eurad

European Joint Programme on Radioactive Waste Management

STRATEGIC RESEARCH AGENDA

Scientific and technical domains and sub-domains and knowledge management needs of common interest between EURAD participants.

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The Strategic Research Agenda (SRA) of the European Joint Programme on Radioactive Waste Management (EURAD) describes the scientific and technical domains and sub-domains and knowledge management needs of common interest between EURAD participant organisations.

It has been developed in a stage-wise manner, Step 1 - taking over entirely the scope developed within the EC JOPRAD Project (See, D4.2 Programme Document), and Step 2 – enhanced with a small number of additional needs identified by ongoing EC projects and approved for inclusion between the key contributors of EURAD.

The SRA scope is structured by seven Scientific Themes, as illustrated in Figure 2. These themes are also used in the roadmap. Although all technical in nature, Theme 1 is an overarching theme, Themes 2-5 are predominantly focussed on fundamental science, engineering, and technology, and Themes 6 and 7 include aspects more of an applied science and integration focus.

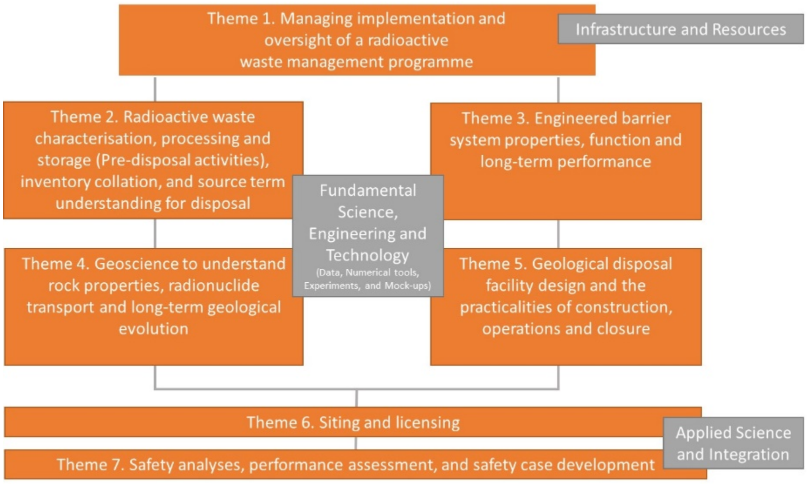
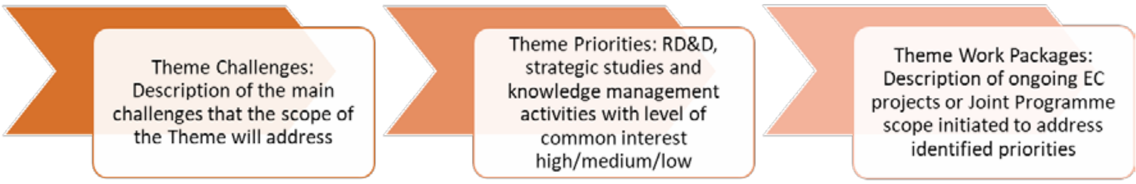


Figure 1. Scientific Themes of EURAD SRA

Within each theme, the SRA provides (i) a short introduction and background section, broken down into a number of topics that are further used in the roadmap. The SRA then provides (ii) a list of RD&D priorities, strategic studies and Knowledge Management activities of common interest to be addressed by EURAD, using the tasks numbers from the EC JOPRAD project (in the future version a new numbering system shall be implemented). For each there is an indication of relevant cooperation and past EC projects that should be considered at the time of task initiation; and (iii) a summary of ongoing and active work (including Horizon 2020 projects) that address in-part, or in-full, the activities and priorities identified for each Theme. This structure is further summarised by Figure 3 below.

An important consideration in developing the SRA themes, and their further delineation into topics and sub-topics, has been to avoid grouping scientific and technical scope according to rock type (e.g. clay, hard-rock, or salt systems) or by disposal concept and design (e.g. vertical borehole, horizontal tunnel or vaulted systems). Rather, EURAD SRA considers integration of scope across programmes with varying rock types and concept designs as highly beneficial, resulting in enhanced cross-fertilisation between established communities of practice for specific areas of scientific and technical competence.

Figure 2. The Structure of EURAD SRA



EURAD SRA does not describe activities that are handled by individual Member States' RD&D programmes, and should not be considered an exhaustive list of all RD&D initiatives or active work within Europe. It only includes initiatives that are currently coordinated and funded by the EC and those that have been brought to the attention, and considered relevant for cooperative work, by Joint Programme participants. Recognising the potential overlaps with existing initiatives and the coordination needed to ensure that EURAD delivers on its remit to provide European added value, for each RD&D activity, the SRA includes an indication of known opportunities for interaction. This will also be addressed within the knowledge management activities. (*Note that this activity has yet to be completed in coordination with IAEA).

The SRA Tables of RD&D Priorities indicate the surveyed High, Medium or Low level of Common Interest, as identified by EC Project JOPRAD (see Annex I). The enabling Knowledge Management, Strategic Studies and other Cross-cutting Activities identified of common interest (by JOPRAD) that relate to each Theme are included without an indication of High, Medium or Low level priority. It is anticipated that the first implementation phase of EURAD (EURAD-1 – 2019-2024) will address this by additionally surveying Member-States needs on these aspects and developing a specific list of priorities as a basis for EURAD work, beyond the collaborative RD&D scope.

EURAD's SRA will be a dynamic and living document that shall be updated periodically in order to integrate outcomes of RD&D activities as well as any emerging collaboration needs identified by the RWM community during the implementation phases of EURAD.

We anticipate that there will be regular 'soft' updates to make minor edits and additions. This will be complemented by periodic extensive updates to coincide with future Work Package developments where it is anticipated that significant changes may result to take account of learning from EURAD-1 (2019-2024) and align the SRA, Roadmap and Work Package scope and methodologies with how things evolve, particularly with respect to the EURAD governance scheme and how the criteria used to identify needs of the Waste Management Organisations (WMOs), Technical Support Organisations (TSOs) and Research Entities (REs).

THEME 1: MANAGING IMPLEMENTATION AND OVERSIGHT OF A RADIOACTIVE WASTE MANAGEMENT PROGRAMME

Introduction and background

Programme planning

Radioactive waste management (RWM) programmes present special challenges in their planning and execution, for which on-going programmes have already lasted for several decades. They involve not only significant science, technology and engineering, but also substantial elements of programme management, regulation, politics, financing, resourcing, and most importantly, public participation and stakeholder engagement. Such elements are included in the Waste Directive and elaborated further in the ENEF NAPRO Guide. International collaboration on these aspects hold many advantages for both early-stage programmes and advanced programmes, and although not considered pure RD&D, they require expert technical knowledge, sharing of good practice, and hence are included within EURAD scope.

Establishing very early on a national programme with decision milestones, and clear roles and responsibilities, enables all parties (i.e. government, regulator, operator and public) to commit to progress. Particularly when implementing geological disposal, public participation and stakeholder involvement has great importance to the planning of the programme. Lessons learned from past programme experiences show that engineering aspects tend to be well understood, with sufficient experience to accurately plan the effort and resources required. In contrast, the scientific effort (site characterisation, process modelling, safety assessment etc.), while already providing understanding of process understanding and impacts on safety, is evolving over time leading to new view points and sometimes new uncertainties and it is less predictable in the outcome, duration or resources that may eventually be required. Accounting for such uncertainty has become a key part of successful programme planning, and would benefit from continued sharing of methodologies and experience.

A clear strategy and commitment to involvement of stakeholders is essential to the decision-making process at all stages of a waste management programme. This will include how stakeholders with interest in RD&D will be involved and ways of communicating the scientific basis of waste management solutions for a range of audiences, including those for disposal. Throughout the preparatory work of the Joint Programme EURAD (see, the EC JOPRAD project), experts of Civil Society have contributed to and influenced the scope of work to be addressed.

Organisation

All programmes benefit from an established waste management and disposal policy and regulatory framework established prior to the initiation of substantial site work. These should be clear, comprehensive and in line with accepted principles promulgated internationally. It is essential that those working in direct support of the national regulatory bodies continue to network and harmonise views on how to develop, maintain and apply regulations.

The Waste Directive requires Members States to ensure they have National Programmes leading to implementation of safe and responsible management of spent fuel and radioactive waste. This includes the requirement to each develop a dedicated RD&D programme and transparent policy, see Waste Directive Articles 12 (1,F) and 12(1,J). Member States completed their first notification to the Waste Directive in 2015, however their responses have not been made available or used directly to determine the scope of EURAD. Rather, Member States with this responsibility are able to influence EURAD scope through their participation. Inputs from early-stage programmes have already been included into EURAD by earlier work undertaken by the Implementing Geological Disposal Technology Platform (IGD-TP) which prepared a preliminary Guide on RD&D programme planning for geological disposal in 2015, the PLANDIS Guide. Aimed at early-stage programmes, it suggested a number of activities that would benefit from further guidance, anticipated to be developed within EURAD Knowledge Management Scope.

Resources

In the perspective of decades-long programme management, organisational capabilities related to resources (competence maintenance, education and training), financing (forecasting and costing), and the adoption of sound management systems and processes are all needed.

Across Europe there are a large number of organisations within many countries with resources (databases, equipment, capabilities, etc.) relating to the management and disposal of radioactive waste. Further networking and documentation of such infrastructure could aid early-stage programmes to tap into an existing talent pool and also help advanced programmes manage emerging skill gaps either for new competencies identified, or to manage capacity when key individuals have retired or local/national resources are unavailable. Sharing of competence matrices for different roles (regulator versus implementor) and how these evolve through successive phases of a waste management programme would be highly advantageous.

Information management, record keeping and maintaining memory are important activities within the context of implementing geological disposal (and long-term waste storage). The IAEA and OECD-NEA are involved in providing guidance in support of those aspects. The outcome of their work is transferred through participation in project activities establishing the guidance and recommendations, as well as through dissemination of the outcomes through conferences, proceedings and guides.

RD&D Priorities and Activities of Common Interest to be addressed by EURAD:

Theme 1: Managing implementation and oversight of a radioactive waste management programme	• **EU research infrastructure:** To document the extent of European research infrastructure and competencies, and establish conditions allowing for transnational access to and/or sharing of facilities and established networks (J3.15/High). - Expected outcomes and impact: Improved understanding of the breadth and depth of research infrastructure across Europe. - Cooperation and relevant past projects: possibility to explore training / mobility exchange at some sites / URLs
	• **Pre-licensing management:** To identify RD&D and knowledge transfer needs in support of defining pre-licensing activities that can support success in the siting and licensing phase/process (J3.11/Low). - Expected outcomes and impact: Enable programmes to structure and prepare successfully for licensing. - Cooperation and relevant past projects: ?

Enabling Knowledge Management, Strategic Studies and other Cross-cutting Activities Identified of Common Interest that relate to Theme 1:

How to establish and implement a radioactive waste management RD&D programme: To develop a common guidance document to support waste management programmes, including disposal, with establishment and implementation of a RD&D programme (Originates from needs identified by the IGD-TP PLANDIS Guide.

- **Training and competence maintenance of skills and expertise to support safe radioactive waste management including disposal:** To ensure knowledge is managed and disseminated, and that there is competence maintenance, education and training of the workforce (J3.16).
- **Information management:** To maintain information, knowledge and records over the long lead- and implementation-timelines of geological disposal programmes, from pre-licensing through to the post-operational phase (J3.14/Medium).

Ongoing and active work (inc. Horizon 2020 projects) addressing Theme 1:

As previously mentioned, the Member States responses to the Waste Directive, together with Member States responsibility towards the IAEA Joint Convention provide considerable inputs and enable access to networks, resources and experience for how to establish the key components of a RWM programme at a national strategic level.

Regarding training, the EC ANNETTE project (2016-2019) is consolidating existing achievements to tackle the challenges in ensuring a qualified nuclear workforce is available to support future nuclear energy, decommissioning and waste management requirements. ANNETTE aims to enhance European-wide efforts initiated in the past decades by different organisations belonging to academia, research centres and industry to maintain and develop education and training in the different nuclear areas. Links between ANNETTE and EURAD Knowledge Management Work Package on Training are anticipated.

Within EURAD-1, it is anticipated that one of the first guidance documents to be produced will be on establishing and implementing a RWM RD&D programme, building on the work of the IGD-TP PLANDIS Guide.

THEME 2: RADIOACTIVE WASTE CHARACTERISATION, PROCESSING AND STORAGE (PRE-DISPOSAL ACTIVITIES), AND SOURCE TERM UNDERSTANDING FOR DISPOSAL

Introduction and background

Waste handling, characterisation, treatment and packaging

Sufficient knowledge of the waste characteristics is necessary to define suitable treatment and conditioning, both for passive safety and for final disposal. Spent Fuels and vitrified high-level wastes are generally well characterised. Remaining uncertainties include inventories of some long-lived beta emitting activation products like Cl36, C14 etc.

Regarding long-lived intermediate level and low-level wastes, often, countries need to manage historical radioactive waste without adequate information about their origin and radionuclide content, and in some cases waste streams have been mixed. The problem may be more pronounced in countries having small amounts of radioactive waste which may not have the necessary funds to characterise the waste using available technology. Therefore, there is a need for developing reliable and affordable technologies for cost-effective characterization and segregation of historical preconditioned radioactive waste. Non-destructive assay techniques could enable the rapid characterisation of wastes prior to packaging, during storage, prior to dispatch to a GDF, or upon receipt at a GDF. These techniques could allow characterization of the gamma-radionuclide content, fissile content, physical and chemical characteristics of waste packages.

Significant progress has been made in the development of robust disposal concepts (including packaging options) for spent fuel, high-level wastes and many intermediate and low-level wastes. There is an opportunity for the identification of good practice between Member States where disposal concepts have been developed, however there is also a need to develop novel conditioning technologies for problematic wastes and further explore less-investigated waste conditioning options, such as geopolymers.

Interim storage

Radioactive waste may be transported and placed in interim storage prior to disposal covering a timespan of several decades up to a century or more. Unexpected delays in disposal programmes may extend storage periods beyond what was originally anticipated in the national programme. Therefore key considerations include degradation of the wasteforms and packaged waste during these relatively long or extended timespans, and the resulting impacts on the safety of the storage facility, as well as on the operational and post-closure safety of the geological disposal facility. Key considerations currently include waste package storage monitoring systems, aging and sealing of spent fuel storage casks, potential impacts of defects on spent fuel performance and re-packaging and/or re-working of packaged waste.

Transportation between facilities

Once a disposal facility is constructed and regulatory authorisation has been given to accept wastes for disposal, waste will need to be transported safely and securely to the facility from the sites where it is being stored. International standards and guidance for the safe transport of radioactive materials have been developed on the basis of world-wide experience and best practice. This experience is distilled into the International Atomic Energy Agency (IAEA) Transport Regulations, which apply to road, rail, sea and air transport of radioactive materials. Within EURAD, we anticipate sharing of good practice and experience to continue, particularly as advanced programmes move closer to transport and emplacement of waste in Europe's first geological disposal facilities.

Radionuclide inventory and source term

The nature and quantity of wastes for disposal, including their chemical and physical form, their packaging / conditioning and their radionuclide and chemical composition are known as the radioactive waste inventory for disposal. Improved understanding of (i) the inventory, (ii) the radionuclide source term and (iii) more generally, the evolution of the waste behaviour throughout the planned interim storage, operational and post-closure phases of a geological disposal facility lifecycle is important for designing the disposal system.

For wastes, such as Spent Fuel or vitrified High-level Waste, their wasteform is fixed, and therefore their physical and chemical form is used as a direct input to design of the disposal system, including disposal packaging. For other wastes (e.g. long-lived ILW), where more varied processing and treatment options are encountered, some enhancements in the robustness of the wasteform (and disposal package), and its contribution to overall safety performance of the disposal system may be considered, and therefore may vary depending on the disposal approach and concept adopted by each disposal programme owner to complement site conditions. For these wastes, knowledge of the radionuclide and chemical inventory (including metals and organic compounds) and the chemical state of its components are important. Data quality of waste inventories is variable, with uncertainty often dominated by waste heterogeneity.

In general, only a small subset of radionuclides will dominate the post-closure safety case of a disposal facility. However, since the composition of a wasteform contributes to the overall performance of the disposal multi-barrier system, improved mechanistic understanding for the release kinetics of the radionuclide and chemical species may enhance understanding of the source-term for key species in performance assessments.

The source term for a wasteform is not always an intrinsic wasteform property but may also depends as well on its disposal environment. Oxidizing or reducing disposal environments or the presence of hydrogen are of particular importance for the source term from spent nuclear fuel waste packages. In the case of vitrified waste, strong coupling exists between the wasteform performance and the presence of near field materials (e.g. clay interactions with iron corrosion products). The presence of water vapor in unsaturated settings of disposal vaults, or water flow rates in saturated environments are also an important factor influencing the source term. Fundamental understanding of these couplings is available, but the long-term operation of the governing mechanism needs to be assured. Some work on natural analogue systems may help clarify such long term post-closure process understanding.

The EC CAST project (2013- March 2018) provided understanding of the ^{14}C source term (focused on speciation) for graphite, activated metals (Zircaloy and stainless steel) and ionic exchange resins. Further understanding may be helpful, particularly in support of the disposal of intermediate and low-level wastes, in order to provide confidence that the environmental and radiological impact of any release of these species will be acceptable. The management of some radioactive waste is still a challenge, while for some others there is the potential for optimisation. This includes operational wastes, by-products from existing processes (e.g. sludges), chemically reactive wastes, irradiated graphite, etc. Radioactive waste treatment processes (for example, thermal treatment) could be applied to a wide range of waste streams and could provide benefits in feasibility to meet waste acceptance criteria at a disposal facility, safety demonstration, volume and hazard reduction and cost savings.

Regarding spent fuel, the EC FIRST Nuclides project aimed to determine the fraction and the chemical form of some relevant elements, mainly ^{14}C, ^{36}Cl and ^{79}Se. Quantification of the activation products ^{14}C and ^{36}Cl that arise from N and Cl impurities in fuel, and understanding the impurity level ranges in fuels from different suppliers is still an open question identified at the end of the project. Internationally, considerable effort has been devoted to the long-term consideration of fission and activation product releases from spent fuel that may become exposed to groundwater once its container is breached (post-closure/disposal phase).

Waste acceptance criteria

As programmes move close to implementation, understanding of the nature and quantities of waste becomes formalized by waste acceptance criteria (WAC). This criteria includes a set of requirements for each waste management facility (including a geological disposal facility), taking into account specific characteristics of the waste to be disposed, the disposal concept adopted, and local site conditions. International cooperation and coordination in developing better understanding of the processes governing the source term and how this translates into waste acceptance criteria, as well as its use in the safety assessment, requires ongoing development.

Multi-national, regional or shared facilities

Some programmes across Europe consider the feasibility of regional or shared facilities (including multi-national repositories) that can provide infrastructure for all, or part, of the waste management route for a specific waste type. Planning of such facilities encompasses important and innovative developments (including the legal framework), which have been considered in work under the auspices of the EC or IAEA (See, IAEA - Developing multi-national radioactive waste repositories). Within EURAD, scope undertaken to understand waste management routes, as part of pre-disposal activities may consider aspects that are important to those national programmes that consider the use of multi-national, regional or shared facilities.

RD&D Priorities and Activities of Common Interest to be addressed by EURAD:

Scientific Theme 2: Radioactive waste characterisation, processing and storage (Pre-disposal activities), and source term understanding for disposal.	• **Identifying good practice in the management of inventory data and uncertainty treatment.** - Expected outcomes and impact: Improved understanding of those species that dominate the transport, operations and post-closure safety cases and targeted fit-for-purpose assay that can enable cost-effective data quality improvements (J1.1.1/High). - Cooperation and relevant past projects: EC FIRST Nuclides project
	• **Developing novel conditioning technologies for non-mature and problematic waste.** - Expected outcomes and impact: Identification and sharing of good practice and in waste conditioning and packaging approaches for problematic wastes (J1.1.3/High). - Cooperation and relevant past projects: Check for EU-wide waste producers forum?
	• **Improved understanding of radionuclide release from existing and future wasteforms other than Spent Fuel.** - Expected outcomes and impact: Improved understanding of the radionuclide release mechanisms and associated kinetics for vitrified waste (ILW and HLW), metallic wastes, high organic content wastes, graphite, and cementitious wasteforms (J1.1.4/High). - Cooperation and relevant past projects: EC CAST project
	• **Developing reliable and affordable technologies for the radiological characterization and segregation of historical preconditioned radioactive waste.** - Expected outcomes and impact: Develop and demonstrate enhanced and/or novel non-destructive assay techniques (which maintain waste package integrity and containment) to provide quality assurance of packages being stored, transported or received at a disposal facility (J1.1.2/Medium). - Cooperation and relevant past projects: EC CHANCE project
	• **Improved understanding of the impacts of extended storage on waste package performance.** - Expected outcomes and impact: Identification, characterisation and management of uncertainties related to the performance of the final waste package (including the waste form) during prolonged storage, e.g. ageing, confinement integrity, handling constraints, including effects on specific materials of casks for dry storage of Spent Fuel (J1.2.2/High). - Cooperation and relevant past projects: ?
	• **Improved understanding of the generation and release of radioactive trace gases and bulk gases from wasteforms and waste packages.** - Expected outcomes and impact: To further understand bulk gas generation from ILW, and gas generation from HLW and spent fuel, and potential impacts on the disposal system. To identify and resolve outstanding RD&D requirements arising from the EC CAST project, to increase understanding of the generation and release of gases (H2, CO2, CH4, HCl, CO, HF, HCN, etc.) resulting from radiolysis of polymers, including the influence of temperature, and to increase understanding of the generation and release of hydrogen resulting from corrosion (J1.4.2/High). - Cooperation and relevant past projects: EC CAST project
	• **Demonstration of geopolymer performance in representative disposal conditions.** - Expected outcomes and impact: To develop an appropriate understanding of the radiolytic performance and product stability, gas-permeability, resilience to cracking from gas production, fire performance and long-term chemical stability

	(leach performance) of geopolymers used for waste solidification in the context of the disposal environment (J1.1.5/Medium). - Cooperation and relevant past projects: Existing development group?
	• **Improved understanding of the nature and quantities of the likely chemotoxic component of common wastes.** - Expected outcomes and impact: Enhanced confidence in packaging and conditioning methods, and of the long-term environmental and radiological impact of wastes containing chemotoxic elements (J1.1.7/Medium). - Cooperation and relevant past projects: Existing development group?
	• **Optimisation of radioactive waste treatment techniques where there is potential for volume/hazard reduction and potential cost savings.** - Expected outcomes and impact: Optimisation of waste treatment options leading to potential benefits in terms of Waste Acceptance Criteria, safety demonstration, volume and hazard reduction and cost savings (J1.1.8/Medium). - Cooperation and relevant past projects: EC projects CAST, Carbowaste and THERAMIN
	• **Improved understanding of the behaviour of packaged Spent Fuel for a range of hypothetical fire and impact scenarios during operations and transport, and consolidation of existing understanding of post-closure Spent Fuel release processes.** - Expected outcomes and impact: Improved mechanistic understanding of the release of fission products from the different types of spent fuels to better predict the radionuclide source term for operational and post-closure safety assessment (J1.1.9/Medium). - Cooperation and relevant past projects: EC projects SFS, MICADO, FIRST Nuclides, DISCO
	• **Fourth generation (Gen (IV)) wastes.** - Expected outcomes and impact: To understand the nature and quantities of wastes arising from a fourth generation of nuclear reactors, identify challenges to the disposal of such wastes and enable early feedback to reactor system designers in order to mitigate associated risks (J1.1.6/Low). - Cooperation and relevant past projects: ?
	• **Quantification of fissile content of spent fuel.** - Expected outcomes and impact: Improved understanding of the characteristics of spent fuel (J1.1.10/Low). - Cooperation and relevant past projects: ?

Enabling Knowledge Management, Strategic Studies and other Cross-cutting Activities Identified of Common Interest that relate to Theme 2:

Strengthened links between Implementers and Waste Producers: To enhance cooperation in the process of spent fuel and nuclear waste disposal solutions and to improve understanding of spent fuel arisings, including those from innovative fuel types (J3.7)

Inventory collation and forecasting: To ensure that all countries implementing a disposal facility develop a comprehensive inventory (J3.5).

Methodologies applied to define radionuclide inventories: To further understand evolution of the radionuclide inventory after disposal including the use of radionuclide vectors, and uncertainties about databases of radionuclide properties (J3.6).

Understanding of the potential for long-term storage as a management option for disused sealed radioactive sources: To understand the potential impact of improving technology for the treatment or re-use of disused sealed radioactive sources as an alternative to disposal (J3.10).

Management of damaged waste packages and the criteria and methods for reprocessing aged waste: To share good practices with respect to minimising radiological consequences and addressing waste acceptance criteria in the event that packages have aged and require re-processing or have become damaged prior to transfer to a geological disposal facility (J1.2.4)

Operational lifespan of interim storage facilities: To support the safe management and safety assessment of existing storage facilities and design criteria for new storage facilities (J.2.4.5).

Waste acceptance criteria: To develop good practice guides for the derivation of waste acceptance criteria and increase confidence in, and further refinement of, inventory uncertainty quantification methods, including sensitivity studies (J2.1.6).

Ongoing and active work (inc. Horizon 2020 projects) addressing Theme 2:

With the purpose of sharing experience and knowledge on waste management routes between interested organisations from different countries, with programmes at different stages of development,

with different amounts and types of radioactive waste), a strategic study (EURAD WP9-ROUTES) has been initiated to look holistically at waste management routes in Europe from cradle to grave. Specifically this will look across the spectrum of challenging wastes, characterisation approaches and waste acceptance criteria established across Europe, and identify areas of focus for the EURAD in the future.

The EC Horizon2020 call, supported 4 projects running from 2017-2021 which will contribute further understanding and knowledge to address remaining challenges in Scientific Theme 1 - CHANCE, DISCO, INSIDER and Theramin.

The CHANCE project aims to address the as yet unsolved and specific issue of the characterization of conditioned ILW radioactive waste (CRW). CHANCE will establish a comprehensive understanding of current characterization methods and quality control schemes for conditioned radioactive waste in Europe. CHANCE will develop, test and validate already-identified and novel new techniques that will undoubtedly improve the characterization of CRW. One of the project's key tasks will be identification of links and overlaps between waste acceptance criteria and actual waste characterization technologies available, in order to identify specific, as yet unsolved, methodology issues and technology gaps.

The DISCO project aims to fill the gap of knowledge on spent fuel dissolution arising from the development and use of novel types of fuel (Cr-doped and MOX). The project aims to enhance understanding of spent fuel matrix dissolution under conditions representative of failed containers in reducing repository environments and to assess whether novel types of fuel behave like the conventional ones. This project aims to expand the database on spent fuel dissolution with results from dissolution studies. The effects of dopants will be investigated through experiments using both spent nuclear fuel and synthetic materials specifically designed for the project. In addition, chemical modelling will be employed to enhance understanding.

The INSIDER project aims to develop new methodologies for more accurate initial estimation of contaminated materials, resulting waste volumes and timely planning during decommissioning and dismantling (D&D) operations. The envisaged project outcomes will enable building of a fit-for-purpose representation of the radiological status of facilities (or components), at a relevant precision level allowing improved decision making when considering different D&D scenarios and options.

The Theramin project is focussed on thermal treatment for radioactive waste minimisation and hazard reduction. Relevant technologies include in-container vitrification, gasification, plasma treatment and hot isostatic pressing. Project outputs will provide an EU-wide strategic review and assessment tool to assess the value of thermal technologies applicable to a broad range of waste streams (ion exchange media, soft operational wastes, sludge, organics and liquids). This will include the applicability and achievable volume reduction of the technologies through ‘first-of-a-kind’ active and non-active full-scale demonstration tests, and will assess the disposability of residues. THERAMIN will establish a pan-European network of expertise on thermal treatment, will provide for cross-European technology transfer, and will identify prospects for sharing of facilities between countries facing similar problems.

Within EURAD first phase, an RD&D work package on spent fuel characterisation and evolution has been established. This will study the properties, behaviour and associated uncertainties of spent nuclear fuel from the time when it is irradiated in the reactor up to the time it is emplaced in a geological disposal facility. Both experimental and numerical activities are proposed. The work seeks to understand fundamental out-of-core behaviour of fuel and cladding to ultimately ensure safe, reliable and economical use of storage and disposal systems. The work package includes Knowledge Management activities, including a state-of-the-art review on spent fuel characterisation and sources of uncertainties, and the development of guidance for model calculations, radionuclide inventory calculations, characterization methods and uncertainties calculations for spent fuel.

THEME 3: ENGINEERED BARRIER SYSTEM (EBS) PROPERTIES, FUNCTION AND LONG-TERM PERFORMANCE

Introduction and background:

Spent Fuel and high-level waste disposal canisters

The conditioned waste is placed in a container (sometimes called a canister), creating what is referred to as the waste package. The container must be chosen so that the waste can, if needed, be safely transported and handled leading up to its disposal. The material and design of the container can be chosen to then provide reliable physical containment under disposal conditions for extended periods of time. This can be achieved in a variety of ways, for example, in the case of metallic containers, by using a metal such as copper that is highly corrosion-resistant under certain chemical conditions or by using sufficient thickness of a metal such as carbon steel so that it will take a long time to be corroded through. For HLW and Spent Fuel, packaging developments are relatively mature and hence a continued exchange on latest developments is envisaged within EURAD. With new waste streams (advanced fuel cycles) and new host rock systems under consideration, alternative container materials for HLW/SF may be considered.

Containers for long-lived intermediate and low level wastes

For intermediate and low-level wastes, stainless steel, ductile cast iron and concrete containers are typically considered. Such containers have been used to package wastes across Europe, and therefore there is a wealth of existing information that can be shared through cooperation actions.

Clay-based backfills, plugs and seals

The backfill (or buffer) in this context refers to material that is placed immediately around emplaced waste containers in a disposal facility. The material and design can be chosen so that the buffer or backfill provides one or more beneficial functions.

Many studies have been performed to characterise the behaviour of swelling clay, including bentonites. The main requirements are on swelling capacity to fill the technological voids and on low hydraulic conductivity. This implies a good understanding of physical processes that occur throughout the lifecycle of the bentonite component (EBS, sealing or backfill) and a capacity to perform robust predictive simulations. Studies have concerned several types of bentonites in several physical forms, such as compacted blocks or pellet mixtures. Investigations of the behaviour of bentonites under particular conditions associated with their use in an industrial context need to be pursued. Especially, the role of heterogeneities due to installation or to external conditions such as local water inflow or temperatures in excess of 100°C. Such phenomena may lead to changes in the mineralogical composition of the bentonite, particularly in its clay content. These changes may affect the component as a whole (e.g. illitization) or an interface zone with the perturbation source (e.g. alkaline transformation).

For clay-based materials (e.g. bentonite) intended for use as a seal or to backfill galleries in the disposal facility, ongoing needs are also recognised. The main need is to consolidate the long-term performance of the seals at the component scale, taking into account all the (T)HMC perturbations between the different materials (concrete, bentonite, host-rock). For instance, there is still a need to improve our understanding of the consequences of chemical interactions at the interface between clay-based materials and concrete on long-term THM behaviour of the seals.

Cementitious-based backfills, plugs and seals

Cement-based backfills are envisaged for a number of disposal facilities for intermediate level wastes across Europe, and are commonly used as liners in disposal cells or as part of waste containers in many Member States existing facilities for low level waste / near-surface disposal. Further understanding is required to support their use as a backfill material for longer-lived wastes in geological disposal, particularly to understand their contribution to overall system performance during late post-closure timeframes. For cementitious materials, their physical behaviour, especially during the operational phase and post-closure THM-transient periods, is strongly influenced by boundary conditions, controlled by both the disposal system and the host rock (water saturation, temperature, etc.). To assess the evolution of the performance of the cementitious components these studies have to be extended to a longer time-period, considering various operating conditions.

Cementitious materials are also extensively planned to be used as disposal structures (buffer, plugs, waste matrices) which require further understanding of their long-term degradation behaviour, including the impacts of organics. This is especially the case for low pH cements.

Salt backfills

Salt backfill regimes and seals are essential elements of the EBS for a HLW repository in salt.

EBS system understanding

At the disposal-cell scale, once packaged wastes, and backfills and seals are emplaced in the disposal facility, the spectrum of processes and interactions to be considered in the performance assessment is rather broad and covers waste-container, container – backfill/buffers, and waste package-host rock interactions. Regarding data and models to support the long-term safety assessment, feasible and well-instrumented integral experiments and improved models may provide for more realistic understanding of engineered barrier system (or near-field) evolution and related uncertainty treatment.

Across the range of backfill and buffer materials under consideration, there is a need for improved understanding of the coupled mechanical/chemical evolutions at the interfaces with the waste package materials (glass/iron/clay, cement/bentonite, cement/metal, bentonite/metal) and between these materials and the host rock (iron/clay interactions, alkaline perturbation). Of particular interest are unsaturated conditions, where glass is corroded by water vapor. Understanding further relatively ‘short-term’ interactions (e.g. resaturation) versus ‘long-term’ interactions (e.g. development of gas pressure, backfill degradation etc.) occurring at interfaces is considered important. Another perturbation which has to be addressed is the influence of gases and microbes on geochemistry. These studies need to be supported by mock ups (at different scales) and in-situ experiments to verify that the components will behave as expected and that all the relevant processes have been taken into account, but also to demonstrate the ability to build complex components (buffer, plugs and seals).

Co-disposal of radioactive waste of different classifications or properties may be possible in some geological disposal facilities. Interactions between wastes with different properties may occur, unless only one type of waste is disposed of (e.g. spent fuel, vitrified waste, etc.). Even when disposing of one waste type, such as long-lived alpha containing waste, the diversity of the waste may lead to a situation where dissolution plumes can influence each other. Therefore there is an ongoing interest in optimisation of the disposal of wastes with differing characteristics and properties and the appropriate selection of engineered barrier materials when co-disposed in a single geological facility.

RD&D Priorities and Activities of Common Interest to be addressed by EURAD:

Scientific Theme 3: Engineered barrier system (EBS) properties, function and long-term performance	• **Improved understanding of the interactions occurring at interfaces between different barriers including waste packages in the disposal facility.** - Expected outcomes and impact: Knowledge of the physical and chemical transformations at the interface between waste packages and different barriers and materials and development of pore-scale models describing the impact on radionuclide migration and fluid transport, potential clogging in bentonite/cement or host-clay/cement interfaces, or increase in porosity in other interfaces under real repository conditions (J1.2.1/High). - Cooperation and relevant past projects: ?
	• **Characterised bentonite / clay-based material evolution under specific conditions to provide data on hydro-mechanical, thermal and chemical behaviour.** - Expected outcomes and impact: Enhanced understanding of post-closure safety considerations of bentonite and clay-based materials by extensive characterisation of different phenomena, including variations of properties

	arising from barrier installation, hydration history, elevated temperatures and chemical influences on long-term evolution behaviour (J1.3.1/High). - Cooperation and relevant past projects: EC BENIPA and BELBaR project
	• **Improved chemical and microbial data to better quantify gas generation and the consequences of microbial processes.** - Expected outcomes and impact: Improved mechanistic understanding, rather than bounding assumptions, to quantify kinetics of microbial catalysis of both gas consumption or gas production reactions, and the competition between them, and improved understanding of the topological description of rock surfaces interacting with gases (J1.3.2/High). - Cooperation and relevant past projects: EC MIND project
	• **Improved quantification and understanding of cement-based material evolution to improve long-term modelling and assessments.** - Expected outcomes and impact: Increased confidence in simulations by reducing uncertainties in input data and understanding of key processes (for both young and aged materials), taking into account specific conditions for waste disposal (temperature, radiation, redox etc.) and considering hydromechanical behaviour (shrinkage and creep), and passive and active corrosion impacts (J1.3.3/High). - Cooperation and relevant past projects: EC CEBAMA project
	• **Improved understanding of the impacts of different metallic and cementitious component phenomena on near-field evolution via improved models.** - Expected outcomes and impact: Improved geochemical models used in near-field modelling through numerical and experimental characterisation of their evolution and identification of the key THMC evolution processes (including metal corrosion / secondary phase formation, cement alteration and alkaline perturbations on the host rock) (J1.3.5/High). - Cooperation and relevant past projects: EC projects CAST, Carbowaste and THERAMIN
	• **Improved understanding of gas reactivity in the EBS.** - Expected outcomes and impact: Increased understanding of gas reactivity in the EBS and host rocks under representative conditions and its potential impacts on geochemistry, safety-relevant processes and radionuclide migration (J1.4.4/High). - Cooperation and relevant past projects: ?
	• **Improved understanding of the performance of plugs and seals.** - Expected outcomes and impact: To further understand the coupled THMC behaviour of plugs and seals throughout the post-closure phase and to develop improved modelling capability to provide reassurance over the long-term (J2.2.2/High). - Cooperation and relevant past projects: EC projects RESEAL II, DOPAS
	• **Developing alternative HLW and Spent Fuel container material options and improved demonstration of their long-term performance.** - Expected outcomes and impact: Identification of alternative container materials or coatings beyond combined copper/cast iron or carbon steel, suitable for fulfilling container safety functions in current disposal systems and suitable for packaging novel wasteforms (J1.2.3/Medium). - Cooperation and relevant past projects:
	• **Improved understanding of low pH cements.**

	- Expected outcomes and impact: Increased understanding of low pH cements and their evolution (pH, mineralogy), including their composition, their potential for retarding particular radionuclide migration, determining suitable methodologies for measuring the pH of cements, understanding of the reinforcement corrosion process in low pH concrete if reinforced concrete is used, and their behaviour under high temperatures (up to 90 °C) (J1.3.4/Medium). - Cooperation and relevant past projects: EC CEBAMA project
	• **Improved description of the spatial and temporal evolution of transformations affecting the porous media and degrading materials in the near-field of HLW and ILW disposal systems.** - Expected outcomes and impact: Improved understanding of coupled interactions between reactive transport models, the waste alteration (e.g. corrosion of glass, polymer radiolysis/hydrolysis, etc.) and near-field materials (e.g. steel, concrete, etc.) (J1.3.7/Medium). - Cooperation and relevant past projects: ?
	• **Improved understanding of a salt backfill.** - Expected outcomes and impact: Improved understanding of the long-term behaviour and properties of a salt backfill, including influences of pressure and temperature on behaviour (J1.3.6/Low). - Cooperation and relevant past projects: EC BAMBUS II project, NEA-Salt Club
	• **Identify co-disposal interactions of importance to long-term safety.** - Expected outcomes and impact: Identified waste types and compositions that can generate plumes problematic for the integrity and retention of other wastes in a single facility and assessment of their potential impact on safety to support design optimisation (1.3.8/Low). - Cooperation and relevant past projects: ?

Enabling Knowledge Management, Strategic Studies and other Cross-cutting Activities Identified of Common Interest that relate to Theme 3: Engineered barrier system (EBS) properties, function and long-term performance

Use of clay-based materials in a geological disposal facility: To understand the properties and performance of different clay-based materials depending on their origin or mineralogy (1.3.1).

Low pH cement understanding: To consolidate existing knowledge on low pH cements, including their composition, impact on radionuclide migration and practical implementation (1.3.4).

Ongoing and active work (inc. Horizon 2020 projects) addressing Theme 3:

There are several ongoing EC projects that will provide information and knowledge to support understanding of the Engineered Barrier Systems. The Horizon 2020 call supported the EC BEACON project running from 2017-2021 which will develop and test the tools necessary for assessment of the hydro-mechanical evolution of an installed bentonite barrier and its resulting performance in a disposal facility. Now that several European national programs are moving towards licensing, construction and operation of repositories, verification of EBS component behaviour is of high common interest. Therefore within BEACON, cooperation between design and engineering, science and performance assessment experts is planned in order to verify the performance of current designs for buffers, backfills, seals and plugs as part of the EBS.

A project nearing completion with outputs of direct relevance to this Theme includes the EC MIND project. It is a unique multidisciplinary project which brings together a broad range of leading research institutions and stakeholders in the field of radioactive waste disposal. The project aims to reduce uncertainty of safety-relevant microbial processes controlling radionuclide, chemical and gas release from long-lived intermediate level wastes (ILW), high-level waste and spent fuel geological disposal. Outputs will be of direct relevance to several of the EURAD-1 projects (Work Packages) described herein, so supporting ongoing dissemination activities with the knowledge management activities is recognised.

Completing in 2019, the CEBAMA project addresses key issues of relevance for long-term safety and key scientific questions related to the use of cement-based materials in nuclear waste disposal applications. It includes materials used as waste forms, liners and structural components as well as sealing materials in a broad variety of applications. It aims to provide insight on general processes and phenomena and to develop a model for predicting the transport characteristics such as porosity, permeability and diffusion parameters of cement-based materials in contact with the engineered and natural barriers of repositories in crystalline and argillaceous host rocks.

Within EURAD first phase, a work package is included to understand the influence of temperature on clay-based material behaviour. Both clay host rock and bentonite buffer and their behaviour at high temperature are included (ranging from 100 °C to ~150°C). Mechanical behaviour is the focus area, with an overall objective to evaluate whether an increase of temperature is feasible and safe. The programme of work will aim to provide results that are applicable to a wide range of buffer material and clay host rocks, which can be useful for different national programmes.

Within EURAD a work package is included to support the assessment of the chemical evolution at the disposal cell scale . It considers interactions between disposal system components/materials and thermal, hydraulic and/or chemical gradients of relevance to ILW and HLW disposal concepts. The study of the disposal cell in this work package ranges from microscale processes at interfaces between different materials up to interactions of waste packages with their immediate surrounding near field environment and the host rock. The main objective is to identify, understand and describe the relevant processes driving the chemical evolution within selected generic disposal cell designs by analysing and combining information from available experimental studies and modelling exercises at both the process and system levels.

Also supported within EURAD is a work package dedicated to cement-organics-radionuclide-Interactions (CORI). Organic materials are present in some nuclear wastes and as admixtures in cement-based materials and can potentially influence the performance of a geological disposal system, especially in the context of low and intermediate level waste disposal. Therefore CORI aims to develop improved knowledge on organics degradation, organics-cement-interactions, and radionuclide-organics-cement-Interactions, all within the content of the post-closure radionuclide transport pathway for geological disposal facilities for ILW and LLW/VLLW, including surface/shallow disposal.

THEME 4: GEOSCIENCE TO UNDERSTAND ROCK PROPERTIES, RADIONUCLIDE TRANSPORT AND LONG-TERM GEOLOGICAL EVOLUTION

Introduction and background:

Long-term stability (uplift, erosion and tectonics)

A site should be geologically stable in order to ensure safety and also be predictable over long timescales to the extent required for assessing safety performance. A stable geological environment is not likely to be subject to sudden or rapid detrimental changes over long timescales because of its resilience with respect to internal and external perturbations. The geosphere contributes to isolation by providing a stable location deep underground that protects the geological disposal facility from any significant perturbations to the natural environment that may occur over the timescales of interest. The geosphere also contributes to containment by delaying the movement of any potential small amounts of long-lived radionuclides that are released from the EBS/near field, enabling their decay before they can pose a hazard to the biosphere.

The natural processes which may impact on the geosphere over the very long timescales associated with geological disposal are tectonics, uplift or subsidence and erosion, and the impacts of future climate, particularly potential future glaciations and related subglacial erosion and permafrost formation. Processes generally occur more slowly at depth; therefore reasonable predictions of long-term behaviour and evolution can be made.

Perturbations (gas, temperature and chemistry)

The properties of the host rock and geosphere control the slow release and migration of radionuclides in both the gas and aqueous phase once released from the EBS. The key issues to be addressed depend upon the geological environment and the associated disposal concept for the facility.

In a low permeability host rock, such as the Clay stones or evaporites, there is the possibility that gas could be generated at a faster rate than it can be removed without inducing fracturing in the host rock. Thus, depending on the likely rates of bulk gas generation, the potential for significant over-pressurisation may need to be considered for these concepts. For a disposal facility in a fractured higher strength rock it is likely that transport of gas through the host rock would be sufficient to prevent significant over-pressurisation of the EBS. In several disposal concepts, the potential for migration of free gas containing gaseous radionuclides to the biosphere is an important issue.

The EC FORGE (Fate Of Repository Gases) project investigated gas migration issues of relevance to geological disposal performance assessment.

Further needs identified include water (including solutes) and gas transfer during the resaturation phase, and understanding further complexity with respect to the coupling between hydraulic and other processes. The coupling with thermal processes is already implemented in most of the two-phase flow numerical codes and can be used on large scales. Concerning mechanical coupling however, the high complexity of incorporating full coupling, limits for the moment its use to a restricted volume. Having a simplified version of such a coupling, enabling its use in a full scale two-phase flow evaluation, would be highly useful.

Aqueous pathways and radionuclide migration

Regarding the aqueous phase releases, the rate of radionuclide migration depends not only on the distance of the disposal area from the biosphere and the rate of groundwater flow, but radionuclide migration is further retarded by the interaction of dissolved radionuclides with the diverse surfaces of wasteform and container degradation products, backfill materials, minerals and organic matter. Retention on solid surfaces may be reduced by the formation of soluble solution complexes and organic or inorganic colloids. The migration process is different for each type of radionuclide and influenced strongly by the geochemical environment.

There has been research on the various topics of radionuclide migration for more than 30 years, often funded by the European Commission. This has included both detailed mechanistic and applied studies. The present programme focuses on remaining uncertainties related to the influence of temperature, organic ligands, microbial perturbations, colloidal interactions and redox conditions on radionuclide behaviour (within the engineered barrier system – in Theme 3) the excavated disturbed zone, host rock and the far field (i.e. the geosphere). Scope continues to include laboratory-scale experiments, modelling and also the upscaling of process understanding through the use of URLs and large-scale mock-ups and/or full scale in situ testing.

RD&D Priorities and Activities of Common Interest to be addressed by EURAD:

Scientific Theme 4: Geoscience to understand rock properties, radionuclide transport and long-term geological evolution	• **To increase understanding of gas migration in different host rocks.** - Expected outcomes and impact: Further understanding of gas generation and migration through the EBS and far field, including the fate of reactive gases (including upscaling from laboratory / URL studies) and the mechanical behaviour of host rock. Scope to consider carbon-14 migration, gas flow in EBS materials at elevated temperatures, gas interactions between packages and backfill, the impact of engineering design on gas migration, refined models of gas migration, including the treatment of uncertainty arising from the nature of the geological environment (J1.4.1/High). - Cooperation and relevant past projects: EC CAST and GASNET Project
	• **Improved understanding of gas reactivity in different host rocks.** - Expected outcomes and impact: Increased understanding of gas reactivity in the EBS and host rocks under representative conditions and its potential impacts on geochemistry, safety-relevant processes and radionuclide migration (J1.4.4/High). - Cooperation and relevant past projects: ?
	• **Improved representation of sorption mechanisms and coupled chemistry / transport processes for various media.** - Expected outcomes and impact: To represent heterogeneous media (cement-based materials, clay-rock, crystalline rocks, bentonite, corrosion products…) in speciation, sorption (considering competitive effects) and transport models considering the variability of barrier properties at all scales (J1.5.2/High). - Cooperation and relevant past projects: EC CatClay project
	• **Improved understanding of bounding conditions for the effects of microbial perturbations on radionuclide migration to support performance assessments.** - Expected outcomes and impact: Quantification of microbe populations, energy and carbon source availability, and their impact on radionuclide migration, barrier performance and chemical environmental conditions as a function of time (J1.5.5/High). - Cooperation and relevant past projects: EC project MIND
	• **Develop and implement two-phase flow numerical codes to increase gas transient representation at the disposal scale.** - Expected outcomes and impact: Increase the degree of representativeness of two-phase flow models which may be used at the disposal scale by increasing the level of coupling with mechanics especially (J1.4.3/Medium). - Cooperation and relevant past projects: ?
	• **Quantification of long-term entrapment of key radionuclides in solid phases to inform reactive transport models.** - Expected outcomes and impact: Experimental thermodynamic and kinetic data and supporting models to quantify mechanisms for irreversible entrapment in solid phases for key radionuclides (e.g. 14C

	and U as carbonates and 79Se in sulphur-bearing phases) (J1.5.3/Medium). - Cooperation and relevant past projects: Project SKIN (Slow processes in close-to-equilibrium conditions for radionuclides in water/solid systems of relevance to nuclear waste management).
	• **Improved understanding of the transport of strongly sorbing radionuclides.** - Expected outcomes and impact: Improved representation of heterogeneous media, anoxic environmental conditions, and retention of redox sensitive radionuclides or toxic elements in transport models (J1.5.4/Medium). - Cooperation and relevant past projects: EC projects SKIN, CatClay
	• **Improved understanding of the role of organics (either naturally occurring or as introduced in the wastes) and their influence on radionuclide migration.** - Expected outcomes and impact: Improved understanding of the nature of the organic molecules generated by the organic waste or admixture degradation, their stability with time, their effects on radionuclide migration, organic mixtures, the nature and release rate of organic compounds resulting from polymers radiolysis and hydrolysis, and implementation in a reactive transfer model (J1.5.6 & J1.5.10 / Medium). - Cooperation and relevant past projects: ?
	• **Improved understanding of the influence of temperature on radionuclide migration and representation of effects in geochemical models.** - Expected outcomes and impact: Improved understanding of sorption constants for radionuclides (distribution coefficients or surface complexation constants) as a function of temperature, groundwater composition as a function of temperature, and the effect of temperature on potential transformations of solid phases, radionuclide speciation and any associated impact on solubility (J1.5.7/Medium). - Cooperation and relevant past projects: EC projects MIND
	• **Improved understanding of the role of colloids and their influence on radionuclide migration.** - Expected outcomes and impact: Experiment data and model development for colloid generation and transport, including transport parameters for inorganic colloids and radionuclide/organic complexes (J1.5.8/Medium). - Cooperation and relevant past projects: EC project BELBAR
	• **Improved understanding of the influence of redox on radionuclide migration.** - Expected outcomes and impact: Improved understanding of the temporal and spatial evolution of redox conditions in engineered barrier systems, the effect of redox perturbations able to modify the expected oxidation states (and mobility) of radionuclides, and the role of kinetics of radionuclide reduction/oxidation (J1.5.9/Medium). - Cooperation and relevant past projects: EC project ReCosy
	• **Developing a geochemical model for volatile radionuclides.** - Expected outcomes and impact: To develop a geochemical model for a non-saturated system describing the distribution of volatile radionuclides between surface films of water, the aqueous phase and the gas phase, and to develop understanding of the capacity of host rocks and cement-based materials to interact with mainly 3H and 14C (J1.5.11/Medium). - Cooperation and relevant past projects: EC project Carbowaste, CAST
	• **Enhanced treatment of climate change, non-human biota, land-use and parameter derivation in biosphere models**

	- Expected outcomes and impact: To enhance understanding of biosphere processes so as to improve safety case confidence (J2.2.6/Medium). Cooperation and relevant past projects: EC projects BIOCLIM, BIOMOSA
	• **Developing models of groundwater evolution.** - Expected outcomes and impact: To increase understanding of groundwater evolution, including composition and flow, relating to past and future events, such as climate change, glaciation and related subglacial erosion and permafrost formation (J1.6.3/Medium). • Cooperation and relevant past projects: ?
	• **Improved understanding of the processes of fracture filling.** - Expected outcomes and impact: Further understanding of fracture filling, including modelling of the composition of fracture filling minerals and the associated mechanical strength of the fillers as a function of temperature and time (J1.6.1/Low). - Cooperation and relevant past projects: EC CROCK project
	• **Improved understanding of the impact of rock-matrix diffusion on radionuclide travel time through the geosphere.** - Expected outcomes and impact: Improved understanding of the impact of rock-matrix diffusion on radionuclide travel time through the geosphere (J1.6.4/Low). • Cooperation and relevant past projects: ?

Enabling Knowledge Management, Strategic Studies and other Cross-cutting Activities Identified of Common Interest that relate to Theme 4:

Impact of rock matrix diffusion on travel time through the geosphere: To ensure that learning from site characterisation activities in advanced programmes is disseminated to less-advanced programmes (J1.6.4).

Development of site evolution models, and how to manage data as it is obtained during the site characterisation phase: To further knowledge on site evolution models, and how the physical, geochemical, geotechnical and hydrogeological properties of the host rock and disposal facility change over time (J3.2).

Ongoing and active work (inc. Horizon 2020 projects) addressing Theme 4

Within EURAD a work package on mechanistic understanding of gas transport in clay materials is included. It aims to determine the range of conditions under which each identified gas transport regime is possible, in clay materials representative of the potential host rocks (and EBS components – relevant for Theme 3) considered in Europe. In this way, data will be obtained in conditions spanning low (diffusion) to high (advection) gas generation rates. For each of these gas transport regimes, the effects on performance related properties of the materials being tested will be investigated. The experimental effort will be complemented by the development and evaluation of modelling tools for simulating gas transport in clay-rich media for a wide range of gas transport regimes.

Also supported by EURAD is a work package which is focussed on fundamental understanding of radionuclide retention. Scope covers radionuclide and chemical species migration focussed on sorption processes, heterogeneous redox processes and in particular overall radionuclide mobility in “real” systems. Regarding sorption, the work package will address open issues on sorption reversibility, uptake mechanisms (adsorption vs. incorporation), molecular structure of surface complexes, effect of temperature as well as the thermodynamics of porewater-surface interfaces (acid/base surface properties, Kw), sorption site density (e.g. accessibility), sorption competition and surface diffusion. Investigations on surface induced (heterogeneous) redox processes will provide a better understanding of the coupled sorption and electron transfer interface reactions governing the retention of redox-sensitive radionuclides at Fe(II)/Fe(III) bearing minerals surfaces so as to improve our capacity to model, and thus predict, the fate of these elements in the context of radioactive waste storage. Studies on the mobility of radionuclides in “real” clay rocks as well as crystalline rocks will provide insight into the role of microstructures and the impact of chemical boundary conditions on radionuclide migration.

THEME 5: GEOLOGICAL DISPOSAL FACILITY DESIGN AND THE PRACTICALITIES OF IMPLEMENTATION

Introduction and background:

Facility and disposal system design

The feasibility and suitability of a selected or preferred disposal concept(s) is an ongoing activity to review design and layout of the disposal system, together with the associated evaluation of operational and long-term safety and an assessment of socio-economic aspects. With respect to overall concept feasibility assessment, a common view on areas of significant safety impact could be identified and proposal formulated for appropriate degree of regulatory control. As disposal programmes progress through successive stages of development, the process for concept adaptation and optimisation requires careful consideration.

An important part of the facility design is asset management, which refers to the strategic plan, processes and actions that are needed to upkeep the disposal facility production system in an efficient and effective manner over the whole life cycle of the system. Engineering asset management offers a set of processes, methods and tools for system reliability evaluation, life cycle cost assessment, maintenance development and setting Key Performance Indicators for asset management operations.

Constructability, demonstration and verification testing

There is a need to demonstrate that the concepts for disposal are practical in terms of their actual implementation in a host rock. There are many aspects to this, from large-scale testing of systems and equipment, to iterating the final design of the facility to allow for adaptations to actual site conditions. This is often referred to as the industrialisation phase of a disposal programme which, together with optimisation activities (including optimisation of radiation protection), remains a key part of advanced programmes currently moving towards construction and operations.

Once facilities become operational, there will be an ongoing need to evaluate the behaviour of key components of the disposal system, or the impacts of the disposal system and its operation on the environment – and thus to support decision making during the disposal process and to enhance confidence in the disposal process. Observations may be continuous or periodic in nature, and may include measurements of engineering, environmental, radiological or other parameters and indicators / characteristics.

Health and safety during transport, construction, operations and closure

During facility operations, all activities performed shall respect the requirements of long term safety. Nevertheless, some technologies and practices, if improperly implemented, may result in harm to workers and negative impacts on the long-term performance of the disposal system. It would therefore be beneficial to share lessons learned from other operational experience, incidents and health and safety -related accidents internationally.

Monitoring and retrievability

During the operational phase of a geological disposal facility it is likely that appropriately selected parameters will be monitored in order to provide reassurance of the as-built integrity of the disposal facility. In practice, the selection of monitoring technologies is based on the safety case, concept and requirement for each parameter (measuring period, frequency). Although considerable effort has been invested, further development utilising evolving technologies would be beneficial. The combination of non-invasive techniques is considered an essential aspect of monitoring due to their advantages over common intrusive methods. The ambition includes an increase in the range of physical and chemical properties that are monitored to allow the means for cross-correlating monitoring results.

Monitoring technology selection is also based on the need to provide minimal disturbance to the engineered barriers. R&D is necessary in order to develop and characterise improved monitoring technologies that will not disturb the disposal cell, seal and plug, and that may be functional for long periods of time (for example, in excess of one hundred years).

Retrievability of wastes and reversibility of waste emplacement and decision making during implementation are treated at the national level, as they are pursuant to local and national requirements and legislation. How such requirements impact on design criteria has been an area of ongoing work within EC projects and NEA initiatives. Some technologies for retrievability of wastes packages were developed and tested within the EC ESDRED project, however further work is identified to continue development of technologies to retrieve waste packages (e.g. development of robots and sensors). Likewise, many challenges remain with respect to reversibility of decisions, including those related to safety and the economy.

RD&D Priorities and Activities of Common Interest to be addressed by EURAD:

Scientific Theme 5: Geological disposal facility design and the practicalities of construction, operations and closure	• **Developing monitoring strategies appropriate to the operational phase (including facility construction and work acceptance) of geological disposal facilities that will not adversely affect the performance of the disposal system** - Expected outcomes and impact: To capitalise on recent advances in monitoring technologies by developing, trialling and assessing a range of monitoring strategies utilising state-of-the-art cost-efficient monitoring technologies. To investigate the impact of monitoring technology on the performance of a range of disposal systems (J2.5.1/High). - Cooperation and relevant past projects: EC Projects SOMOS, MoDeRn, MoDeRn 2020.
	• **Developing innovative monitoring technologies.** - Expected outcomes and impact: To develop innovative technical solutions and improvement of existing technologies to facilitate the integration of monitoring technologies into the final repository design and to maintain the reliability of the monitoring systems (J2.5.3/High). - Cooperation and relevant past projects: EC Project MoDeRn 2020.
	• **Developing appropriate monitoring technologies for closure and a period of post-closure institutional control in links with relevant parameters for safety.** - Expected outcomes and impact: To provide reassurance of conditions following closure by identifying possible parameters for monitoring during the post-closure stage up to the end of institutional control including the development of appropriate monitoring techniques (e.g. wireless transmission, large energy autonomy technologies) (J2.5.2/Medium). - Cooperation and relevant past projects: ?
	• **Optimisation of backfilling and other major implementation processes, including waste emplacement, retrieval and sealing technologies.** - Expected outcomes and impact: To characterize at various scales (from laboratory scale to demonstration at full scale) the capability of the backfill material to meet the main requirements. This would require the study of mixtures between excavated rock with some additives such as cement to improve mechanical properties or bentonite to increase swelling capacity. Effects of long term storage should also be studied as it could lead to storage recommendations (J2.5.7/Medium). - Cooperation and relevant past projects: ?
	• **Developing cost-effective asset management strategies for use in the design.** - Expected outcomes and impact: To enable definition of the requirements arising from the upkeep and improvement of assets in the facility design, including a preliminary asset management strategy (J2.5.8/Medium) - Cooperation and relevant past projects: ?

	• **Developing operational hazard assessment methodologies (inc. flooding risk)** - Expected outcomes and impact: To identify potential pathways for water ingress from representative geological disposal facility designs. To assess impacts of flooding on operational safety and long-term safety and performance (J2.4.2/Low). - Cooperation and relevant past projects: ?.
	• **Improved understanding of waste package durability and disposal facility infrastructure with respect to retrievability.** - Expected outcomes and impact: To improve understanding of the durability of waste packages ensuring their ability to be handled, durability of structures ensuring the maintenance of functional free play, removal operations performed without jeopardising safety, and the aptitude for dismantling of partial closure components (for cells and drifts) and for re-equipping the facility (J2.5.4/Low). - Cooperation and relevant past projects: EC ESDRED project
	• **Assessment of the technical feasibility and lifecycle adaptation of a geological disposal concept for a specific site and specific nuclear waste type.** - Expected outcomes and impact: Development of a common view on areas of significant safety impact with respect to technical feasibility of a geological disposal concept. Development of change control approaches to appropriately capture design adaptation and feedback into safety assessment (J2.5.5& 3.8/Low). - Cooperation and relevant past projects:?
	• **Verify robustness of disposal system designs using large scale mock ups.** - Expected outcomes and impact: To verify the robustness, and demonstrate feasibility and performance of disposal facility designs and to demonstrate the capacity to build some complex components such as seals or the engineered barriers (J2.5.6/Low). - Cooperation and relevant past projects:?

Enabling Knowledge Management, Strategic Studies and other Cross-cutting Activities Identified of Common Interest that relate to Theme 5:

Accident management and emergency preparedness: To improve the understanding of potential safety issues with regards to RWM, including disposal (J2.4.4).

Asset management: To develop criteria for managing assets that balances risk, cost and benefit of the assets over their life cycles and evaluate alternative scenarios for asset management approaches (J2.5.8).

Managing co-disposal: To optimize the use of geological facilities by enabling disposal of wastes with a variety of compositions and properties (J3.12).

Radiation protection optimisation principle: Improved methodologies for applying the principles of 'Best Available Technology' (BAT), 'As Low As Reasonably Practicable' (ALARP) and 'As Low As Reasonably Achievable' (ALARA) to disposal system development to ensure the safety and radiological risks resulting from the disposal system throughout its lifecycle are reduced so far as reasonably practicable and immediate (operational) risks are balanced against the post-closure risk (J3.13).

Reversibility: To develop a common position across Europe, and to exchange good practices (J3.17).

Ongoing and active work (inc. Horizon 2020 projects) addressing Theme 5:

Based on the outcomes of the EC MODERN project, collaborative efforts continue through MODERN2020 on monitoring technologies and strategies for use in a geological disposal. It aims to provide the means for developing and implementing an effective and efficient repository operational monitoring programme, that will be driven by safety case needs, and that will take into account the requirements of specific national contexts (including inventory, host rocks, repository concepts and regulations, all of which differ between Member States) and public stakeholder expectations (particularly those of local public stakeholders at (potential) disposal sites). The work in the Modern2020 Project will address: i) Strategy: development of detailed methodologies for screening safety cases to identify needs-driven repository monitoring strategies and to develop operational approaches for responding to monitoring information; ii) Technology: carry out research and development (R&D) to solve outstanding technical issues in repository monitoring, which are related with wireless data transmission technologies, alternative long term power supplies, new sensors, geophysics, reliability and qualification of components.; iii) Demonstration and Practical Implementation: enhance the knowledge on the operational implementation and demonstrate the performance of state-of-the-art and innovative techniques by running full-scale and in-situ experiments; and iv) Societal concerns and Stakeholder Involvement: Develop and evaluate ways for integrating public stakeholders concerns and societal expectations into repository monitoring programmes.

THEME 6: SITING AND LICENSING

Introduction and background:

The selection of a site (or sites) for a geological disposal facility is clearly the most important challenge to the successful implementation of long-term management of radioactive wastes. Therefore this topic is of great interest to early-stage programmes that have yet to identify a preferred site for a geological disposal facility, including in this case those programmes that have experienced reversals in past site selection projects. This theme represents the clearest example of the importance of societal engagement in decision-making, including the necessity to engage at national, regional and local community levels. This engagement has to take full account of the relevant formal policies, legislation and regulations laid down by society. An implementing organisation must earn “a licence” to proceed at all stages of its programme and this typically translates into a formal regulatory requirement for licensing at key stages. Site selection policies and procedures, regulatory arrangements and licensing requirements vary between member states, reflecting inter alia the socio-political context, geological factors, and the waste inventory. Therefore there is no single best practice in meeting this key challenge, but there are common components that can contribute to a successful outcome. These form the basis for EURAD activities on this theme.

Site selection process

The process to be followed in selecting a site for a GDF is typically determined at national government level but, in establishing the relevant policy, the implementing organisation, regulators and civil society are likely to be required to play a part. Increasingly emphasis is placed upon the involvement and support of potential, “host” communities that would be most affected by eventual development of a GDF. The process is likely to involve the initial evaluation of a number of potential sites with a progressive narrowing down, eventually to identify a single preferred site. In order to maximise the prospect of a successful outcome, the stakeholders and in particular potential host communities must be provided with the information that they require to make informed decisions and be confident that the process is open, transparent and legitimate. A wide range of criteria are involved in selecting a preferred site, including impacts of development and operation on the natural environment and landscape, impacts on any specially designated natural or archaeological features, impacts on the human environment especially the transport infrastructure, impacts on socio-economic conditions, and costs. Whereas these might be required to be evaluated to an unusually high standard in the case of a GDF, these criteria and their evaluation are familiar in many major civil engineering projects. There is scope in investigating the best means of making the relevant information accessible to stakeholders, for example by means of on-line geographical information systems.

Although by no means the only selection criterion, the main focus of EURAD in this area concerns the geological conditions at potential sites. At the initial stages of a site selection process it is unlikely that detailed information will be available on the geology at GDF depth such that the process has to progress with a recognised level of uncertainty. At these early stages it is valuable to identify the relevant national geoscience database, giving the already-known characteristics of the geology at depth, and to develop methods to make this information accessible to stakeholders. At the outset of evaluating geology, it is usually necessary to identify exclusion criteria in an open and transparent manner. Exclusion criteria are likely to include the presence of exploitable mineral or hydrocarbon resources, the existence of significant geological instability such as seismically active zones or volcanism, the existence of unfavourable hydrogeological activity such as thermal springs or karstification (dissolving of minerals such as limestone),or the existence of large-scale hydraulic features such as large fracture zones. Particularly for this last criterion the implementing organisation needs to use survey methods such as aeromagnetic surveying and classical surveys of rock outcrops and to build confidence that the relevant features can be detected and a potential siting area eliminated if necessary. Generally there is much good practice that can be shared.

Detailed site investigation

At some point in the site selection process when the number of potential sites has been narrowed down sufficiently, it becomes necessary to conduct more detailed geological investigations with the aim of establishing whether a GDF can be developed, meeting the required levels of safety and security, at one or more of the remaining sites and possibly to support the identification of a preferred site. There is considerable overlap with Theme 4 (Site characterisation) at this stage but in this Theme 6 the focus is on developing and improving methods that support the decision-making process. Good practice in advanced programmes has shown the benefit of developing what is termed a site-descriptive model (SDM) at the same level of detail for each of the sites undergoing detailed geological investigation. The SDM captures the key results and conclusions of the investigations in a relatively short report that makes the relevant information accessible to stakeholders and provides a traceable audit trail to the relevant underlying technical reports. There is scope for investigating how best to develop and present the SDM. A further valuable development is to present a "confidence assessment" recognising that there remain residual uncertainties and discussing whether these uncertainties should prevent progressing to the next stage, i.e. further investigations from the surface, going underground to obtain more detailed information that is inaccessible from the surface, or if appropriate moving directly to develop the GDF. In the case of going underground to undertake more detailed investigations, there is useful guidance available on this step (See, NEA – Underground Testing, and Underground Research Facilities).

As site investigations proceed there is a need to develop and refine the layout and design of the prospective GDF to take account of the developing knowledge of the geology at depth. There is considerable overlap with Theme 5 (GDF design) but in this Theme 6 the focus is on developing approaches to demonstrating optimisation in the prospective exploitation of the site. Important aspects are likely to include selection of the optimal depth for the disposal tunnels/ rooms, determination of spacings of disposal tunnels/ rooms and spacings between waste packages, development of exclusion criteria to apply at specific disposal locations, and the relationship of the underground excavations to the surface waste receipt facilities and the means of access to the underground, classically whether by inclined drift tunnel or vertical shafts – or a combination.

Licensing

It has to be recognised that the formalities of licensing and the number of licensing steps will vary considerably between member states. In some countries a single regulator is largely responsible for the various stages of GDF implementation whereas in other countries a large number of regulators can be involved over the different stages, including those responsible for land-use planning, mining, radiological protection (of both public and workers), transport, long-term safety, security and safeguards. Licence applications will have to be tailored to match these arrangements and there will be no single best practice in this regard. However there is scope for developing and improving the information and argumentation in support of licence applications, particularly in respect of long-term, post-closure safety. There has been a significant reduction in the reliance once placed on numerical modelling results and a corresponding increase in the use of more qualitative arguments alongside evidence of the level of understanding of physical processes. More specifically regulators and stakeholders need to have confidence that, at a given stage of implementation, the residual uncertainties have been identified and that sufficient evidence has been presented to justify progressing to the next stage of implementation. There is scope for developing and improving approaches to this aspect.

Although a distant prospect for even the most advanced member state programmes, it is envisaged that an application will eventually be made for the withdrawal of regulatory control of the operator of a GDF site and pass the responsibility of institutional control to the state once all the relevant wastes have been emplaced. Whereas it would not represent a good use of resources at present to study such an application in detail, it would be valuable at this stage to understand any technical aspects that may be required to be in place from the early stages of implementation to support such an application in the future.

RD&D Priorities and Activities of Common Interest to be addressed by EURAD:

Scientific Theme 6: Siting and licensing	• **Maintaining and developing understanding of tools and techniques for developing site descriptive models.** - Expected outcomes and impact: To ensure that state-of-the-art techniques needed to interpret and model site characterisation information are available or can be made available in a timely manner to support site investigation activities (J1.6.5/High). - Cooperation and relevant past projects: ?
	• **Developing state-of-the-art on the methods of uncertainty management associated with site characteristics.** - Expected outcomes and impact: Identification, characterisation and management of uncertainties related to site characteristics, including possible geodynamics and tectonic perturbations of the site in the long-term (J1.6.2/Medium). - Cooperation and relevant past projects: ?

Ongoing and active work (inc. Horizon 2020 projects) addressing Theme 6:

Siting and licensing of facilities are typically very specific to national and political considerations, often involving local communities and technical work in support of addressing needs that are site-specific. Thus at present there are no dedicated ‘technical’ or ‘scientific’ work packages envisaged that related to this Theme in the first phase of EURAD. Within EURAD Work Package on Uncertainty Treatment (further described in Theme 7), methodologies for site uncertainty treatment will be explored.

THEME 7: PERFORMANCE ASSESSMENT, SAFETY CASE DEVELOPMENT AND SAFETY ANALYSES

Introduction and background

Integration of safety-related information

Prior to construction, and throughout successive phases, most disposal programmes are centred around key milestones and regulatory licencing to demonstrate safety. This includes transport, construction, operational and post-closure safety for the very long-term of the disposal facility. There are well-established existing international networks, NEA/OECD and IAEA guidance to support programmes in their preparation of safety cases and supporting analyses, in addition to state-of-the-art examples from advanced disposal programmes (See, IAEA Safety Standards Series SSG-23). A safety case is a set of statements concerning the safety of the disposal, substantiated by a structured collection of both quantitative and qualitative arguments and evidence. The development of the safety case and the task of integrating of all the necessary information will always be specific to the system evaluated and thus, in this area, each country has to develop its own capabilities in interaction with its local stakeholders, however, there is added value with seeking the help of experienced experts from elsewhere and adopting international good practice with respect to safety case methodologies. The safety case needs to be updated regularly by improved treatment of process understanding and refinement of modelling capabilities, particularly with respect to upscaling and coupling of processes during the post-closure phase but as well for safety during the operational phase.

Performance assessment and system models

To evaluate the long-term evolution of all disposal facility components, a sufficient understanding of coupled thermal-hydro-mechanical and chemical (THMC) processes is needed. Further improvements identified include: Component material descriptions and their degradation during storage periods, together with understanding of post-closure evolution descriptions, particularly the transition from the non-saturated system to fully saturated one; The potential development of microorganisms which can catalyse certain chemical reactions; The variation of redox conditions, including the impact of substances released from waste packages ; The thermo-hydro-mechanical behaviour of the rock and, in particular, the evolution of the damaged zone is of interest; Gas generation and identification of transfer pathways; Water saturation and swelling of bentonite used for backfill, plugs and seals; and Thermal evolution of the host rock and engineered barriers.

One of the challenges is to describe all of the couplings between those processes and to identify those most relevant both for performance and safety assessment. Modelling long-term THMC performance of the host rock, Excavated Disturbed Zone, bentonites, or disposal system components is usually done by means of a spatial and temporal finite element analysis. Upscaling of THMC models in time and space and the study of its validity and representativeness at all scales, constitutes a large field of research. This will combine both numerical developments and experimental work to confirm the choices in terms of representative volumes. This includes the representation of THMC parameters which could exhibit, in some cases, a significant natural variability.

Understanding of physio-chemical processes affecting the evolution of disposal components and geological systems, and their consequences on radionuclide transfer, is based on both an experimental approach and the use of predictive modelling at different temporal and spatial scales. Relevance of modelling and numerical simulation is strongly linked to the development of tools able to represent complex systems in terms of processes and geometry over large time and space scales. Thus, the complexity of some mechanisms, strong multiple couplings, multi-scale approaches, complexity of objects and heterogeneities to be simulated, management of uncertainties to identify key parameters, and integrated systems are all potential areas for RD&D in order to improve the understanding of disposal systems, and increase robustness in performance and safety assessment applications. In this field, some particular topics that would benefit from further development include multi-scale approaches from the atomic scale (< nm) to the scale of the geological formation (> 100 m) in order to validate relevant phenomena and input data utilizing homogenization and up-scaling techniques.

Management of heterogeneity at all scales, such as natural variability of properties, anisotropy, singularities (fractures, fissures network), non-porous materials and voids, and numerical techniques which allow such heterogeneities to be taken into account are of continued interest. Development of multiple-process modelling, including development of algorithms and numerical methods for strong couplings at the large scale continues. Capability gaps exist in two-phase flow, reactive transport modelling and THMC couplings. Development / improvement (performance, accuracy, robustness) of tools in the area of high performance computing, as applied to system modelling, with numerical resolution methods allowing representation of complex integrated and heterogeneous systems is also of interest.

Treatment of uncertainties

Management and treatment of uncertainties (epistemic, aleatoric) in process understanding, in complex models as well as in its safety implications both for the long term and the operational phase is a continuous activity, in order to identify the key input data of the integrated system, to identify priorities or research and as well to gain confidence in a repository project among stakeholders.

As advanced programmes move close to implementation, consideration of the safety case and its ongoing management and development during construction and operations has become of interest. Linked closely to the implementers management system, understanding of deviations in planned implementation scenarios and pre-closure disturbances, and their effect on performance assessment outputs, safety implications and design adaptation is of continued interest.

RD&D Priorities and Activities of Common Interest to be addressed by EURAD:

Scientific Theme 7: Performance assessment, safety case development and safety analyses	• **Improved understanding and models for the impact of THMC on the behaviour of the host rock and the buffer materials.** - Expected outcomes and impact: To further understand the impact of THMC on the behaviour of the host rock and the buffer materials, and to develop appropriate models coupling all the relevant phenomenology impacting the key processes during the transition from the non-saturated period to saturation following closure (J2.2.1/High). - Cooperation and relevant past projects: EC project BENCHPAR, HE (Heater Experiment).
	• **Improved understanding of the upscaling of THMC modelling for coupled hydro-mechanical-chemical processes in time and space.** - Expected outcomes and impact: To extend deterministic and/or stochastic approaches to take into account the upscaling aspects regarding THM parameters (J2.2.4/High) - Cooperation and relevant past projects: ?
	• **Improved multi-scale reactive transport models.** - Expected outcomes and impact: To further develop the capability to model the migration of contaminants from the repository to the biosphere (J2.3.4/High). - Cooperation and relevant past projects: ?
	• **Further develop transparent and quality assured thermodynamic databases for use in performance assessments and supporting models.** - Expected outcomes and impact: Improved thermodynamic data for key radionuclides, principal elements of the disposal system, secondary phases and solid solutions, filling gaps for specific environments and using natural analogues to assess slow kinetic constraints (metastability). Thermodynamic data may be required in order to validate predictions at higher temperatures and salinity, and to underpin models considering cement phases, alkaline conditions, redox, etc. Improved treatment of uncertainty in thermodynamic data is also anticipated (J1.5.1/High).

	- Cooperation and relevant past projects: NEA TDB Project, Thermochimie (WMOs: ANDRA, RWM, Ondraf)
	• **Improved understanding of the influence of pre-closure disturbances on long-term safety.** - Expected outcomes and impact: To develop common approaches (including scenarios) for safety case adaptation and update during facility operations and closure (J2.1.1/Medium). - Cooperation and relevant past projects: ?
	• **Further refinement of methods to make sensitivity and uncertainty analyses.** - Expected outcomes and impact: Develop common approaches to demonstrate operational and post-closure safety and overall facility lifecycle evolution. Improved uncertainty treatment (models and data) using evolution scenarios (i.e. improved system representation during different timescales and for complex scenarios such as those involving multiple strongly coupled processes) (J2.1.3/Medium). - Cooperation and relevant past projects: ?
	• **Improved performance assessment tools.** - Expected outcomes and impact: Improved mathematical methods to analyse the importance of physical properties defined as input of a simulation on the relevant output of the simulation (sensitivity analysis), and to quantify the effect of uncertainties on these outputs (uncertainty analysis) (J2.3.1/Medium). - Cooperation and relevant past projects: ?
	• **Improve geosphere transport models.** - Expected outcomes and impact: Improved representation of the transport of contamination through the geosphere in support of the safety case (J2.3.3/Medium). - Cooperation and relevant past projects: ?
	• **Improved understanding the role of physical/chemical processes at different scales and linking bottom-up and top-down approaches in performance assessments.** - Expected outcomes and impact: To extend up-scaling to the materials involved in radioactive waste disposal, e.g. cementitious-based materials, to develop multi-scale approaches for coupled processes (including chemistry, mechanics, hydraulic, etc.) and to develop multi-scale strategies to represent complex phenomena (redox processes, microbiology, mineral transformation, etc.). (J2.3.5/Medium). - Cooperation and relevant past projects: ?
	• **Improved treatment of heterogeneity.** - Expected outcomes and impact: To provide a modelling capability which can integrate available site data to account for heterogeneities in the near field (J2.3.6/Medium). - Cooperation and relevant past projects: ?
	• **Improved computing.** - Expected outcomes and impact: To enable the use of numerical and highly parallelized code on a heterogeneous grid or cluster, to represent hydraulic and solute transfer in huge integrated systems (disposal and geological media), two-phase flow and transfer at the system level, reactive transport at the scale of many components, and THM couplings at a large scale. (J2.3.7/Medium). - Cooperation and relevant past projects: DECOVALEX

	• **Improved understanding for the impact of deviations in planned implementation scenarios on the performance assessment outputs of the disposal facility.** - Expected outcomes and impact: Understanding how deviation (unplanned events) may impact the handover state of the facility as the starting condition for long-term performance assessments. Develop improved scenario treatment and communication of deviations from normal operating scenarios to understand key controls on the performance assessment (J2.1.5/Low). - Cooperation and relevant past projects: ?
	• **Improved understanding of the spatial extent and evolution with time of oxidative transients, as well as the possible impact on safety functions.** - Expected outcomes and impact: To investigate the oxidative transient in the near field during the construction and operational phases, notably with regard to corrosion of metallic components (J2.2.3/Low). - Cooperation and relevant past projects: EC projects BENIPA, NF-PRO, FEBEX
	• **Open-source performance assessment code** - To develop high performance computing oriented code which can simulate multi-phase flow and transport in unsaturated porous media (J2.3.2/Low) - Cooperation and relevant past projects: ?
	• **Improve fire and impact assessment** - To assess the impact of fire or explosions on the underground systems during the operational phase (J2.4.1/Low). - Cooperation and relevant past projects: ?
	• **Improve understanding of the impacts of operational safety** - To minimise the disturbance of operations on long-term safety sharing by lessons learned across operating facilities within the nuclear industry and other mining operations (J2.4.3/Low). - Cooperation and relevant past projects: GEOSAF

Enabling Knowledge Management, Strategic Studies and other Cross-cutting Activities Identified of Common Interest that relate to Theme 7

Assessment methodologies: To continue to share good practice internationally and continue development of advanced methodologies for construction and facility licensing (J2.1.2).
Dose thresholds: To facilitate exchanges on good practice on the development of safety indicators applied in specific safety cases taking into account realistic facility evolution scenarios and time periods. To undertake epidemiological studies of low-dose radiological impacts (J2.1.4).
Use of natural analogues: To verify and build confidence in long-term, large-scale processes, and upscaling of models to repository scale (J2.2.5).
Safety case guidelines, management and review: To evaluate experience from different countries' arrangements for identification of possible gaps or weaknesses in the expertise function's expectations. To develop a common view on areas of significant safety impact and proposals formulated for an appropriate degree of regulatory control (J3.9).
Improve understanding of the impacts of operational safety: To minimise the disturbance of operations on long-term safety sharing by lessons learned across operating facilities within the nuclear industry and other mining operations (J2.4.3).

Ongoing and active work (inc. Horizon 2020 projects) addressing Theme 7	The European Commission (EC) PAMINA project – Performance Assessment

Methodologies in Application to Guide the Development of the Safety Case – was conducted over the period 2006-2009 and brought together 27 organisations from 10 countries. PAMINA had the aim of improving and developing a common understanding of performance assessment (PA) methodologies for disposal concepts for spent fuel and other long-lived radioactive wastes in a range of geological environments. This was followed by a Nuclear Energy Agency (NEA) sponsored project on Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste (MeSA).

EURAD first phase includes a number of networking activities to promote knowledge sharing, including a strategic study on understanding of uncertainty, risk and safety from the perspectives of different participants. The objective is to identify precise areas of focus that could be taken forward in future phases of EURAD. The strategic study will develop a common understanding among the different categories of participants (WMOs, TSOs, REs & Civil Society) on uncertainty management and how it relates to risk and safety. In cases where a common understanding is beyond reach, the objective is to achieve mutual understanding on why views on uncertainties and their management are different for different actors.

ANNEX I - DEVELOPMENT OF THE EURAD STRATEGIC RESEARCH AGENDA

The Strategic Research Agenda of EURAD has been developed in a stage-wise manner, Step 1 - taking over entirely the scope developed within the EC JOPRAD Project (JOPRAD Programme Document D4.2), and Step 2 – enhancing with a small number of additional needs identified by ongoing EC projects and approved for inclusion between the key contributors.

Step 1 – Taking over the EC JOPRAD Project Scope: EURAD has reorganised the JOPRAD scientific and technical scope into 7 Scientific. Each activity has retained (i) the activity title (with some minor editing to make the research objectives more SMART - Specific, Measurable, Attainable, Relevant and Timely); (ii) the indicator of High, Medium or Low for the 'level of common interest' between the WMOs, TSOs, and REs groups represented within JOPRAD, and further commented on by an open European consultation (managed by the JOPRAD project) during the summer of 2017; and (iii) an indication of whether scope to address the identified activity would benefit from a Knowledge Management component.

*The EC JOPRAD project methodology for identifying the scientific and technical basis of the JOPRAD SRA was carried out in 5 steps:

1. **Compiling Activities for Inclusion**: Drafting a first compilation of combined activities suggested as suitable for inclusion within a potential future Joint Programme. A key part of this step was to organise and coalesce suggested activities (identified from WMO, TSO and RE-specific SRAs) into a suitable structure, considering the different types of activities suggested and the adoption of a common terminology and appropriate scope definition for a potential future Joint Programme;
2. **Surveying Representative Joint Programme Participant Views**: Eliciting JOPRAD participants' opinions on their preferences and motivations for prioritising activities. This was completed by issuing a comprehensive questionnaire of suggested activities, allowing JOPRAD participants to comment and express views on activities suggested by all the represented groups for the first time;
3. **Identifying Priorities and Activities of High Common Interest**: Analysing the questionnaire responses to identify the themes with high common interest, and the adoption of screening criteria used to prioritise what should be included in EURAD. This step included development of a methodology to cross-check that all prioritised activities met with the established boundary conditions for EURAD;
4. **1st Draft SRA**: Drafting a first compilation of EURAD scientific and technical scope with a clear description of prioritised RD&D activities agreed and supported by all JOPRAD participants;
5. **SRA Consultation and Finalisation**: Consultation of the draft scientific and technical scope within the broader European radioactive waste management community. Obtaining feedback and end-user input to facilitate updating of the final Programme Document.

The JOPRAD Programme Document also includes specific "socio-political confidence building themes" addressing the complexity of RWM. Three main areas of scope were identified, which could be integrated within future R&D and strategic studies WPs, where appropriate. Integration in this way would ensure the Joint Programme does not give rise to self-standing social and political research activities, separate from the technical aspects of RWM.

EURAD Themes	JOPRAD RD&D Sub-topics and New Scope (*greyed boxes show new scope since JOPRAD and origin / title changes made in EURAD, shown in italics and brackets*)	Level of Common Interest for RD&D	Identified Knowledge Management Activity
Theme 1: Managing Implementation and oversight of a Radioactive Waste Management Programme	3.15 EU Research Infrastructure	High	✓
	Establishment and implementation of a RD&D programme (Originates from guidance needs identified by the IGD-TP PLANDIS Guide)	High	✓
	3.14 Information Management (NEA RepMet)	Medium	✓
	3.16 EU DGR Curricular (*EURAD title: Training and competence maintenance of skills and expertise to support safe radioactive waste management including disposal*)	Low	✓
	3.11 Pre-licensing Management	Low	✓
Theme 2: Radioactive waste characterisation, processing and storage (Pre-disposal activities), and source term understanding for disposal	1.1.1 Inventory Uncertainty (*EURAD title: Identifying good practice in the management of inventory data and uncertainty treatment*)	High	✓
	1.1.3 Non-mature and Problematic Waste Conditioning (*EURAD title: Developing novel conditioning technologies for non-mature and problematic waste*)	High	✓
	1.1.4 Radionuclide Release from Wasteforms other than Spent Fuel (*EURAD title: Improved understanding of radionuclide release from existing and future wasteforms other than Spent Fuel*)	High	✓
	1.1.2 Waste Characterisation Techniques (*EURAD title: Developing reliable and affordable technologies for the radiological characterization and segregation of historical preconditioned radioactive waste*)	High	
	1.2.2 Impacts of Extended Storage on Waste Packages (*EURAD title: Improved understanding of the impacts of extended storage on waste package performance*)	High	✓
	1.4.2 Gas Generation Processes (*EURAD title: Improved understanding of the generation and release of radioactive trace gases and bulk gases from wasteforms and waste packages*)	High	
	2.4.5 Interim Storage Facility Safety (*EURAD title: Operational lifespan of interim storage facilities*)	High	
	Waste Management Routes across Europe considering different waste types and their specified endpoints (Originates from networking needs identified by ENEF NAPRO Guide)	High	✓
	1.1.5 Geopolymers (*EURAD title: Demonstration of geopolymer performance in representative disposal conditions*)	Medium	
	1.1.7 Chemotoxic Species (*EURAD title: Improved understanding of the nature and quantities of the likely chemotoxic component of common wastes*)	Medium	
	1.1.8 Novel Radioactive Waste Treatment Techniques (*EURAD title: Optimisation of radioactive waste treatment techniques where there is potential for volume/hazard reduction and potential cost savings*)	Medium	
	1.1.9 Spent- Fuel Evolution (*EURAD title: Improved understanding of the behaviour of packaged Spent Fuel for a range of hypothetical fire and impact scenarios during operations and transport, and consolidation of*	Medium	✓

	existing understanding of post-closure Spent Fuel release processes)		
	3.5 Inventory Collation & Forecasting	Medium	✓
	2.1.6 Waste Acceptance Criteria	Medium	✓
	1.1.10 Spent Fuel Fissile Content (*EURAD title: Quantification of fissile content of spent fuel*)	Low	
	3.7 Link to Waste Producers/ Fuel Manufacturers (*EURAD title: Strengthened links between Implementers and Waste Producers*)	Low	✓
	3.6 Evolution of Waste Inventory (*EURAD title: Methodologies applied to define radionuclide inventories*)	Low	✓
	3.10 Disused Sealed Radioactive Sources (*Understanding of the potential for long-term storage as a management option for disused sealed radioactive sources*)	Low	✓
	1.2.4 Reworking of Damaged and Aged Waste Packages (*EURAD title: Management of damaged waste packages and the criteria and methods for reprocessing aged waste*)	Low	✓
	1.1.6 Fourth generation (Gen (IV) wastes	Low	
Theme 3: Engineered barrier system properties, function and long-term performance	1.2.1 Waste Package Interfaces (*EURAD title: Improved understanding of the interactions occurring at interfaces between waste packages and different barriers in the disposal facility*)	High	
	1.3.1 Bentonite and other Clay Based Components (*EURAD title: Characterised bentonite / clay-based material evolution under specific conditions to provide data on hydro-mechanical, thermal and chemical behaviour*)	High	
	1.3.2 Microbial Influence on Gas Generation (*EURAD title: Improved chemical and microbial data to better quantity gas generation and the consequences of microbial processes*)	High	
	1.3.3 Cementitious Component Behaviour (*EURAD title: Improved quantification and understanding of cement-based material evolution to improve long-term modelling and assessments*)	High	
	1.3.5 Metallic & Cementitious Chemical Perturbations (*EURAD title: Improved understanding of the impacts of different metallic and cementitious component phenomena on near-field evolution via improved models*)	High	
	1.4.4 Gas Reactivity in the EBS (*EURAD title: Improved understanding of gas reactivity in the EBS*)	High	
	2.2.2 Performance of Plugs and Seals (*EURAD title: Improved understanding of the performance of plugs and seals*)	High	
	1.2.3 Alternative HLW/Spent Fuel Container Material Development (*EURAD title: Developing alternative HLW and Spent Fuel container material options and improved demonstration of their long-term performance*)	Medium	
	1.3.4 Low pH Cements (*EURAD title: Improved understanding of low pH cements*)	Medium	
	1.3.7 HLW/ILW Near-field Evolution (*EURAD title: Improved description of the spatial and temporal*	Medium	

	evolution of transformations affecting the porous media and degrading materials in the near-field of HLW and ILW disposal systems)		
	1.3.6 Salt Backfill (*EURAD title: Improved understanding of a salt backfill*)	Low	
	1.3.8 Co-Disposal Interactions (EURAD title: Identify co-disposal interactions of importance to long-term safety)	Low	✓
Theme 4: Geoscience to understand rock properties, radionuclide transport and long-term geological evolution	1.4.1 Gas Migration through the Excavated disturbed Zone/EBS and Far-Field (*EURAD title: To increase understanding of gas migration in different host rocks*)	High	
	1.4.4 Gas Reactivity in the Geosphere (*EURAD title: Improved understanding of gas reactivity in different host rocks*)	High	
	1.5.2 Sorption, Site Competition, Speciation and Transport (*EURAD title: Improved representation of sorption mechanisms and coupled chemistry / transport processes for various media*)	High	
	1.5.5 Effects of Microbial Perturbations on Radionuclide Migration (*EURAD title: Improved understanding of bounding conditions for the effects of microbial perturbations on radionuclide migration to support performance assessments*)	High	
	3.2 Site Evolution Models (*EURAD title: Development of site evolution models, and how to manage data as it is obtained during the site characterisation phase*)	High	
	1.4.3 Gas Transients (*EURAD title: Develop and implement two-phase flow numerical codes to increase gas transient representation at the disposal scale*)	Medium	
	1.5.3 Incorporation of Radionuclides in Solid Phases (*EURAD title: Quantification of long-term entrapment of key radionuclides in solid phases to inform reactive transport models*)	Medium	
	1.5.4 Transport of Strongly Sorbing Radionuclides (*EURAD title: Improved understanding of the transport of strongly sorbing radionuclides*)	Medium	
	1.5.6 Organic-Radionuclide Migration (*EURAD title: Improved understanding of the role of organics (either naturally occurring or as introduced in the wastes) and their influence on radionuclide migration*)	Medium	
	1.5.7 Temperature Influence on Radionuclide Migration (*EURAD title: Improved understanding of the influence of temperature on radionuclide migration and representation of effects in geochemical models*)	Medium	
	1.5.8 Colloid Influence on Radionuclide Migration (*EURAD title: Improved understanding of the role of colloids and their influence on radionuclide migration*)	Medium	
	1.5.9 Redox Influence on Radionuclide Migration (*EURAD title : Improved understanding of the influence of redox on radionuclide migration)*	Medium	
	1.5.10 Ligand-Influenced Transport Modelling (*EURAD title: Improved understanding of the role of organics (either naturally occurring or as introduced in the wastes) and their influence on radionuclide migration*)	Medium	
	1.5.11 Transport of Volatile Radionuclides (*EURAD title: Developing a geochemical model for volatile radionuclides*)	Medium	

	2.2.6 Biosphere Models (*EURAD title: Enhanced treatment of climate change, non-human biota, land-use and parameter derivation in biosphere models*)	Medium	
	1.6.3 Groundwater Evolution (*EURAD title: Developing models of groundwater evolution*)	Medium	
	1.6.1 Fracture Filling (*EURAD title: Improved understanding of the processes of fracture filling*)	Low	
	1.6.4 Rock Matrix Diffusion (*EURAD title: Impact of rock matrix diffusion on travel time through the geosphere*)	Low	
Theme 5: Geological disposal facility design and the practicalities of its safe management:	2.5.1 Operational Monitoring Strategies (*EURAD title: Developing monitoring strategies appropriate to the operational phase (including facility construction and work acceptance) of geological disposal facilities that will not adversely affect the performance of the disposal system*)	High	
	2.5.3 Monitoring Technologies (*EURAD title: Developing innovative monitoring technologies*)	High	
	2.5.2 Monitoring Strategies for Closure and Post-closure (*EURAD title: Developing appropriate monitoring technologies for closure and a period of post-closure institutional control in links with relevant parameters for safety*)	Medium	
	2.5.7 Industrialization (*EURAD title: Optimization of backfilling and other major implementation processes, including waste emplacement, retrieval and sealing technologies*)	Medium	
	2.5.8 Engineering Asset Management(*EURAD title: Developing cost-effective asset management strategies for use in the design*)	Medium	✓
	2.5.4 Retrievability (*EURAD title: Improved understanding of waste package durability and disposal facility infrastructure with respect to retrievability*)	Low	
	2.5.5 Concept and Design Adaptation (*EURAD title: Assessment of the technical feasibility and lifecycle adaptation of a geological disposal concept for a specific site and specific nuclear waste type*)	Low	
	2.5.6 Mock-up Experiments (*EURAD title: Verify robustness of disposal system designs using large scale mock ups*)	Low	
	2.4.4 Accident Mgt. and Emergency Preparedness	Low	✓
	2.4.2 Flooding Risk Assessment (*EURAD title: Developing operational hazard assessment methodologies (inc. flooding risk*)	Low	
	3.8 Concept Adaptation and Optimisation (*EURAD title: Assessment of the technical feasibility and lifecycle adaptation of a geological disposal concept for a specific site and specific nuclear waste type*)	Low	✓
	3.12 Co-disposal Interactions (*EURAD title: Managing co-disposal*)	Low	✓
	3.13 Radiation Protection Optimisation Principle	Low	✓
	3.17 Reversibility	Low	✓
Theme 6: Siting and licensing:	1.6.5 Site Descriptive Models (*EURAD title: Maintaining and developing understanding of tools and techniques for developing site descriptive models*)	High	✓

	3.1 Site Uncertainty Treatment *(EURAD title: Methodologies for site uncertainty treatment)*	High	✓
	1.6.2 Geological Uncertainties (*EURAD title: Developing state-of-the-art on the methods of uncertainty management associated with site characteristics*)	Medium	
	3.3 Site Selection Process	Medium	✓
	3.4 Technical and Socio-political Siting Criteria	Low	✓
Theme 7: Performance assessment, safety case development, and safety analyses:	2.2.1 THMC Evolution (*EURAD title: Improved understanding and models for the impact of THMC on the behaviour of the host rock and the buffer materials*)	High	
	2.2.4 Upscaling THMC Models (*EURAD title: Improved understanding of the upscaling of THMC modelling for coupled hydro-mechanical-chemical processes in time and space*)	High	
	2.3.4 Multi-scale Reactive Transport Models (*EURAD title: Improved multi-scale reactive transport models*)	High	
	1.5.1 Chemical Thermodynamics (*EURAD title: Further develop transparent and quality assured thermodynamic databases for use in performance assessments and supporting models*)	High	
	2.1.1 Pre-closure disturbances (*EURAD title: Improved understanding of the influence of pre-closure disturbances on long-term safety*)	Medium	✓
	2.1.2 Assessment Methodologies	Medium	✓
	2.1.3 Uncertainty Treatment (*EURAD title: Further refinement of methods to make sensitivity and uncertainty analyses*)	Medium	✓
	2.2.5 Natural Analogues (EURAD title:)	Medium	✓
	2.3.1 Performance Assessment Tools (*EURAD title: Improved performance assessment tools*)	Medium	
	2.3.3 Long-range Transport Models (*EURAD title: Improve geosphere transport models)*	Medium	
	2.3.5 Upscaling in Support of Performance Assessment (*EURAD title: Improved understanding the role of physical/chemical processes at different scales and linking bottom-up and top-down approaches in performance assessments*)	Medium	
	2.3.6 Heterogeneity (*EURAD title: Improved treatment of heterogeneity*)	Medium	
	2.3.7 Improved Computing	Medium	
	3.9 Safety Case Guidelines, Management & Review	Medium	✓
	2.1.4 Dose Thresholds	Low	
	2.1.5 Managing Deviations (*EURAD title: Improved understanding for the impact of deviations in planned implementation scenarios on the performance assessment outputs of the disposal facility*)	Low	
	2.2.3 Oxidative Transients (*EURAD title: Improved understanding of the spatial extent and evolution with time of oxidative transients, as well as the possible impact on safety functions*)	Low	
	2.3.2 Open-source Performance Assessment Code	Low	
	2.4.1 Fire and Explosion Assessment (*EURAD title: Improve fire and impact assessment*)	Low	

	2.4.3 Improve Understanding of the Impacts of Operational Safety	Low	

Further details of the JOPRAD methodology for identifying the scientific and technical basis of EURAD is presented in Section 4 of JOPRAD deliverable D4.2 Programme Document.

Step 2 – EURAD has been developed in parallel with the completion/near completion of EC Horizon 2020 projects. Several new needs have therefore been identified as a result of recent RD&D results, and / or that are now considered of higher common interest by the contributors and participants of EURAD. These needs have been approved for inclusion in the SRA through various meetings between representatives of WMOs, TSOs and RE's to ensure the needs meet with the same boundary conditions used by JOPRAD, and are suitable for Joint Programming.