July 2021)

The following tables provide the latest extended EURAD Roadmap Goals Breakdown Structure (Issue 2, July 2021). This structure will be taken over by the EURAD Knowledge Management Work Packages and further refined and/or elaborated, based upon continuous feedback and iteration cycles as the part of the ongoing population of the EURAD Roadmap. Change control of the extended GBS will be managed accordingly and reported via periodic update to this Roadmap Guide and by update to the EURAD Roadmap Webpages (https://www.ejp-eurad.eu/roadmap).

EURAD Roadmap: National Programme Management Theme 1 Goals Breakdown Structure (Issue 2, July 2021)	
Theme (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)

EURAD Roadmap: Pre-disposal Theme 2 Goals Breakdown Structure (Issue 2, July 2021)	
Theme (Level 1)	
2. In conjunction with waste producers, 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 producers (Planning)	2.1.1 Evaluate waste inventory from producers 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 implementation phase, considering cost-benefit ratio and availability (Technology Selection)
	2.1.4 Evaluate options to apply 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 Stabilise and minimise the quantity and volume of radioactive waste through pre-treatment, treatment and conditioning (Processing)
	2.2.3 Package waste accounting for future transport and deposition, and maintain safe interim storage of packages (Storage)
	2.2.4 Transport radioactive wastes between facilities in accordance with regulatory requirements (Transport)
2.2 Enhancing predisposal operations through iteration with waste producers and repository operators, to develop and deliver safe and cost-effective solutions (Operations)	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 holistic operations (Secondary Waste Management)

EURAD Roadmap: Engineered Barrier Systems Theme 3 Goals Breakdown Structure (Issue 2, July 2021)	
Theme (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	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)

and evolution under storage and disposal conditions (Waste packages, for disposal)	
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)

EURAD Roadmap: Geoscience Theme 4 Goals Breakdown Structure (Issue 2, July 2021)	
Theme (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.

EURAD Roadmap: Disposal Facility Design and Optimisation Theme 5 Goals Breakdown Structure (Issue 2, July 2021)
Theme (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 nuclear facilities and protect sensitive technology, software and information (Security and safeguards)	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).
	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 and reducing the consequences (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)

EURAD Roadmap: Siting and Licensing Theme 6 Goals Breakdown Structure (Issue 2, July 2021)	
Theme (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 producers 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)

EURAD Roadmap: Safety Case Theme 7 Goals Breakdown Structure (Issue 2, July 2021)	
Theme (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)

Theme Overviews and Domain Insights (z-axis)

The Roadmap Matrix of Phases vs. Themes > Sub-themes > Domains is used to create a suite of roadmap documentation to codify important knowledge. For each of the seven roadmap themes, a **Theme Overview** is available. This describes broadly the typical RWM activities and capability that is required to successfully achieve each of the roadmap goals, including how activities and programme capability evolves through different RWM phases.

At the next level down, the roadmap will be populated by short context documents called **Domain Insights.** Each will link existing and available knowledge to generic safety and implementation goals and provide a broad but not detailed overview of each domain relative to knowledge maturity, areas of uncertainty, and signpost to existing resources such as guidance, training and mobility, or more detailed knowledge via networks or documents, including historic EC project reports.

Together these documents can be used to map and help users navigate:

(1) Theme Overviews:

Guidance on typical goals and activities for RWM – Activities (which may be of variable importance and scope depending on the nature of the disposal programme) provide generic guidance on how to achieve key programme goals and how priorities evolve throughout programme phases, from advanced programmes perspectives.

Competencies for RWM – Needed competencies (and accessible infrastructure) for successfully managing a disposal program within the different phases of implementation.

(2) Domain Insights:

Functionality – Contextual information about how activities and knowledge associated with a domain contribute towards achieving generic safety and implementation goals.

Maturity and State-of-Knowledge (SoK) – Links to available SoK are included, providing an Experts' view of the most relevant knowledge and associated uncertainties (including areas of ongoing scientific and technological enquiry) in a specific domain applied in the context of a radioactive waste management programme.

Safety and Implementation Significance – Contextual information about how activities and knowledge associated with a domain impact long-term safety or practical implementation.

WHERE CAN I ACCESS THE EURAD ROADMAP?

The first published version of the EURAD Roadmap was made available in printable A3 sheets contained at the back of the EURAD Founding Documents – RD&D Priorities of the SRA (EURAD, 2019).

Since this time, the roadmap has been extended using the GBS for the broader scope of all activities needed for RWM leading to geological disposal, making it less centred on only RD&D and more modular and useful for end users. Theme Overviews are currently in publication which will be available as webpages on the EURAD website (https://www.ejp-eurad.eu/roadmap).

Domain Insights are in production and will also be made available at the same webpage once reviewed and issued.

Longer term EURAD is establishing a broader basis for the roadmap as the central framework for a sustainable European knowledge management and networking programme. This will include development of an improved user interface and more permanent home for storing or signposting critical knowledge in RWM. A key consideration will be long term maintenance and update to knowledge captured during EURAD, and the practicality of obtaining Member State support and co-financing.

All issued roadmap documents have been authored by a domain expert and subject to peer review.

EURAD Roadmap Webpages:
www.ejp-eurad.eu/roadmap

WHAT ARE PROGRAMME GOALS AND ACTIVITIES?

EURAD guidance on typical goals and activities for RWM programmes leading to geological disposal

- The EURAD roadmap has adopted a goals breakdown structure (GBS) as a way of organising existing and available information, data and knowledge in the field of RWM. This is effectively the EURAD roadmap classification scheme.
- The use of goals provides a more dynamic and instructional guidance to end users, rationalising the objective of specified activities relative to programme implementation.
- The numbering and order of themes, goals and specified activities has no significance. On the contrary themes, goals and activities are often inexplicitly linked. The implementation of RWM is a complex, multi-disciplinary, and multi-dimensional business.
- The generic activities specified have been established by Theme Experts who have decades of experience, and who have each provided their view of what is important to consider. The focus is on activities that are typical and common to RWM programmes, but it is not an exhaustive list. Member states should use these as a guide, and further elaborate, expand and/or adapt activities to suit the boundary conditions for their own programme.

Top Tips

1. The EURAD Roadmap Goals Breakdown Structure and Activities specified in each Theme are developed from the perspectives of advanced programme implementation, to learn from organisations that have ‘done it before’.
2. Activities that are closely related or that have significant interdependencies across different Themes are indicated.
3. The scope of the EURAD Roadmap activities focuses on scientific and technical activities needed to implement radioactive waste management leading to geological disposal, broadly covering:
    - Radioactive waste characterization and processing (incl. treatment, conditioning, and packaging)
    - Interim storage of radioactive waste
    - Disposal solutions - mainly geological disposal of spent fuel, high-level waste (HLW) and long-lived intermediate level waste (ILW)

WHAT CAPABILITY IS ESSENTIAL FOR RWM?

EURAD guidance on available capabilities

- The EURAD roadmap has considered the broad capability needed for RWM which assumes that most national programmes have a generally lean waste management organisation (implementor) of highly skilled and suitably qualified and experienced individuals, supplemented by expert contract support from the supply chain (market).
- Theme Overview documents in the roadmap describe available capabilities which are categorised according to: knowledge and understanding; experts and practical skills; laboratories and centres of excellence; equipment, tools and technology, industrial facilities and manufacturing; and contractors and human/material resources.

Top Tips

1. Competence is defined as the ability to apply knowledge, skills and attitudes in order to perform an activity and/or job to specified standards in an effective and efficient manner. In EURAD we consider competence as skills (and infrastructure) that is available to an organisation either in-house or accessible from outside third parties.
2. The roadmap guidance on needed RWM capability presented in each theme captures not just physical activities (build x, document y) but also competence needed, including when it is needed nationally, what must be maintained/developed, or that which can be accessed from the international RWM market.
3. The roadmap guidance considers essential competence needed now, when there are relatively mature disposal solutions, and not necessarily the competence that advanced programmes needed to develop such solutions.

HOW DO I ACCESS TRAINING AND MOBILITY IN RWM?

EURAD training and mobility

- The EURAD roadmap can be used by MS's to orientate their own capability development needs, and to understand where there are training and mobility resources available (details can be accessed via the EURAD School of Radioactive Waste Management www.euradschool.eu).
- Scope within EURAD to develop new training courses and material will be aimed at acquiring both state-of-the-art scientific background and at accessing the vast amount of "tacit" knowledge available within EURAD through targeted hands-on training.
- The mobility programme will provide access to dedicated infrastructures associated with the Mandated Actors/Linked Third Parties within EURAD.

Top Tips

1. A diverse portfolio of tailored basic and specialized courses will be composed within EURAD with content linked to the EURAD Roadmap. This portfolio will contain a list of existing initiatives (e.g., IAEA and NEA courses), and new training courses to bridge identified gaps.
2. EURAD does not formally endorse or approve a specific sub-set of training providers, it simply aggregates what is existing focused on the experience of EURAD participants and aligned to RWM implementation needs.
3. The EURAD 'school of RWM' is also used to describe this aggregation and is an umbrella term for the dedicated work package on training and mobility, linked to:

   - EURAD beneficiaries (organised and owned by); and

   - External providers.
4. Recognising that EURAD Work Packages include many PhDs and new entrants to the field of RWM, more general courses and learning initiatives such as lunch and learn sessions are also pursued.

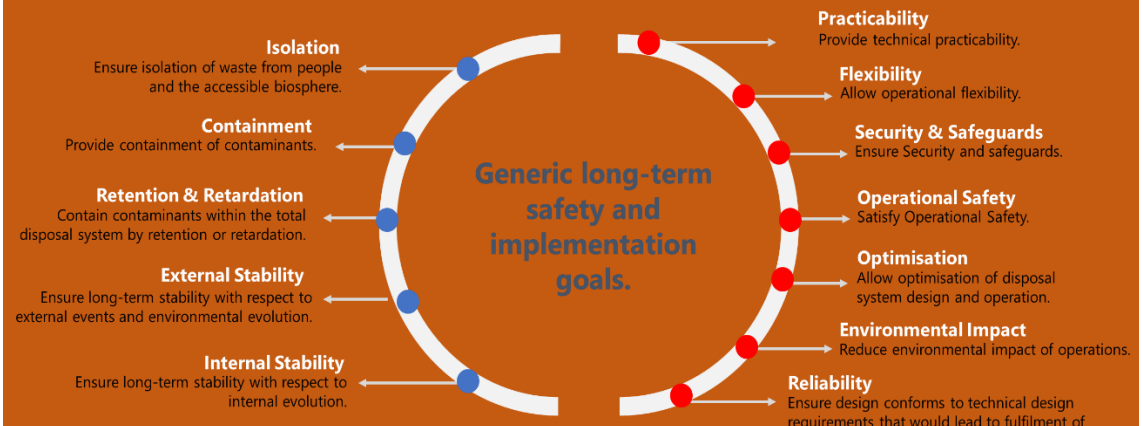
HOW CAN I ORIENTATE EXISTING KNOWLEDGE TO FUNCTIONAL REQUIREMENTS?

EURAD Generic Safety and Implementation Goals

- For many domains of the roadmap, their orientation relative to functionality in terms of contributions to safety and implementation goals is necessary. This provides context to end users of the functional-oriented view on facility objects - the 'what can it offer' question.
- EURAD generic safety and implementation goals (Appendix A) are used in the roadmap documents to contextualise knowledge domains. The approach of linking knowledge to goals (or requirements) is standard practice when communicating the 'golden thread' between claims, arguments and evidence in decision making processes and safety cases. This enables end users to orientate knowledge for specific disposal concepts and programme boundary conditions.
- Safety and implementation goals are specified and used by RWM programmes differently. The safety goals (sometimes referred to as safety functions) developed by EURAD are generic and are based on the approach adopted by advanced programmes (SKB and Posiva, 2017).

Top Tips

Use the generic long-term safety and implementation goals to link knowledge to DGR requirements.



WHAT IS THE STATE OF KNOWLEDGE (SOK) IN EACH DOMAIN OF THE ROADMAP?

Domain Insights & State of Knowledge (SoK)

- The roadmap domain insight documents provide a high-level evaluation of current state of knowledge.
- Aspects of a domain that have safety and implementation significance are communicated.
- Experts' view of the most relevant knowledge and associated uncertainties (including areas of ongoing scientific and technological enquiry) in a specific domain are broadly described.
- Openly accessible state of knowledge (SoK) documents are signposted, and new SoK documents are generated by EURAD to fill identified gaps. Together these documents provide end users with an entry point for accessing the more detailed scientific and technological basis in each domain.
- Domain insights, and their evaluation of knowledge maturity and impact, make clear that contents are the view from a certain point of time (and the view of authors) – this provides an orientation for today.

Top Tips

1. The evaluation of knowledge maturity for each domain of the EURAD Roadmap represents a broad international view, substantiated by key references to enable end users to access existing knowledge and its application at different phases of RWM programme.
2. Although domains are considered mature, technological and scientific advancements continue. The EURAD roadmap reflects such areas of ongoing advancement in a broad way, which complements the EURAD SRA (EURAD, 2019) which includes a sub-set of RD&D of common interest between the 3 different Colleges of EURAD.
3. The domain insights and related SoK documents provide a framework within which to look inside and see whether sufficient information/ knowledge exists (KM), or whether additional RD&D is needed (SRA).
4. Signposting to accessible knowledge has been completed with continuous engagement with IAEA, NEA and EURAD Colleges to ensure EURAD does not duplicate similar work planned or delivered by others.

References

EURAD (2019), Strategic Research Agenda, 2019.

IAEA (Pre-publication Copy), A roadmap for developing a geological disposal facility, In preparation 2021.

Posiva SKB (2017), Safety functions, performance targets and technical design requirements for a KBS-3V repository, Posiva SKB Report 01, January 2017.