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# The Euratom Research and Training programme in support of the innovation and the R&D in the field of radioactive waste management

Seif Ben Hadj Hassine

*DG Research & Innovation, Directorate C, Unit C4, Euratom Research, European Commission Brussels 1049, Belgium*

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**Summary.** — This paper describes the recent efforts made to verify the applicability of Artificial Intelligence technologies to legacy wastes. In particular, it is introduced the image evaluation technology, using deep learning models, which is closely related to the non-destructive evaluation technology and the sensing technology.

## 1. – Introduction

As a consequence of the recent political developments in Europe and the war in Ukraine, the security of energy supply in the European Union is challenged. In the past years, the European Commission has been working on a proposal for an EU Taxonomy system that lists the economic activities that are considered environmentally sustainable for investment purposes [9, 10]. In July 2022, a Complementary Delegated Act was voted in the European Parliament. The text foresees that nuclear would be included in the Taxonomy as transitional activity. This would however be the case only in a limited number of circumstances and under strict conditions [11].

As of today, there are 109 nuclear powerplants in 13 Member States that produce around 25% of the total electricity in the Union [12]. Additionally, the extension of the lifetime of the reactor fleet from 40 years to 60 years is strongly considered and a number of Member States have expressed their intention to build new nuclear power plants, large or small considering the development of Small Modular Reactors [13, 14].

In this new socio-political landscape, one could say that the nuclear industry enters a new era in Europe. While the nuclear reactor fleet is to be refurbished, the number of nuclear reactors that will have to be dismantled in the next decades will significantly increase. The World Nuclear Association reports that at least 200 reactors are to be decommissioned 30 years from now [16]. It is a common misconception that the lifecycle of a nuclear facility ends with the decommissioning and rehabilitation of the site. The management of the radioactive waste generated by the operations and the decommissioning of the facility is a long process that needs to be anticipated upstream. The IAEA strongly recommends an integrated radioactive waste management system that identifies the waste streams from its generation and defines the relevant routes they should follow to its ultimate disposal. To ensure a safe management of the waste at every step of the process, dedicated R&D programmes are usually initiated by the relevant stakeholders at the national level.

Since 1975, the Euratom Research and Training Programme has been implemented by the European Commission, under the provisions of the European Atomic Energy Community (Euratom) Treaty and aims at supplementing and coordinating the Member State programmes to perform joint cutting-edge research and to support knowledge generation and preservation [17]. A 5-year framework programme (with a 2-year extension) is implemented via annual or biannual work programmes publishing calls for proposals which are evaluated by independent experts. The selected research projects are then funded up to a duration of five years.

Since the first Framework Programme 1975-1979, radioactive waste management has always been an essential topic covered by the successive work programmes. While RWM is governed by national legislation and international conventions, it was only since 2011, that a Community framework was established by the Waste Directive (Directive 2011/70/EURATOM) [15]. The Directive supplements the basic standards referred to in the Euratom Treaty and aims at ensuring the responsible and safe management of spent fuel and radioactive waste. The implementation of the waste directive on the long term is support by the national research programmes and the Euratom Research and Training programme which supplements the national initiatives. As described in the waste Directive (Recital (30)), “the different steps in spent fuel and radioactive waste management are closely interrelated. Decision taken in one individual step may affect a subsequent step”. Additionally, Recital (28) establishes “the need of the timely implementation of all steps of spent fuel and radioactive waste management from generation to disposal”.

The new research framework programme Horizon Europe kicked off in 2021 just after its predecessor Horizon 2020 came to an end in 2020. Both included a number of projects and programmes strongly related to decommissioning and RWM. In the following, we dwell on the main highlights of the past and on-going projects since Horizon 2020 was launched in 2014. The overview of the achievements of the past and on-going projects over the last decade will rely on this holistic approach to RWM (fig. 1) and each one of the main steps in RWM will be briefly introduced.

This article describes recent efforts to verify the applicability of AI technologies to legacy wastes. In particular, we introduce the image evaluation technology using deep learning models, which is closely related to the non-destructive evaluation technology and the sensing technology for sorting mentioned above.

## 2. – Decommissioning

As explained above, there is a need in further research and innovation in order to be able to manage the decommissioning of the nuclear facilities in a safe and responsible way. The Euratom Research and Training programme plays an important role in supporting the R&D efforts in the Member States by funding joint collaborative projects that would result in an EU added value for the whole Community. There is a relative consensus that

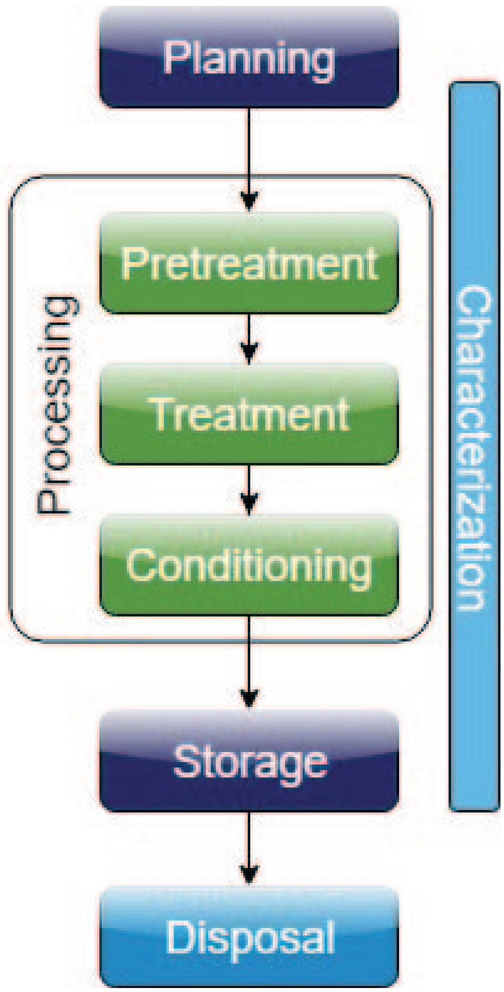


Fig. 1. – The different steps in radioactive waste management from its generation to its disposal (source: AIEA).

the decommissioning operations have to take into account the future steps in managing the generated radioactive waste.

One important Coordination and Support Action (CSA) that was implemented within the Horizon 2020 framework is the SHARE project [18]. Based on a consultation methodology, the project established an inclusive roadmap [19] for research in technical and non-technical areas, to enable stakeholders to jointly improve safety, reduce costs and minimise environmental impact in the decommissioning of nuclear facilities. Figure 2 schematically describes the methodology of the SHARE project. Based on a gap analysis, more than 140 activities were identified and assigned to four different categories: R&D, Knowledge Sharing, Harmonisation of Practices and Education and Training. The roadmap goes a step further by compiling the various activities by activity bundles that are prioritised to establish a visibility of the necessary actions in 5, 10, and 15 years from the stakeholder perspective.

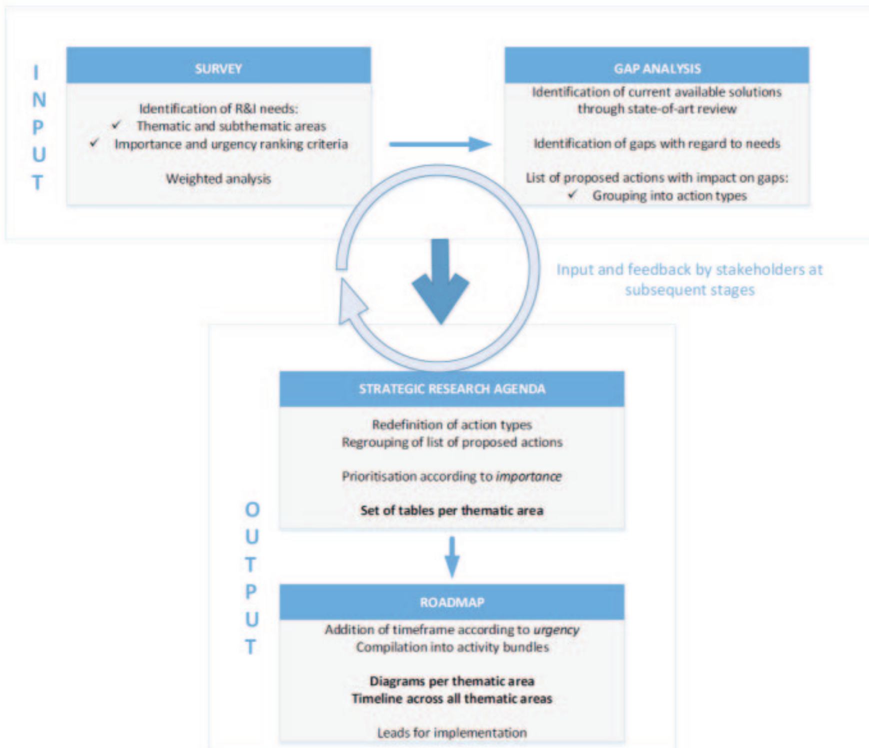


Fig. 2. – The SHARE project methodology.

While the EC strategy is to combine all the Euratom research actions related to radioactive waste management into one single Partnership involving all the Member States and associated countries, the decommissioning field is ruled out of its scope. The high commercial interests of the decommissioning research actions do not comply with the shared added value and the vision of the EC on the Partnership on RWM. However, the Euratom Research and Training programme continues to support research on decommissioning topics via additional Coordination and Support Actions (such the HARPERS project [20]) and Innovation Actions in line with the SHARE roadmap (*e.g.*, CLEANDEM [21], INNO4GRAPH [22], PLEIADES [23], LD-SAFE [24]). Additionally, the 2021-2022 Work Programme supported some of the European projects by awarding the best ones with Innovation Prizes. This type of actions might be renewed in the future.

## 3. – Characterisation

The characterisation of radioactive waste has been identified as a critical and important topic by the SHARE project but also by the Euratom Programme Committee in the past Work Programmes. The topic covers a broad scope of research actions: the radioactive waste streams have to be properly characterised at their generation, prior to their treatment and conditioning, following their processing, in some cases during their interim storage and finally before their final disposal.

Each one of these characterisation steps targets specific properties of the waste; these can be radiological but also physical and chemical properties of the material that characterise its short and long term behaviour. Which properties are the most relevant to characterise and at which step of the process highly depend on the waste acceptance system established by the national stakeholders.

Due to the long time frames imposed by the nature of radioactive waste management operations, characterisation of the waste at its generation has to take into account the future requirements of its processing, storage and disposal. Research and innovation are thus still needed on these topics to develop characterisation techniques and methodologies to address gaps in the properties that are required to be characterised but also to optimise the existing techniques in terms of secondary generated waste, exposure to radioactivity, accuracy and detection limits and costs.

Therefore, some of the major EC projects focused on the characterisation of the waste: the DISCO project [6] was solely about the characterisation of the spent fuel at different degradation state, the CHANCE project [7] specifically addressed the characterisation of cemented waste packages and their disposability and the MICADO project [8] aims at developing a cost effective non destructive technique of the characterisation of the radioactive waste in the context of decommissioning operations.

As highlighted above, decommissioning activities of nuclear facilities are expected to significantly increase over the next decade. The MICADO project (Measurement and Instrumentation for Cleaning And Decommissioning Operations) focuses on non-destructive radiological characterisation of the low and intermediate level waste. The project team aims at developing an integrated system that would allow the full characterisation of the waste based on different technologies: hot spot localisation, Gamma spectroscopy, Gamma spectrometry, active and passive neutron measurements, photofission, radiofrequency identification and a long-term monitoring grid. The developed platform will help defining a procedure for the characterisation of the waste with specific guidelines depending on the geometry and the nature of the waste. The developed platform relies on five essential pillars: flexibility and adaptability to the waste characteristics, transportability and practical deployment of the platform, digitisation of the data and real-time acquisition of the measurements, quantification of fissile fertile mass and the actinides content and finally traceability of the compiled data over time. The final demonstration of the project successfully took place on 25th of January 2023.

For each radioactive waste stream or category, a management route is specifically devised based on the nature and the radioactivity level of the waste. Spent nuclear fuel (SNF) is in particular considered separately due to its characteristics and high activity levels. The characterisation of SNF and its behaviour in representative conditions of its storage and/or disposal is thus an essential element in safety assessment. The DISCO (Modern Spent Fuel Dissolution and Chemistry in Failed Container Conditions) project focused on the characterisation of SNF with additives and on the effects of fuel type, sample preparation and sample history on the crystal structure, the uranium valence and the microstructure. The results showed how the reactivity of the oxide is changed depending on the type and amounts of additives with different valence. Using alpha-doped material, hydrogen peroxide and air-saturated systems, the effect of additives on the oxidative dissolution of uranium has been investigated and the results showed that the studied additives do not negatively affect the matrix dissolution of the spent fuel. The experiments also emphasized the importance of the chemical environment on the fuel dissolution; the use of different solution composition and atmospheres showed that the aqueous speciation is fundamental for the development of the system. The released uranium behaviour depends on the chemical environment regardless of the system being in oxidative or reducing conditions. The experiments also confirmed that the oxidative spent fuel dissolution rate is significantly reduced by hydrogen for both fuel types MOX and ADOPT. Finally, part of the work accomplished by the DISCO project was dedicated to the modelling of the dissolution of the SNF. Existing models have been improved to be used in safety assessments. In particular, the adequacy and adaptability to the modern types of fuel have been tested and validated.

The characterisation of the SNF and of raw radioactive waste in general is essential to determine how to process it, store it and dispose of it in a consistent manner. All raw radioactive waste will have to eventually be conditioned or immobilised in a matrix to ensure that the radioactivity is confined and that the waste form is stable over time. Conditioned radioactive waste packages have thus to be properly characterised after the processing and prior to their disposal. In particular, one important challenge that has to be addressed is the legacy conditioned waste which in some cases lacks essential data on the raw waste to safely manage it. The CHANCE project (Characterisation of Conditioned Nuclear Waste for its Safe Disposal in Europe) focused on developing new techniques and methodologies for the characterisation of conditioned waste. New equipment was developed and relied on three techniques: calorimetry (calorimeter able to host 200L drums), cavity ring-down spectroscopy for C14 detection and Muon tomography. Combining calorimetry with Gamma and neutron measurements improved the detection of plutonium and the measurement precision when characterising large, dense and heterogeneous waste packages, such as concrete waste packages. These non-destructive measurements were also supported by numerical models. Further development of the techniques will still be needed before their industrial deployment.

## 4. – Processing

Processing the raw radioactive waste covers a broad range of operations that the waste undergoes in order to render it more easily and practically manageable. The waste can first be treated, mechanically, chemically or thermally to either reduce its volume or transform it in one or multiple more stable and/or durable waste forms. The THERAMIN project (Thermal treatment for radioactive waste minimisation and hazard reduction) aimed at the promotion of thermal treatment of low and intermediate level waste prior to its disposal. A strategic review was carried out to determine which radioactive wastes could potentially be thermally treated and which thermal technologies were available. A series of guidelines were then issued for waste managers and decision makers on how to select the most appropriate waste and thermal treatment option for their particular need. Additionally, demonstrations were carried out for six thermal treatment technologies for selected relevant waste streams (both hot and simulated samples). The considered waste streams included raw wastes but also conditioned waste forms in cementitious or bituminised matrices. The thermally treated materials were then characterised and their disposability assessed based on generic waste acceptance criteria.

Additionally, the PREDIS project (Predisposal management of radioactive waste) aimed at identifying, developing and improving innovative technologies in predisposal for low and intermediate level radioactive waste. The used methodology was based a two-step gap analysis to identify the needs and priorities of the stakeholders which led to a Strategic Research Agenda on predisposal activities. The project targeted metallic wastes, liquid and solid organics and concrete waste packages. Its scope covered radiological characterisation techniques (*e.g.*, gamma spectrometry), innovative chemical treatment techniques (such as decontamination silica and alumina gels for metallic surfaces) and innovative conditioning materials (*e.g.*, Magnesium-phosphate cements, alkali activated binders and geopolymers for the conditioning of organics-containing waste streams). The PREDIS project also focused on the demonstration that these innovative new treatment and conditioning techniques and materials are robust and durable and that they will improve the long-term safety of the RWM. The treatment techniques and conditioning materials that have been largely used for the last 3 decades are relatively simple, based on mechanical tools and conventional cementitious materials. However, many of the innovative techniques and materials promoted by the PREDIS project are reaching today a level of technological readiness that would allow them to be used on an industrial scale.

## 5. – Storage

When the radioactive waste has been treated, conditioned in a stable matrix and fully characterised, the conditioned waste package is usually temporarily stored in a suitable facility before its ultimate disposal. The characterisation of the waste form is essential to predict its behaviour during the storage and disposal phases. There is no prescribed time limit to the interim storage phase except for durability of the waste package and the waste form. Therefore, monitoring and inspection of the stored waste packages can quickly become an unavoidable research topic.

The above mentioned PREDIS project includes for instance a work package dedicated to developing monitoring solutions and digital twins for waste packages and interim storage facilities. The aim is to evaluate more efficiently their long-term safety and lifetime performance. These digital tools and non-destructive monitoring techniques can also support the management of the waste packages, in particular for the disposability assessment at the end of the interim storage phase.

## 6. – Disposal

Another project that addressed the monitoring of waste packages is Modern2020. While PREDIS focuses on the interim storage, Modern2020 was dedicated to the monitoring of the waste package during the disposal phase. Its objectives were to develop a methodology for the selection of the monitored parameters, further improve the existing monitoring techniques, develop solutions for the management of the collected data and engage with the relevant stakeholders. The research work was also closely linked to existing geological facilities to ensure that the feasibility of the selected monitoring strategies could be demonstrated. It is noteworthy that the Modern2020 project has started where its predecessor, the Modern project, stopped and its final results have been carried on by its successor, the MODATS work package which was included within the European Joint Programme on Radioactive Waste Management, EURAD [25].

EURAD has started in 2019 with the ambitious objective of bringing together all of the EC projects related to radioactive waste management from its generation to its disposal within one single co-funded research joint programme (with the exception of decommissioning activities that are considered out of the scope of the joint programme). The work achieved by the joint programme has shown high scientific and technical value and addresses a wide variety of topics. EURAD also provides a platform for cooperation at the European level in all aspects of disposal of radioactive waste, benefitting both the more advanced countries as well as the early stage programmes. The joint programme is also an opportunity for researchers from different disciplines to interact and to learn for other areas what is important for the safe disposal of radioactive waste. EURAD will end in 2024 and new Partnership on RWM will carry on and will include all the other research initiatives on the topic, including predisposal operations. Therefore all of the above mentioned projects have closely collaborated with EURAD to guarantee their smooth integration in the upcoming Partnership.

## 7. – Conclusion

In the current socio-political context in Europe, the relative renewal of the nuclear industry raises important challenges to the research community, in particular on the topics of decommissioning and management of the radioactive waste. Established in 1975, the Euratom Research and Training programme aims at supplementing the Member State research programmes and promotes joint coordinated cutting-edge research in support of knowledge creation and preservation.

The Horizon 2020 programme was launched in 2014, ended in 2020 and was followed by the on-going Horizon Europe Programme. Both Euratom programmes have significantly contributed to the R&D and to the innovation in the fields of decommissioning and radioactive waste management. Over the last decades, the EC has funded a number of projects covering the whole radioactive waste management strategy from its generation to its disposal. On the decommissioning topic, the SHARE roadmap on research and innovation for the next 15 years has been published; it lists the needs and priorities identified by the relevant stakeholders and describes how it could be implemented.

Characterising the radioactive waste has been and is still an important topic that needs to be addressed by the research community. Characterisation takes place at every step of the process of managing the radioactive waste and covers radiological properties as well as mechanical, chemical and physical characteristics of the waste. A number of EC projects has included the topic in their research work plan and continue to provide the community with significant scientific and technological achievements.

In the area of processing, treatment and conditioning of the waste, one major project is the PREDIS project. The topic continues to be an area of research opportune to innovation and will be further promoted within the upcoming Partnership on RWM. Additionally, as some Member States move gradually to the management of an increasing inventory of radioactive waste packages and to the definition to their disposal strategy, monitoring of the waste behaviour over time has also grown in importance and priority and has to be addressed by the research community.

Finally, the EURAD programme will reach its end next year and a new Partnership on radioactive waste management should carry on. The new 3-year Work Programme is expected to be published in early March 2023 [26]. All activities related to RWM (with the exception of decommissioning) will be covered by the new Partnership and it should continue to promote cooperation between the different countries and knowledge generation and preservation.

## REFERENCES

[1] *Report from the Commission to the European Parliament, the Council and the European Economic and Social Committee*, Interim evaluation of the Euratom Research and Training Programme 2014-2018, COM/2017/0697 final.

[2] European Commission, *Directorate-General for Research and Innovation*, Euratom research and training programme 2021-2025 (Publications Office) 2021, https://data.europa.eu/doi/10.2777/200656.
[3] The THERAMIN project, http://www.theramin-h2020.eu/.
[4] The PREDIS project, https://cordis.europa.eu/project/id/945098.
[5] The Modern2020 project, https://cordis.europa.eu/project/id/662177.
[6] The DISCO project, https://cordis.europa.eu/project/id/755443.
[7] The CHANCE project, https://cordis.europa.eu/project/id/755371.
[8] The MICADO project, https://www.micado-project.eu/project/.
[9] Overview of sustainable finance, https://finance.ec.europa.eu/sustainable-finance/overview-sustainable-finance_en.
[10] Strategy for financing the transition to a sustainable economy, https://finance.ec.europa.eu/publications/strategy-financing-transition-sustainable-economy_endelegated.
[11] EU taxonomy for sustainable activities, https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en.
[12] Eurostat Electricity and heat statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_and_heat_statistics.
[13] WNA, *Nuclear Power in the World Today*, https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx.
[14] WNA, *Small Nuclear Power Reactors*, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.
[15] Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011L0070.
[16] Energypost.eu, 200-400 Nuclear reactors to be decommissioned by 2040, https://energypost.eu/200-400-nuclear-reactors-to-be-decommissioned-by-2040/#:~:text=At%20least%20200%20reactors%20are,fight%20climate%%5B3%5D.
[17] Euratom Research and Training Programme, https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/euratom-research-and-training-programme_en.
[18] The SHARE project, https://share-h2020.eu/.
[19] The SHARE Roadmap, https://share-h2020.eu/wpcontent/uploads/2022/10/SHARE_D4.2-Roadmap.pdf.
[20] The HARPERS project, https://www.harpers-h2020.eu/.
[21] The CLEANDEM project, https://cleandem.wordpress.com/.
[22] The INNO4GRAPH project, https://www.inno4graph.eu/.
[23] The PLEIADES project, https://pleiades-platform.eu/.
[24] The LD-SAFE project, https://ldsafe.eu/.
[25] The EURAD programme, https://ejp-eurad.eu/.
[26] Funding & tenders portal, https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topicsearch;callCode=null;freeTextSearchKeyword=euratom;matchWholeText=true;typeCodes=1;statusCodes=31094501,31094502,31094503;programmePeriod=null;programCcm2Id=null;programDivisionCode=null;focusAreaCode=null;geographicalZonesCode=null;programmeDivisionProspect=null;startDateLte=null;startDateGte=null;crossCuttingPriorityCode=null;cpvCode=null;performanceOfDelivery=null;sortQuery=sortStatus;orderBy=asc;onlyTenders=false;topicListKey=topicSearchTablePageState.