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REVIEW ARTICLE OPEN ACCESS

Reflections on achievements, activities, and emerging issues of strategic nature within the current and future EURATOM RTD programme on radioactive waste management

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Abstract. This paper provides a review of and some reflections on radioactive waste management activities (including disposal) at the strategic level in connection with the ongoing 'European Joint Programme on Radioactive Waste management – EURAD' and the European 'PREDIS' project on pre-disposal issues. The review took advantage of the large number of contributions made during the FISA 2022/EURADWASTE '22 conference. The paper addresses the key characteristics of EURAD and PREDIS and highlights some of the key strengths of Joint Programming in supporting the member states with implementing waste management activities. Then, it discusses topics of strategic importance for waste management and the contributions of EURAD and PREDIS to these topics. This includes a summary of waste management strategies, the current status of implementing disposal solutions, the importance of knowledge management (taking the long duration of disposal programmes into account) and the importance of societal support of ongoing and future waste management activities. Finally, some remarks are made about issues of importance when organizing future joint activities on radioactive waste management at the European level.

1 Scope of this paper

This paper looks at issues of strategic nature related to the currently ongoing EURAD Joint Programme and the PREDIS project and at emerging issues based on discussions within EURAD and PREDIS and in the broader waste management community. This paper also points to issues of potential relevance for a future European Joint Programme on radioactive waste management (EJP).

The paper looks mainly at the development since the last EURADWASTE conference three years ago and is primarily based on material presented during the strategic and other sessions of the EURADWASTE '22 conference and/or discussed in connection with that conference. The paper also considers insights of the author based on his role as Chief Scientific Officer (CSOff) of EURAD. To better capture the context, sometimes also older issues are mentioned.

The structure of this paper is as follows:

- scope of the paper (this chapter).
- Implementation and structure of EURAD and PREDIS.
- Topics of strategic importance for radioactive waste management (RWM) and contributions by EURAD and PREDIS.
- Looking ahead.
- Summary and conclusions.

2 Implementation and structure of EURAD and PREDIS

2.1 EURAD

EURAD – the European joint programme on radioactive waste management – started in 2019 and consists of ten work packages (WPs)[1] on RDD and two WPs[2] on strategic studies and has a strong Knowledge Management programme with 3 WPs relying on a roadmap produced and managed by the Project Management Office (PMO). Joint programming takes place through the involvement of three colleges – Waste Management Organisations (WMO) in charge of implementing disposal solutions, Technical Sup-

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[1] The current RDD studies are related to (i) the source term, the engineered barriers, the nearfield; (ii) the geosphere barrier & the performance of clay material barriers (e.g., buffer, seals, ...); (iii) perturbing effects (enhanced temperatures, gas generation, organic complexants, etc.); (iv) methods, strategies, and tools.

[2] The current strategic studies are related to methods, strategies, tools and interactions.

port Organisations (TSO) supporting regulatory activities and Research Entities (RE) – and the participation of Civil Society (CS) representatives and is managed by a coordinator, the PMO and the Bureau representing the three colleges. The Chief Scientific Officer (CSOff) reports to the General Assembly (GA) of EURAD and participates in important meetings, including management meetings. With its WPs and governance structure, EURAD covers a broad range of issues that are either of scientific-technological or of strategic relevance (see Chap. 3 and e.g., [1]).

EURAD involves 51 mandated actors[3] from 23 countries (20 Member States and 3 associated countries) that are supported by 62 linked 3rd parties and 3 international partners. Furthermore, CS representtatives and end-users are also involved. With the 23 countries, a broad range of waste management programmes are involved – from advanced programmes with large inventories to early-stage programmes with small inventories, with the complexity of waste inventories varying significantly between the different programmes.

The steps towards implementation of EURAD were strongly supported by EC co-financed activities that started several years ago. This included:

- the implementation of the three colleges: (i) the waste management organisations with IGD-TP founded in 2009 [2], (ii) the technical support organisations started with SITEX their activities in 2012 that did lead to the foundation of the SITEX network in 2018 [3], and (iii) the European research entities with EuradScience founded in 2019 [4]. Thus, all three colleges are formally organised and have their procedures to form common views, e.g., through position papers.

  It should be noted that the regulators are not directly involved; this decision was made to maintain their independence. However, the regulators can participate as end-users or indirectly by becoming a member of SITEX – however, regulators are not fully involved as mandated actors.
- The EC co-funded project JOPRAD investigated the options of a European Joint Programme and supported the planning and development of the corresponding material to submit a proposal for a European Joint Programme on Radioactive Waste Management (EURAD) to the EC in 2018.
- The well-thought-out structure of the call for an EJP by the EC allowed to develop and submit a proposal with a suitable framework for the successful implementation of a European Joint Programme.

The experience and findings up to now indicate that the foundation documents are very suitable for Joint Programming and would also be a good starting point for a new EJP (with some small adaptions). Experience, however, shows that the preparation of an EJP with the WPs for a first phase is fully developed, and will need considerable time. This should be kept in mind for a follow-up EJP of EURAD.

[3] WMO: 19 organisations; TSO: 13 organisations; RE: 19 organisations.

EURAD is a step-change compared to earlier EC co-funded projects:

- EURAD provides a platform that ensures the structured and efficient interaction between key actors in RDD that have a formal responsibility to support the implementation of radioactive waste management activities, including disposal, in their respective member states/programmes. The interaction within EURAD takes advantage that the actors are organized in colleges with each college having its distinct functions (see e.g., [3] (presentation)).
- The ability of the three colleges and the representatives of CS to constructively work together within EURAD increases trust and mutual understanding between the partners and will eventually lead to a 'common' culture, with each of them fulfilling its distinct functions.
- EURAD leads to increased cooperation and enhanced information exchange to assess specific issues (e.g., supported by strategic studies and position papers prepared by the colleges) with the possibility to form common opinions within EURAD (not yet fully exploited):
  - EURAD fosters the interaction between the colleges and the different member states through formal activities and informal contacts through becoming a 'big family'.
  - EURAD is an excellent platform for early-stage programmes to learn about state-of-the-art, to have access to the most recent information and to develop personal contacts.
  - EURAD allows advanced programmes to discuss and share information and through that support the early-stage programmes in advancing their projects.
  - EURAD is of significant value for the interaction between SIMS (small inventory member states) and LIMS (large inventory member states) with the possibility to learn from each other and identify potential synergies.
- EURAD is more efficient in the administrative management of the work than the earlier EC co-funded projects; it makes better use of resources (economy of scale).
- EURAD allowed to define of the needed work upfront by the members of the EJP and thus by the member states. It gives the flexibility to the EJP to define and/or adapt the detailed programme of work (see e.g., the identification of the themes and the development of the 2nd wave WPs, the possibility for small modifications in individual WPs, etc.). Thus, it is now the members of the EJP that define what needs to be done (within certain bounds) and not anymore the EC.
- EURAD ensures that the impact of new findings and experience on future RDD is periodically evaluated by updating the Strategic Research and Knowledge Management Agenda (SRA), see [5].
- EURAD shows the importance to have a knowledge management programme as an integral part of the EJP that ensures that KM actually takes place and that the needs of the broad spectrum of EURAD participants are taken into account. With the approach chosen (using the roadmap to provide structure and context), 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', the 'why' and the 'by whom'. It is envisaged that in the longer run, the KM programme will also allow active networking through 'communities of practice' – this is of special relevance to young professionals entering the field of RWM.

- The combination of RDD (10 WPs), strategic studies (2 WPs to discuss/network on emerging issues) and knowledge management activities (3 WPs, roadmap and 'lunch & learn' also for networking) within one EJP leads to significant synergies.
- The strong participation in EURAD with 23 countries being involved with 51 mandated actors, 62 linked 3rd parties and 3 international partners ensures that the information produced is known, and will be directly accessible and used by a broad community.
- The involvement of the IAEA (see e.g., [6]) and NEA (see e.g., [7]) already in the preparation of EURAD and the current cooperation are beneficial for both sides; IAEA and NEA are important partners of EURAD (and PREDIS). Through 'learning-by-doing' a working mode is established between EURAD and the international organisations that ensure that no duplications will occur (see e.g., [6,8]).
- To summarize: the EJP concept is a very powerful instrument to support the implementation of radioactive waste management activities in the member states and associated countries. With EURAD and PREDIS being at the interface between RDD and implementation, they can be very efficient. This, however, requires an efficient interaction between the Member States and EURAD/PREDIS.

2.2 PREDIS

PREDIS – the project on the pre-disposal management of radioactive waste – is complementary to EURAD and provides many of the detailed aspects of theme 2 (pre-disposal) of EURAD. The main emphasis of PREDIS is on L/ILW and consists of 7 WPs with 4 of them looking at specific waste streams and the other related to management, strategic issues and KM. With this, PREDIS can provide an integrated view of the management of the different pre-disposal issues and maintain a link towards disposal, see [9].

PREDIS has 47 partners from 17 countries and profits from the strong involvement of end-users (waste producers) and the integration of the SNETP side of the community. Finally, PREDIS also provides a sufficiently close link to decommissioning. Also in PREDIS, strong cooperation and coordination take place with the IAEA (see e.g., [8]) and NEA.

2.3 Concluding remarks

EURAD and PREDIS are well underway and have already produced a considerable amount of valuable information and allowed the development of lively interaction between the different participants, allowing some of them to experience a strong learning curve. EURAD's mid-term review took place early in 2022 and the final report of the experts is available. The experts came to rather positive conclusions about EURAD.

Besides their current work, both EURAD and PREDIS use their network to maintain an up-to-date view of issues for potential future collaborative projects by updating their strategic research and knowledge management agendas. This is done in close cooperation between EURAD and PREDIS.

3 Topics of strategic importance to radioactive waste management, their status and current and possible future contributions by EURAD and PREDIS

Below, topics of strategic importance to radioactive waste management are briefly described and the contributions of EURAD and PREDIS to these topics are discussed.

3.1 Waste management strategy at the highest level

Elements of a waste management strategy: the waste management strategy at the highest level defines the endpoints of waste management for the different waste streams – the envisaged disposal solutions. It defines the path towards the envisaged endpoints – a roadmap with milestones and decision points with the needed activities in between. It also defines in broad terms the governance (the 'who', 'for whom', 'by whom', 'what', 'when' and 'why') and describes the needed RDD, taking the available knowledge into account. At a more detailed level, it also defines what is done within the country itself and what could be done through shared solutions or by 'outsourcing' by relying on service providers external to the programme. Then, it also discusses existing alternatives for the topics to be covered by each country on its own.

These issues are described in the national programme by each of the member states as required by the waste directive ([10]). Progress is reported every 3 years in a report to the Commission on the implementation of the directive. The waste directive also states that geological disposal is at this time at the technical level accepted to represent the safest and most suitable option as the end point of the management of SF and HLW; this is also true for LL-ILW. For LLW and short-lived ILW, disposal in surface or near-surface facilities is the typical concept; however, in some countries, these wastes are also disposed of in geological repositories, often at a more shallow depth than SF/HLW.

EURAD contributes to the issues related to the waste management strategy through the ROUTES work package. In ROUTES, key issues and open questions about the waste management strategies and options ('*from cradle to grave*') are being discussed, [11]. The interactions in ROUTES between Large Inventory Member States (LIMS) and Small Inventory Member States (SIMS) are

important for knowledge transfer to SIMS for them to develop an understanding of the options available to manage their waste streams. The interaction between all the participants also contributes to knowledge exchange on challenging waste streams (small amounts of difficult-to-treat wastes). These interactions also include the identification and discussion of options to optimize waste management. These issues are also of technical and economic relevance and thus, methods are being developed that may have the potential to systematically investigate alternative options (see e.g., [12]).

Looking at the evaluation of the waste management programmes [13], one sees that shared solutions for waste management activities (including disposal) are envisaged as an option by a significant number of countries as part of the so-called dual-track approach (looking both at shared solutions and a solution each country on its own), especially for those without a nuclear power programme. This is also reflected by the ongoing joint activities by a range of countries within ERDO (see [14]). The use of shared solutions requires that the chosen facility is suitable for the disposal of the envisaged waste stream. For this, waste acceptance criteria (WAC) play an important role and thus, the development of adequate (generic) WACs for situations with no disposal solution available yet is also a topic within EURAD (WP ROUTES) and PREDIS (see e.g., [15]). There, a 'no regrets' approach is suggested (see a poster of [15]).

Besides the technical aspects, also regulatory and legal issues can hinder shared solutions. An initiative (project HARPER) is underway that analyses these obstacles; more aligned regulation and legislation may in the long run lead to more favourable conditions also for shared solutions, see [16].

Besides the technical aspects of the envisaged solution, also the pathway for implementation is essential. Implementing disposal solutions is a highly interdisciplinary undertaking that changes its nature from one phase to the next, needing in each phase special capabilities with integrators needed in each of the phases. The phases and their goals are addressed in the EURAD Roadmap [17], which describes in a generic manner the different thematic issues that need to be addressed in the different phases of developing, operating and closing disposal facilities. Although primarily addressing the geological disposal of HLW and LL-ILW, the roadmap can also be used for planning the implementation of disposal facilities for all other waste streams.

Timing of the start of operation of disposal solutions depends upon several factors. On the one hand, the time needed to perform the technical work, e.g as described in the EURAD roadmap [17], but also policy issues (including political and societal issues, financing aspects and decision-making) can be very influential for the start of construction/operation.

3.2 Pre-disposal issues

Pre-disposal is in all programmes with L/ILW a very important issue to achieve an optimal situation for interim storage and eventual disposal in relation to safety (operational safety, radioprotection, post-closure safety), engineering feasibility and economy. To ensure the acceptability of waste packages for storage and disposal, waste acceptance criteria should be available at least in a preliminary format to allow to perform of the necessary activities in a suitable manner. This includes the characterisation and classification of raw wastes in view of their segregation as well as the treatment/conditioning and packaging of the waste (incl. characterisation and quality assurance of the final product, including its documentation). The endpoint of these steps forms the waste acceptance process to ensure the suitability of the waste packages for interim storage, transportation, and disposal.

In some programs, the implementation of disposal solutions is so far away, that no waste acceptance criteria are available at all. This can lead to difficult situations as the discussions within the EURAD WP ROUTES show, see [11].

The work done on pre-disposal issues within PREDIS is devoted to L/ILW; in EURAD, some work is done on Spent Fuel, see [18]. For Spent Fuel (and HLW and LL-ILW in case of a closed fuel cycle) it is important to consider disposal issues very early in the path towards disposal, ideally already in the phase of designing new reactors and in the phase of developing advanced fuels. In that sense, it is very beneficial that the FISA/EURADWASTE conferences take place at the same time; unfortunately, however, the programmes are made such that hardly any discussion/interaction on scientific-technical issues can take place at the conference ([19], summary presentation).

Within PREDIS, different issues related to waste characterisation and treatment of L/ILW are addressed. This includes the segregation of raw wastes and their classification that may benefit from refined characterisation methods, see e.g., [20]. For some of the challenging waste streams (e.g., certain liquid organics) new materials and technologies for conditioning/solidification are being developed that are expected to be more efficient/economic and/or lead to better quality and that are also assessed with respect to environmental impact (see e.g., poster of [21]). Also for waste streams that are since many years solidified in an industrial manner, it is worthwhile to investigate new processes that are expected to have advantages over currently used procedures, see. e.g., [22].

For those cases where disposal will only take place in the more distant future, the evolution of the waste properties during interim storage can become an issue of relevance. For SF, this might be related to changes in cladding properties during dry storage as investigated in the EURAD WP SFC, see e.g., [18]. The potential degradation of L/ILW waste packages may make it advisable to implement specific monitoring activities, see e.g., [23].

3.3 Implementation of geological repositories for SF/HLW

Progress with implementing SF/HLW repositories: with the implementation of SF/HLW repositories, significant progress has been made over the last years by the advanced programmes, e.g.:

- Finland: the operation license application was submitted by the end of 2021.
- Sweden: the license was granted by government at the end of 2021.
- France: the construction license was submitted in January 2023.
- Switzerland: the announcement of the site selected for implementing the repository took place in autumn 2022.
- Canada: currently, two sites are under investigation; the announcement of the site selected for implementation is expected towards the end of 2023.
- China: the excavation of a URL at the potential site in crystalline rock (Beishan region) started in 2022.
- Germany: in 2021, a broad range of regions was proposed for further evaluation, considering three different host rocks (salt (salt domes, bedded salt), clay stones, crystalline rock).
- United Kingdom: the WMO (NWS) is in dialogue with several communities about potential siting with starting some field work (marine geophysical survey).

The progress described above indicates that the scientific and technological basis and knowledge for implementing geological repositories for SF/HLW have reached an advanced stage as demonstrated by the licence applications/granted licenses for repositories in crystalline rock (Posiva, SKB), the prepared licence application for a repository in claystone (Andra) and the corresponding regulatory reviews and governmental decisions. This shows that for these host-rock types, no fundamental open issues exist and that the scientific-technological basis and knowledge are available for licensing of HLW repositories with these types of host rock for well-chosen sites and the repository design tailored to the site conditions and the properties of the waste foreseen for disposal.

However, it is important to note that the corresponding licensing process can be complex and involve not only nuclear safety but also environmental issues, see e.g., [24].

With this recent progress, a big step has been made towards achieving the vision of IGD-TP from 2009 [2] '*Our vision is that by 2025, the first geological disposal facilities for spent fuel, high level waste, and other long-lived radioactive waste will be operating safely in Europe*'.

The advanced programmes will now face the transition from developing a pilot project to the industrialized routine process of construction and operation – this is expected to be a considerable challenge and will take some time. The corresponding IGD-TP vision for 2040 calls for moving '*towards industrialization of radioactive waste disposal in Europe*' that puts the highest priority on safe operations, on optimization and industrialization of planning, construction and operation and that acknowledges the need to tailor solutions for the implementation of additional repositories in Europe ([25,26]).

From a purely technical point of view, implementation of repositories for SF/HLW is feasible within reasonable time scales. Therefore, in an EC-taxonomy document [27] implementation (start of operation) in 2050 is mentioned as a reasonable time point to envisage the start of operation of SF/HLW repositories.

The very strong national RDD programmes of the advanced programmes were essential to reach the current status of implementing HLW repositories. However, also the EC co-funded RDD projects over many years and made very significant contributions to the recent advances. The value of the EC co-funded RDD is manifold: it allows them to interact and learn from each other; cooperative activities are less costly for each of the participants and the work done in international projects is often perceived as the 'highest standard'.

Despite the progress made, RDD will also continue for the advanced programmes for SF/HLW during implementation, e.g., to optimize implementation and to address some safety-related issues (including the management of uncertainties and making the safety arguments more convincing):

- the management of uncertainties includes the identification of uncertainties (including the issue of completeness), analyse of their potential impact on overall system behaviour and performance and, depending upon the importance of the uncertainties, identifying options to manage them (possibilities to avoid them or to mitigate their effects and/or to reduce their likelihood of occurrence e.g., through design measures; accept uncertainties because of their limited significance and/or their low likelihood of occurrence, etc.). These issues are addressed within the WP UMAN, see [28].
- Within the EURAD WPs, contributions are made to reduce uncertainties and to make the safety arguments more convincing. They are related to the source term/engineered barriers/ near field performance (SFC, ConCorD, ACED, MAGIC), the geosphere & performance of clay material barriers (FUTURE), perturbing effects (CORI, GAS, HITEC) and methods/strategies, interactions and tools (ROUTES, UMAN, DONUT, MODATS) with summaries in their respective WP state-of-the-art (SotA) documents.
- Some of the RDD contributes besides improved understanding also to the optimisation of repository design and operation (alternative canister materials (ConCorD), optimise heat loading (HITEC), monitoring (MODATS), etc.) and through reduction of uncertainties in waste properties (e.g., heat output, see SFC).
- To optimize the implementation through innovations. In view of the envisaged industrialisation of implementation (construction, operation, closure) by the advanced programmes, it is expected that RDD will in future also address technological innovations for industrialization of implementation to improve efficiency (time and finances) and maintain reliability.
- Finally, it is important to mention that a review of each of the finalized RDD WP is essential to see where we are and whether anything else (besides maintaining a watching brief) is needed in future. For this, the remaining uncertainties should be discussed in the final report in a manner that their meaning and importance can be assessed quantitatively or at least qualitatively by each end-user for his specific application. A contribution to this is the planned updates of the SotA-documents.

Also, the less advanced programs will need some specific RDD, as each disposal system is to some extent a prototype (differences in geology, waste inventories and legal/regulatory requirements) and thus, the adaptation of the existing scientific and technological basis to the specific system at hand may require some specific focussed development work ('*tailoring of disposal solutions*'). Also for the areas with no need for specific adaption, a good understanding is needed to use the scientific and technological basis in a correct manner.

For these scientific-technical issues, some of the less advanced programmes take advantage of the experience of the advanced programmes – currently, the knowledge transfer takes mainly place through commercial contracts.

In the earlier-stage programmes with a significant NPP programme, progress with implementing their HLW repositories is often not hindered by open RDD issues but much more by the limited progress in political/policy-related decision-making (also influenced by societal aspects). One extreme example is e.g., the USA where after abandoning the Yucca Mountain Project not much has been done towards implementation.

Most programmes with only very limited HLW e.g., from R&D (no NPP-programme) are still at an early-stage of looking at different options for managing their HLW (mined repository, borehole disposal, shared solutions) to find a feasible solution with respect to safety, economy, timing, human resources, etc.

Directing future R&D will profit from the ongoing update of the SRA within EURAD (together with PREDIS) that allows all partners (from both the advanced programmes and the early-stage programmes) to influence the content of a new EJP on waste management by providing their input through their respective college, see [5].

3.4 Implementation of disposal solutions for L/ILW

Progress with implementing L/ILW disposal solutions: the implementation of L/ILW repositories is established already since quite a long time. In many programmes with a significant amount of waste, implementation of the needed repositories occurred already many years ago, with extensions of some of these repositories taking place (e.g., SFR in Sweden) and with optimization continuing.

In some countries, implementation is still under development and operation has not yet started for a range of reasons (incl. political/policy reasons).

As already mentioned for SF/HLW, and also for L/ILW the implementation of RWM activities is for 'small inventory member states' (SIMS) without an NPP-programme each on its own often a challenge – for SIMS, shared solutions at least for part of the RWM activities is an important issue. Many of these programmes follow the already mentioned dual-track approach (both a solution on its own and a shared solution (with different models in principle possible)). The option of shared solutions is also considered by some programmes with a small to moderate NPP programme [14].

However, there are challenges with shared solutions. First of all, countries have to be found that accept host facilities that are also used by other countries. Then, the differences in legal and regulatory requirements in the different countries must be handled. Additionally, there exist difficulties in the transboundary transfer of waste. Finally, waste acceptance criteria and disposal suitability have to be clarified. An initiative outside of EURAD/PREDIS is underway to identify possibilities to reduce the legal & regulatory hurdles for implementing shared solutions (Project HARPERS, see [16]).

The different strategic options (from cradle to grave) for these programmes are discussed within the EURAD WP ROUTES, see [11]. The options to identify the optimal strategy include also shared solutions for the different RWM activities, including disposal. Within that WP also very practical issues are discussed (e.g., the management of poorly understood legacy waste).

Also for L/ILW RDD is ongoing to improve the scientific-technological basis and to improve the detailed understanding of safety. RDD WPs and Strategic Studies WPs of relevance for L/ILW in EURAD are ACED, CORI, DONUT, FUTURE, GAS, MAGIC and UMAN.

3.5 Knowledge management

Implementation of disposal facilities for radioactive waste covers a period of up to 100 years or more and will involve several generations of actors requiring specific knowledge for operational issues but also for post-closure issues (e.g., addressing emerging issues (by science/technology, public, etc.), periodic safety report updates, etc.), the latter requiring both specific expertise and the capability to integrate. This is true for both the implementer (WMO), the regulatory side (regulator and TSO) and research entities (RE). Thus, knowledge management is an important issue. Knowledge management has to address the following elements:

- **availability of capabilities**: knowledge management has to ensure that the capabilities needed are and will remain available for the implementation of the disposal facilities with the corresponding activities up to (and beyond) closure of the disposal facilities. The capabilities include:
  - competences (people (individual competencies) acting in a team (collective capacity) with networks to interact – the 'human capital') with the tacit knowledge to use existing information and the ability to develop new knowledge when needed. This includes both subject matter experts and integrators/generalists,
  - specialist infrastructure needed to perform the necessary activities (e.g., specialized labs),
  - external supply chains to cover all external needs (e.g., special services and products).

Sufficient knowledge (information and capabilities) has to be available within each programme, as each disposal facility is, to some extent, a 'prototype'.

When discussing the availability of capabilities, it may be useful to distinguish between:

– areas of general interest, where broad scientific and technological communities exist, independent of waste management activities. In these areas, capabilities will be available independent of waste management and disposal; however, it is essential to stay connected with the community at large to be able to hire qualified specialists from the market and to properly integrate them into the team. Furthermore, one has to have the ability to make links to specific waste management activities/issues to be a competent customer and to be aware of emerging issues.
To be sufficiently knowledgeable, this will also require in these areas some scientific-technological activities within each disposal programme with the possibility of some coordinated joint activities.
– **Areas specific to waste management and disposal**. In these areas, capabilities will only exist if specific measures are taken. This may include some R&D that educates people, that supports the activities of the 'communities of practice' (for networking between specialists), that maintains specialist infrastructure and that also helps to stay connected with neighbouring scientific communities, also to be aware of any new developments that offer some opportunities or may need some corrective actions (emerging issues). Thus, international cooperation and some joint activities in these areas are important.

For both areas it is critical to attracting bright scientists and engineers already today, as the age profile of people working in the nuclear field is at a critical level – 35% of the workers are at an age of 55 years and more [29]. Thus, disposal projects must be visible in their full dimension to demonstrate their attractiveness; this requires some activities to stay connected with the scientific community. Training and mobility are specific additional measures that may be useful for educating young scientists entering the field in specialist areas. Finally, for some topics, it may also be useful to develop some guidance documents that facilitate the start of newcomers in the area, see e.g., [30], combined with the transfer of tacit knowledge through networking (creation of 'communities of practice').

- **Availability of information and the knowledge needed for its further use**: knowledge management has to make existing and newly developed information 'durable', visible and accessible to those that need it. In combination with adequate competencies (people providing tacit knowledge), this leads to knowledge to support the implementation of disposal facilities.
For DGRs for SF/HLW and LL-ILW, a large body of knowledge (information and competencies providing the needed tacit knowledge) has been developed by the advanced programmes and through European Commission co-funded research over a period of about 40 years, leading to the currently licensed DGR projects.
The scientific and technological basis for these facilities (as documented in the licence applications and in supporting documentation) will be used to further develop and optimize the advanced projects, to perform the needed periodic safety case updates up to the closure of the DGRs and to address emerging issues. These activities will continue over a long time, meaning that this work will sooner or later be done by younger generations not yet in the field. For them, it is important to have the current information available in an understandable form to ensure its correct use in their future work. This also requires that the younger generations receive the needed knowledge, including understanding the rationale for the important choices made.
The information available from advanced programmes is also very valuable for the earlier-stage programmes for further developing their own disposal projects. This may, however, need some adaptation of the existing information to the specific situation at hand. Both the correct use of existing information and the partial adaptation of the information to the specific situation at hand will require knowledge within these programmes that needs to be built up. To some extent, it may be necessary to rely for this on the support of the organisations that developed the knowledge to be used, e.g., through commercial contracts. As soon as the earlier-stage programmes become more advanced, they will also face the same issues as mentioned above for the advanced programmes.
- **Transfer of knowledge between generations**: knowledge management has to assist in the transfer of information and tacit knowledge between generations within the organisations responsible for the disposal facilities, including the regulator. This needs specific measures within each organisation and requires a corresponding culture of the organisations.

Within EURAD and in close cooperation with PREDIS, a knowledge management programme is under development [31]. It addresses the points mentioned above through the following elements:

- it has several RDD work packages and two work packages on strategic issues. Besides generating new knowledge, these WPs also educate young scientists and thus contribute to maintaining a body of experts over the many years to come. The education of scientists is supported by a work package that provides training and supports the mobility of young scientists.
- It has a work package that collects information to provide an overview of existing guidance in areas of importance for waste management. In some areas of interest to several European waste management programmes where no suitable guidance is available yet, the new guidance is being developed. The guidance documents are an important element for knowledge transfer.
- It has a work package to capture the state of knowledge. This work is linked to the EURAD roadmap that provides the structure and context for organising the information in a hierarchical manner. This again is an important element of maintaining and transferring knowledge.
- For the early-stage programmes, the EURAD roadmap provides a suitable tool to support the planning of implementation of disposal solutions (5 generic phases, for each of the phases with a description of the key activities for the 7 broad themes needed for implementation).

This is complemented by guidance documents (currently under development within EURAD).

- The EURAD roadmap provides a framework for national disposal programmes to identify the knowledge and capabilities needed in the different phases of implementation. With this, it becomes visible whether all knowledge areas needed in the near future are already covered or if there is a need to acquire additional knowledge, including competencies, networks, infrastructure and supply chains/external service providers.
- EURAD provides a platform for interaction. This platform should, in the long term, develop into a range of 'communities of practice' that allow ongoing systematic networking and provide the opportunity for newcomers to become fully familiar with the relevant areas and develop their personal network. Such networks are important for both subject matter experts and integrators/generalists. Especially for the integrators, it is important to be involved in a broad range of communities of practice.

Finally, it is important to recognize that a knowledge management programme can only be effective when it continues over a significant period of time – thus, it would be very beneficial if the work started within EURAD [32] could continue in follow-up European Joint Programmes on Waste Management. Such activities within European Joint Programmes would be complementary to the ongoing activities within the IAEA and the NEA that are already in place for many years.

3.6 Importance of society

Societal support is a prerequisite for the implementation of RWM activities. This requires sufficient mutual trust and understanding. Also in EURAD the involvement of civil society (CS) was foreseen from the beginning. The active involvement of CS in EURAD works well with the main involvement of CS in EURAD's strategic studies but some involvement also in the other WPs. However, it still needs to be seen how far this beneficial interaction within EURAD can be transferred to the national programmes to support the constructive cooperation of society in implementing disposal solutions.

To get a better understanding of societal involvement, it might be useful to find out why societal involvement worked in some countries and why it did not work in other countries. Furthermore, it would also be interesting to investigate how repository projects are perceived in different countries and if differences are seen, to investigate the reasons for these differences.

4 Looking ahead – experience with EURAD as input for developing a new European Joint Programme on radioactive waste management

There are clear signals from the EC that a follow-up EJP on RWM to EURAD is envisaged where pre-disposal issues would be integrated within waste management at large (the current EURAD).

Experience within EURAD can and will be used as input for shaping a future EJP on RWM. This could include:

- use the experience made with the basic structure (founding documents with some modifications) and instruments (type of WPs & activities) used in EURAD.
- The ongoing update of the SRA of EURAD and PREDIS (with the activities considered 'characterised' by 'drivers'). In this update or complementary to this update, the following issues are considered important: (i) for areas with RDD for many years, the questions 'how good is good enough for implementation?' and 'where is a continuation for what reason justified?' should also be addressed; (ii) sufficient thought should be given on which new areas might deserve more attention in future. This should also include areas related to the optimisation of implementation.
- The interactions through EURAD stress the importance of having a detailed understanding of the needs of the member states in implementing radioactive waste management activities, including disposal, as an EJP on RWM is at the interface between RDD (DG RTD) and implementation (DG ENER) – remember: the main motivation for an EJP on RWM is to support all member states in implementing radioactive waste management activities, including disposal. For this, the specific needs of each of the following types of programmes should be assessed:
  - advanced programmes (with significant NPP programmes)
  - early-stage/medium-stage programmes (with significant NPP programmes)
  - early-stage small inventory programmes.

This indicates the importance to take the findings of evaluations of the national programmes of member states into account, see e.g., the ARTEMIS reports and the reporting by DG ENER as well as the findings from the Joint Convention reviews.

- **Ensure inclusiveness**
  - by making the boundary conditions such that all member states (and associated countries) with a waste management programme can participate in a new EJP
  - by finding possibilities to include regulators & waste producers in a new EJP through appropriate mechanisms
  - by giving the opportunity to newcomers in RDD to become a partner in RDD projects to get 'hands-on' experience with RDD and develop a network
  - by ensuring a sufficiently broad SRA that should include some novelties
  - by rules that allow the participation of projects/programmes external to the member states and associated countries to participate in a new EJP at their own cost.
- Ensure the active engagement of advanced programmes in the continuation of the KM programme by providing

adequate economic boundary conditions for their participation e.g., for the following contributions:
  – development of KM sign-posting documents (domain insights, SoK's, ...)
  – development of guidance documents
  – becoming 'drivers' within 'communities of practice'.
- Develop position papers and use other measures to provide information to the public to allow them to develop a balanced perception of the disposal of radioactive waste as the endpoint of RWM.

5 Summary and conclusions

European Joint Programming for Radioactive Waste Management offers many benefits in comparison to the earlier EC co-funded projects that were developed through competitive calls:

- joint programming allows to develop of balanced views and approaches, taking the needs of European radioactive waste management programmes into account. With the instrument of mandated actors, the member states have a clear handle on which organisations represent them in the joint programming, in deciding on which work to do and in the detailed organisation of the programme of work and to make changes if needed.
- A European joint programme allows jointly deciding on future RDD projects, strategic studies and knowledge management activities. The programme should also allow and encourage the participation of partners from outside of the EC.
- A European joint programme provides an excellent platform for interaction between the three colleges (WMO, TSO and RE), end-users and civil society organisations and between the different types of programmes (advanced programmes vs. early-stage programmes, large inventory programmes vs. small inventory programmes) to exchange information and to learn from each other, to address emerging issues, to decide on the details of the programme of work, incl. the periodic update of the strategic research and knowledge management agenda (SRA), to form common opinions, to develop position papers and to enhance mutual understanding and trust.
- With the different types of projects implemented in EURAD (RDD WPs, Strategic Studies WPs and KM WPs), experience has been made on the power of each of these instruments and on how to use them.
  Especially the instrument of 'strategic studies' allows to investigate of novel ideas and emerging issues through networking. It is encouraged to use this instrument more strongly in the current phase of re-orientation, taking the need for optimisation (materials, design, ...)/ industrialisation of implementation (novel technologies & methods) in the advanced programmes into account.
- A European joint programme also provides an ideal platform for knowledge management. It has a direct link to knowledge providers and to those that need knowledge and thus ensures efficient transfer of knowledge. For this, experience with a range of instruments (roadmap to provide structure & context, state-of-the-art reports, state-of-knowledge reports, theme overviews, domain insights, guidance, first steps towards 'communities of practice', etc.) have been made and future improvements are expected.
  Through a European joint programme, there are the means to ensure the longevity of the now-implemented knowledge management programme; the EC has to provide an adequate structure and financing for this.
- A European joint programme has the instruments to allow for the strong participation of end-users; this also allows the participation of regulators, waste producers, etc. The participation of end-users is important to ensure that the results produced will meet the expectations of those that are in need of them.
- Finally, a European joint programme allows a more efficient way of managing a big programme than a fragmented number of individual projects for several reasons (easier interaction, synergies, economy of scale, etc.).
- Overall, a European joint programme is a very powerful instrument to support the implementation of radioactive waste management activities in the member states, being at the interface between RDD (DG RTD) & implementation (DG ENER).

Conflict of interests

The paper was prepared on invitation by the European Commission Directorate-General for Research and Innovation (DG RTD) in connection with the EURADWASTE '22 conference in 2022 in Lyon. The author also acts as the Chief Scientific Officer of EURAD, with EURAD having made significant contributions to the EURADWASTE '22 conference.

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Data availability statement

The information used in preparing the paper is all in the open domain in the proceedings of the Euradwaste '22 conference.

Author contribution statement

The author prepared the manuscript alone without any external support and without any involvement of other persons.

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