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Main achievements and impact of EURAD, the European Joint Programme on Radioactive Waste Management (2019–2024)

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Abstract. Co-funded by the European Commission, EURAD has operated for 5 years and has successfully achieved a step-change towards a more effective and efficient use of public funding in Europe by bringing the European waste management community together.
Its main achievements are rooted in its governance structure, fostering interaction and collaboration among Waste Management Organisations, Technical Safety Organisations and Research Entities. A key success factor was the development and update of the Strategic Research Agenda and Roadmap, which guided efforts, addressed emerging challenges and ensured alignment across Member States.
EURAD's impact is highlighted by its comprehensive R&D framework, which covers the entire lifecycle of radioactive waste management. EURAD successfully advanced knowledge in various areas, including advanced waste treatment, geological disposal, and safety assessments. The programme also emphasised the importance of knowledge management, ensuring the transfer and preservation of expertise between waste management programmes and across generations through training, mobility, guidance and the publication of scientific resources, and making information more easily available.
EURAD not only strengthened collaboration among EU Member States but also fostered international partnerships, significantly contributing to the global advancement of radioactive waste management. As EURAD concludes, its legacy will continue with EURAD-2, set to begin in October 2024, further building on the foundations laid by its predecessor.

1 Introduction

The European Joint Programme on Radioactive Waste Management, known as EURAD, played a crucial role in providing scientific and technical expertise in the management and disposal of radioactive waste within the European Union. EURAD has gathered 51 mandated actors, mandated by the ministries of 23 different European countries, as well as 62 Linked Third Parties and 3 international organisations.

This five-year programme, operating between 2019 and 2024, financed by the European Commission under the H2020 programme, has promoted European collaboration by uniting national Waste Management Organisations (WMO), Technical Safety Organisations (TSO), and Research Entities (RE), across three major pillars:

- Complement the national programmes, by supporting compliance with European regulations as well as the Radioactive Waste Management (RWM) innovation and optimisation, by conducting joint research programmes on major aspects of radioactive waste management and by fostering the efficient use of Research & Development (R&D) resources at the EU level;
- Ensure the sustainability of the knowledge, by developing and consolidating existing knowledge, but also by enhancing Knowledge Management (KM) and transfer between organisations, member states and generations;
- Act as a platform fostering mutual understanding and trust between all participants and stakeholders of the joint programme through exchange and cooperation.

2 A step change in European collaboration

The success of EURAD can largely be attributed to the effective governance that was established and to its founding documents.

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2.1 An SRA and roadmap fostering European collaboration

The creation and update of the Strategic Research and Knowledge Management Agenda (SRA), which served as a critical tool in guiding research and development activities related to RWM in Europe, is central to the success of the EURAD programme.

The update of the SRA was specifically designed to identify and address emerging and unforeseen challenges in RWM, ensuring a holistic, integrated view on identified needs of common interest that may require research, development and demonstration (RD&D), strategic studies (think tank), and/or knowledge management activities along the whole chain of radioactive waste management, from cradle to grave, both relevant and forward-looking [1]. By providing strategic insights, the SRA sets the direction for future research and studies, enabling Member States to align their efforts and work towards common goals. Indeed, the Member States had been given, through their Mandated Actors, the power to define the strategic framework of research and Knowledge Management to implement future works.

To make the SRA more useful for the definition of work packages constituting EURAD-2 (follow-up programme), all identified needs were characterised using a common set of drivers. The use of drivers replaces the classification scheme of high, medium and low priority scores previously used in the first SRA [1].

The update has been developed with a 10-year forward horizon, building upon and complementing the extensive knowledge base that exists in radioactive waste management, which has been developed over the past decades by national programmes and international projects.

One of the key updates was the full integration of knowledge management and the alignment of the overall structure of the seven themes with the extended goals breakdown structure of the EURAD Roadmap.

The Roadmap is designed to serve as a high-level checklist outlining typical and generic activities in radioactive waste management (RWM) programs, as well as to guide users to existing knowledge, drawing from the experiences of advanced programs and experts in the field [2]. It is not intended to be exhaustive or to guarantee that a national program will meet national or international RWM or deep geological repository (DGR) legal requirements. Due to its generic nature, the Roadmap focuses on content applicable to all programmes, with a particular emphasis both on technical aspects of improving predisposal practices and developing deep geological repositories for final disposal as well as the knowledge management that needs to be organised over generations.

2.2 A governance favouring interaction and networking

The governance in EURAD was designed to facilitate interactions among its participants. Mandated Actors representing the national programmes and participating organisations defined, executed and reported the complete programme. The different bodies (General Assembly, Bureau, Programme Management Office, Chief Scientific Officer and External Advisory Board) have proven to be effective with only a very few exceptions.

One of the most significant achievements of EURAD has been the successful collaboration of the three Colleges of European Waste Management Organisations (WMO), Technical Safety Organisations (TSO) and Research Entities (RE). The Colleges worked collectively on critical issues, thereby enhancing the overall credibility, impact and effectiveness of the programme. The representation of all three Colleges across all governance bodies and work packages has ensured that diverse perspectives are addressed, enriching discussions. This inclusive approach has been instrumental in delivering substantial added value to the programme, as it leverages the unique strengths and expertise of each College.

Moreover, the joint support of the Colleges for the programme's activities has fostered a deeper mutual understanding and trust among the participants. This collaborative spirit not only strengthens the bonds between the Colleges but also elevates the quality and relevance of the results achieved. By uniting the College's and organisations' efforts, EURAD has been able to produce outcomes that are not only more comprehensive but also reflective of a broad spectrum of professional insights, ultimately contributing to the programme' s success and sustainability.

This approach ensured that the research addressed the most relevant fields of study in RWM, as identified both by those directly involved in EURAD as well as potential End-Users.

2.3 Broad participation covering the diversity of European national RWM programmes

EURAD was developed with the ambition of bringing together and complementing EU Member State programmes in order to ensure cutting-edge knowledge creation and preservation in view of delivering safe, sustainable and publicly acceptable solutions for the current and future management of radioactive waste across Europe.

With 23 European countries represented in EURAD, a broad range of waste management programs was involved, covering a large spectrum in terms of viewpoints and stages of development and levels of advancement, particularly with respect to different plans and national policies towards implementing the Council Directive 2011/70/Euratom of July 2011 [3].

EURAD supported the Member States in their timely implementation of radioactive waste management activities, with the responsibility of the National Programmes to evaluate the output and the results of EURAD with respect to their own needs (towards implementation). The research in EURAD was carried out with the goal of complementing the already existing national RWM programme of each Member State, who will use the research

and results of the programme to benefit their own specific RWM policy.

Five years after its implementation, the EURAD platform ensures structured and efficient interaction between key actors that have a formal national responsibility to support the implementation of radioactive waste management activities, including disposal [3].

More specifically, early-stage programmes benefit by gaining exposure to cutting-edge developments, accessing the latest information, and establishing valuable personal connections within the field. Meanwhile, advanced programmes have the opportunity to engage in in-depth discussions, exchange insights, and share critical information, fostering a collaborative environment for knowledge dissemination. EURAD was additionally able to make existing knowledge more accessible and visible to early-stage programmes, which could benefit from the transfer of knowledge by advanced-stage programmes.

The robust participation of over 110 organisations, including international partners, plays a crucial role in ensuring that the knowledge generated is widely recognised, readily accessible, and actively utilised by the community. This broad engagement not only amplifies the reach and impact of the programme but also strengthens the global exchange of expertise and resources, contributing to the advancement of the field as a whole.

Nearly in parallel to EURAD, PREDIS (pre-disposal management of radioactive waste) was developed. From the start of PREDIS, the systematic coordination of activities was carried out, and close cooperation was developed; this was facilitated by the fact that several persons and organisations participated both in EURAD and PREDIS. The successful coordination/cooperation with PREDIS and the interdependence between these activities has led to the Commission's decision to integrate PREDIS into EURAD-2.

EURAD also benefited from close interactions and synergies with international organisations such as OECD/NEA for example, through exchanges with the Integration Group for the Safety Case (IGSC) and on requirements management. Exchange with their group on 'Information, Data and Knowledge Management (IDKM) helped to avoid replication and join efforts. Also, with the IAEA, strong regular interactions were organized on knowledge management, document dissemination, technical results of specific work packages and invitations to present EURAD at large international conferences, workshops and webinars.

3 Impact and added value

EURAD has provided significant added value to the work carried out by all WPs, which were strategically divided into three categories: there were 10 RD&D WPs, 2 Strategic Studies WPs, and 3 KM WPs. This structured approach ensured a comprehensive and focused effort in advancing the programme's objectives, enhancing the overall impact of each work package within its respective domain.

3.1 In R&D

EURAD has successfully integrated a comprehensive Research and Development (R&D) framework, which includes almost the entire lifecycle of radioactive waste management. The 10 R&D work packages covered a wide range of studies in Radioactive Waste Management (RWM).

Each of the R&D WPs produced comprehensive state-of-the-art reports presenting the knowledge and technical advancements related to themes and task studies. These reports go beyond presenting experimental findings; they contextualise the results, offering valuable insights into best practices on specific aspects of RWM. By consolidating existing knowledge and promoting its application, these reports have significantly reinforced knowledge transfer within the field of RWM.

The results summarised below for each RD&D WP highlight the achievements of EURAD in advancing joint research efforts [4].

- ACED (Assessment of Chemical Evolution of ILW and HLW Disposal Cells [5]) looked at and addressed the processes at the interfaces in ILW and HLW nearfield systems of deep geological repositories (DGRs) with a combination of focused experiments and modelling studies. With these activities, ACED provided a lot of valuable models, information and insights on the nearfield evolution of relevant systems [4].
- CORI (Cement-Organic-Radionuclide-Interactions [6]), looked at and addressed the system (radionuclides – cement – organics), but also the 'sub' systems (cement – organics; cement – radionuclides) with a broad spectrum of experiments providing a lot of additional information and understanding confirming the broad conclusion that 'organics can't be ignored'. Because of budget restrictions it was not planned to perform systematic modelling studies using the new data. Overall, the WP provided much insight and excellent data for assessing the potential impact of organics containing wastes on the safety of repository systems, and also for future modelling activities [4].
- DONUT (Development/improvement of numerical methods & tools for modelling coupled processes [7]), looked at and addressed a broad spectrum of methods and tools, highlighting the importance of numerical models for waste management. It looked at the 'full' story (coupling, different scales, artificial intelligence/machine learning, ...) by making the 'added value' of the deliverables (incl. open-source codes) of WP for waste management well visible, demonstrating the importance of numerical models in radioactive waste management. A dedicated effort was made to discuss 'digital twins' in a broad and well-coordinated effort with the conclusion that 'digital twins' (and KI, machine learning) are expected to be upcoming issues of high importance for waste management [4].
- FUTuRE (Fundamental understanding of radionuclide retention [8]) looked at and addressed several bar-

rier systems, successfully building upon a mechanistic understanding of radionuclide-retention ('bottom up' approach) both in clay and granite systems and provided a clear connection to application – a directly applicable methodology and demonstrated expertise in safety assessment. The WP produced a lot of new high-quality data, with one of the important conclusions being that sorption competition and redox reactions at interfaces are important issues and should be considered in safety assessment. The WP confirmed that the 'bottom up' approach, which has been mechanistic over many years, is a great success [4].

- GAS (Mechanistic understanding of gas transport in clay materials [9]) looked at gas transport through clay materials – a complex issue, with understanding the 'gas issue' being an evolutionary process that started many years ago. A 'full model' is not yet feasible. Thus, the approach taken relies on process-level models and 'visualisation' that are combined with comprehensive 'story boards' and thus provide the 'elements' to build up a convincing chain of arguments to assess the impact of gas and to define 'gas-related' requirements. Furthermore, the WP has developed input to sample handling and experimental protocols for future experimental work [4].
- HITEC (Influence of temperature on clay-based material behaviour [10]), looked at and addressed a highly relevant topic – the optimisation of repository design for SF/HLW. The synergies in the work between clay-based buffer material and clay host rocks turned out to be smaller than originally expected. Modelling tools are now available that are adapted to higher temperatures for system-specific applications [4].
- SFC (Spent Fuel Characterisation and Evolution until Disposal [11]) provided experimentally verified procedures to reliably determine fuel properties for managing the fuel prior to disposal. It was possible to reduce the uncertainty of heat-producing radionuclides in spent fuels and their vectors for optimisation of spent fuel canister loading, to improve the understanding of the behaviour of spent fuel rods/assemblies during prolonged interim storage, encapsulation, transportation, and emplacement in the repository. Furthermore, also the impact of postulated accident scenarios has also been taken into account. With this, the information needed to safely manage the fuel until it has been emplaced in a disposal facility has been extended [4].
- ConCorD (Container corrosion under disposal conditions [12]) was, despite its short duration of only 3 years, able to cover with focused experiments and modelling a broad spectrum of issues, leading to new scientific insights (corrosion (impact of irradiation, microbes), sealing of ceramics, ...) and very valuable material, e.g., for use in performance assessment. This was possible because of the strong participation in the WP and the support provided by a formal 'external' review group [4].
- MAGIC (Chemo-mechanical ageing of cementitious materials [13]) addressed in multidisciplinary approach a broad range multiscale and upscaling issues, filling the gap in the understanding of the long-term physical integrity of underground cement constructions considering chemo-mechanical evolution (effect of carbonation, sulphates) and impacts of microorganism. The WP relied as far as possible on existing experiments. Significant progress has been made; a good starting point has been reached to continue in a future project [4].
- MODATS (Monitoring equipment & data treatment for safe repository operation & staged closure [14]) looked at existing experiments using artificial intelligence and machine learning as new elements. Then, some improvements in technology and tools (including data management) have been made. This provides the means to collect highly relevant data that are also of strong interest to civil society [4].

3.2 On complex strategic issues

Through its two strategic studies work packages, EURAD has brought together actors to elaborate on complex issues requiring interdisciplinary approaches.

The strategic studies WPs represented a think-tank activity on important actual issues in radioactive waste management, addressing representatives of all colleges, many Member States, and Civil Society representatives [4]. This interdisciplinary approach enabled a more comprehensive understanding of the challenges as well as guidance regarding the fields of RWM in which research should be further explored.

Strategic Studies finally contributed to the development of the EURAD Strategic Research Agenda (SRA), which serves as a roadmap for future research and KM activities. By providing a strategic vision and identifying priority areas, the strategic studies ensured that the SRA complied with the long-term needs of Member States and end-users.

The outcomes of the Strategic Studies, detailing the key findings are presented hereafter.

- ROUTES (Waste management routes in Europe from cradle to grave) looked at a broad range of issues, including issues of high importance for small inventory Member States (SIMS), e.g., shared solutions, waste acceptance criteria (WAC), managing challenging waste, etc. Thus, the voices and the needs of SIMS are now better heard and seen. The interaction with civil society increased mutual understanding and trust. The WP was also used to identify R&D needs as input to the update of the strategic knowledge and research agenda (SRA) to incorporate the views of SIMS [4]
- UMAN (Uncertainty Management multi-Actor Network) put the main emphasis on a pluralistic view on uncertainty management while also involving civil society to better understand the different views on uncertainty. As part of the 2nd wave, the scope of UMAN was enlarged to also include the nearfield in the study. As planned, no work was done on mathematical/statistical approaches to uncertainty management; the main emphasis was on the pluralistic view [4].

These results capture the strategic advancements and insights gained throughout the course of EURAD, underscoring their impact on the broader objectives of EURAD.

3.3 Knowledge management

Considering the long implementation timelines for radioactive waste disposal and the varying levels of advancement among EU Member States, there is an increased recognition of the need for a cohesive long-term vision for knowledge management at the European level. In response to this need, EURAD has established three specialised work packages (State-of-Knowledge, Guidance, Training and Mobility) focused on Knowledge Management.

These initiatives were designed to facilitate the capture and transfer of knowledge across Member States, organisations, and generations, thereby ensuring the effective dissemination and application of expertise within the field.The publication of a large quantity of Domain Insights was realised, linking directly to the goals breakdown structure of the EURAD Roadmap.

The Domain Insight documents contained a structured and detailed analysis of specific themes of RWM to enable end-users to assess and comprehend critical issues as well as best practices in the field of RWM. The production of these documents helped in maintaining the knowledge gained throughout the programme and in the field of RWM, as the documents will remain available for all end-users after EURAD and will serve as the basis for the strategic development of Member States' RWM activities. The Domain Insights also served as a tool to disseminate knowledge across the RWM community. The domain insights capture context, illustrating domain maturity and primarily signposting to quality high-level state of knowledge documents, guidance and training materials and active networks or communities of practice.

With the chosen approach, it is expected that the KM system will be easier to use than other systems, as it provides not only the 'what' but also the 'when', 'why', 'how' and 'by whom' [15].

The transfer of knowledge, and more specifically, the preservation of knowledge across generations, was organised in EURAD through the Training and Mobility WP, under the umbrella of a EURAD School of Radioactive Waste Management, mainly through the organisation of training sessions, seminars, workshops, and Lunch-and-Learn sessions.

In total, over 150 trainings and numerous webinars were conducted throughout the five years of the program, highlighting the strong willingness of the participants to share knowledge and learn from each other's best practices regarding RWM. These sessions were all carried out to educate and train the EURAD community on specific topics and practices in RWM, and for the EURAD participants to develop the necessary knowledge and skills in this field for their national programmes.

Additionally, EURAD, via the R&D WPs, has made a profound impact on the education and development of the next generation of experts, supporting over 100 PhD candidates, post-doctoral researchers, and master's students. This investment in young talent not only enriches the programme's outcomes but also ensures the continued growth and innovation in RWM for years to come.

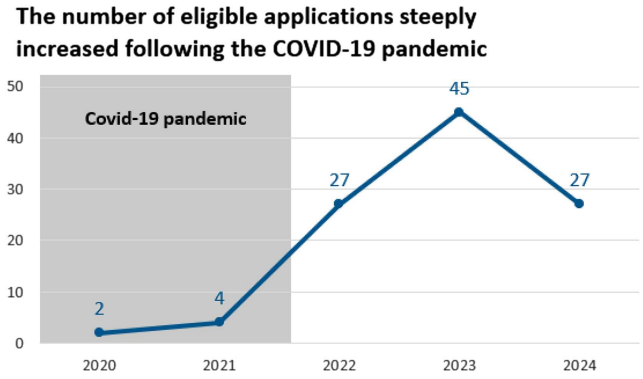

Fig. 1. Number of mobility applications.

Another key action which strongly developed networking and collaboration through the transfer of knowledge in EURAD was the mobility action programme, for which 99 out of 105 applications were approved, and which enhanced tacit knowledge exchange. Many PhD students took part in this mobility programme, highlighting the positive results of the KM programme in EURAD and the will to transfer knowledge in the field of RWM (Fig. 1).

The majority of mobility applications were submitted for participation in conferences or workshops, with a total of 33 mobilities dedicated to these activities. The distribution of mobility actions demonstrates a balanced approach to gender equality, with approximately 50% of mobilities conducted by women and 50% by men.

Finally, the production of a wide range of scientific publications – 351 in total – technical reports, and other scientific resources also served and will continue to serve as valuable references for the scientific community.

Each of the three KM WPs contributed greatly to the success of the programme [16].

- WP State-of-Knowledge worked on the structured representation of up-to-date knowledge to provide context (link to roadmap, hierarchy in documents), prepared information (roadmap & context) and documents and investigated the possibilities to ensure accessibility of knowledge (collecting experience, a web-based system is under development). The activities have to be seen as a successful start to collect and to make knowledge available to the Member States and future generations [4].
- WP Guidance made a careful selection of themes for developing guidance (based on a thorough review of existing guidance), developed some guidance documents while experiencing a learning curve in developing such documents that showed the importance of involving end-users in the development from the beginning (broad participation). This led to the conclusion that producing guidance together with future end-users is the 'way to go'; this could also result in

networking and the creation of 'communities of practice' [4].
– WP Training & mobility organised a programme of training courses and training material, based on a survey investigating the end-user's training needs and on an oversight developed on available training. This resulted in the establishment of a number of training courses (all of them were positively rated) and training material. Furthermore, a mobility programme was launched that allowed 'learning by doing' by visiting experienced institutions with corresponding infrastructure; the mobility programme was initially hindered due to COVID but turned out to be used effectively with 79% of the planned funds used. The School of RWM has demonstrated remarkable success across most of its four main pillars ((i) courses and webinars, (ii) Mobility Programme, (iii) panorama, and (iv) supporting the PhD Community), positioning itself as a valuable resource for end-users. It has proved itself a valuable resource in competence building within the European RWM community (and beyond) [4].

4 Conclusion

EURAD represents a significant step forward in European cooperation on RWM. Through the joint delivery of research, strategic development, and knowledge management activities, the programme has facilitated collaboration, learning, and the dissemination of knowledge across a diverse range of stakeholders. The inclusion of various actors, from waste management organisations to civil society groups, and the participation of both EU and non-EU partners, have ensured a comprehensive and balanced approach to addressing key challenges in the field.

This European programme has successfully united the European radioactive waste management community, creating a step-change in collaboration, innovation, and knowledge preservation, fostering mutual trust and understanding among all participants while providing breaking scientific studies, research and results in RWM.

Thanks to EURAD, the research and the work carried out in the programme are available to all in the European RWM community. The establishment of such a joint programme also offered a common platform for all Member States and participants to work together and even cooperate with international organisations, such as the IAEA and OECD/NEA.

EURAD additionally generated knowledge with excellent science and the insights by Strategic Studies, made possible by bringing Europe's experts and actors together, creating a sense of networking between the Member States and the participating organisations.

EURAD has highlighted the interest and commitment of all European and international stakeholders to work together on joint programming in the field of radioactive waste management, and this European collaboration will continue to develop with EURAD-2, a new five-year programme in continuation of EURAD starting in October 2024.

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Conflicts of interest

The authors declare that they have no competing interests to report.

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