Forty-five years of joint research programmes on geological disposal of radioactive waste and the pioneering role of the HADES Underground Research Laboratory

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Abstract: Since 1975, the European Commission has supported research in the field of radioactive waste management and geological disposal through the Euratom Research and Training Programme. During the first two community programmes (1975–85), the research activities focused on basic knowledge, feasibility and safety assessments of such geological disposal repositories. It was during this first decade of collaborative research activities that the site characterization, preliminary design studies and the application for authorization to construct the first underground research laboratory, the High Activity Disposal Experimental Site facility, took place.

The underground research laboratory (URL) is an essential tool to develop the knowledge needed for demonstration and safety assessment of the geological repository concept. Belgium has been operating the underground High Activity Disposal Experimental Site (HADES) laboratory on the site of Mol since the early 1980s. More than 30 million euros were allocated to the research activities and the *in-situ* experiments in the Boom clay formation, such as the PRACLAY project (https://cordis.europa.eu/project/id/FI2W0003), leading to breakthrough results and feeding the Belgian R&D programme (e.g. SAFIR-1 and SAFIR-2 reports).

Set up in 1995, the European Underground Research Infrastructure for Disposal of nuclear waste in a Clay Environment (EURIDICE) is an economic partnership between ONDRAF/NIRAS, the Belgian waste management organization (WMO), and the SCK•CEN and manages and operates the HADES facility. HADES played a pioneering role in the demonstration of the feasibility of the geological disposal repository (GDR), paved the way to other URLs in Europe and still contributes today to the science behind the geological disposal of radioactive waste through various EU collaborative research programmes.

The first Euratom Community research and training programme on radioactive waste management started in 1975 and was one of the first joint R&D programmes within the Community. At that time, geological disposal repositories were rather a concept that required fundamental research and development to resolve the technical, financial and socio-political challenges its implementation faced. It was also during these first Community programmes that the idea of URLs emerged as essential facilities to carry out various tests and experiments and to pave the way to actual geological repositories. Forty-five years ago, the Boom clay formation in Belgium was already identified as a suitable location for the construction of the first URL in Europe.

The purpose of this paper was to give a broad overview of the Euratom research programmes on radioactive waste management since 1975, to describe how their structure, budgets and objectives changed over time and to highlight how the URLs and specifically the HADES facility contributed to their achievements.

1975–84: preliminary site investigations and the construction of the first URL in Belgium

The first joint programme on radioactive waste management within the Euratom community was launched in 1975 for a period of 5 years. There was a relative consensus by then that a geological repository would be a suitable definitive disposal solution. In order to reach that objective, substantial efforts in research, development and demonstration were needed for another few decades. The first Community Programme was the premise of the Euratom research and training frameworks that we know today and paved the way for the first URLs.

At that time, the Belgian nuclear research centre, SCK•CEN, was one of the main beneficiaries and

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had a clear research strategy involving the construction of an experimental facility in the Boom clay formation. Under this first programme, the preliminary site investigations led to the geotechnical and hydrogeological characterization of rock samples up to a depth of 580 m including the Boom clay formation and the surrounding sandy formations. These analyses were complemented by the development of a first mathematical heat transfer model in a clay mass and the design and feasibility studies for an underground experimental facility. A draft application for authorization was submitted to the Belgian authorities to build what would be in future known as the HADES Underground Research Laboratory.

Several geological formations were being investigated in Europe and some showed favourable technical characteristics for a geological repository. These formations included salt rocks such as the Asse salt mine, lower Saxony, in Germany, then clay formations such the Boom clay in Mol, in Belgium and to a lesser extent crystalline rocks.

The core samples collected from the Boom clay layer were homogeneous and showed suitable characteristics for the construction of the underground facility, even if the mining capability in clay required further studies. In 1978, the Belgian authorities granted a permit to the SCK•CEN to build an access shaft and an experimental chamber in the Boom clay formation under the SCK•CEN technical site at a depth of 225 m in the mid plane of the 100 m-thick Boom clay formation. Additionally, based on the obtained results from the analyses, the long-term radiological impact of the final disposal of high-level radioactive waste in Mol was evaluated and a safety assessment was carried out in 1979.

However, one issue that the drilling campaigns and the characterization tests faced at that time was the general public perception. These aspects also foreshadowed the potential public debates on the disposal of radioactive waste that we are having today.

The overall budget of the projects from the first programme is estimated to be around 18.4 million European Units of Account (the EUA was the most notably used unit of account in the European Community prior to the euro). As an indication, the financial effort of the Community for the two first programmes is estimated to be around 25% of the total research spending. Today, it represents less than 5%.

In May 1980, the results of the first programme were shared at the first European Community Conference on radioactive waste management and disposal, which was held in Luxembourg. All of the results of the research performed during this first phase can be found in the proceedings of the conference published in the EUR report series EUR 6871.

The second research programme was a continuation and a confirmation of the priorities of the first programme. These included two main topics: (1) the treatment and the conditioning of radioactive wastes; and (2) the storage and the disposal of the radioactive wastes. Additional complementary topics were also covered by the programme, such as the waste management strategy and quality criteria for the conditioned radioactive waste.

Regarding the research activities, the work that was launched under the first programme was pursued in the second programme. Extensive geological data were collected on the identified rock formations, the interactions between host rock candidates and radioactive wastes were further studied, and the radionuclides' release from the wastes to the repository barriers and eventually to the biosphere were evaluated. Additionally, the feasibility and the design assessments of such geological disposal facilities were refined and safety models were developed to describe and assess the radiological impacts.

The Community support under the two first programmes helped achieve the objectives. Among these projects was the construction of the HADES URL in Mol, in Belgium. The HADES facility was the first of its kind worldwide to be built in a poorly indurated argillaceous formation. In 1983–84, the first gallery was excavated at a depth of 225 m and was 26 m long and 3.5 m in diameter. The clay was first frozen to harden it and the gallery was then manually excavated. In 1984, the creep rate of the gallery was found to be relatively low. An experimental shaft and a second gallery were then excavated without pre-freezing the clay. At that time, the HADES facility helped confirm the feasibility of construction of such geological disposal facilities.

Under the second research programme, significant progress was achieved in the study of the long-term behaviour of radioactive waste in the conditions of the geological disposal. Two major Community projects were also launched at that time and contributed to the safety analyses: the PAGIS project (Performance Assessment of Geological Isolation Systems; https://cordis.europa.eu/project/id/FI1W0001; European Commission *et al*. 1996) on the geological prospections and the hydrogeological studies and the MIRAGE project (Migration of Radionuclides in the Geosphere; https://cordis.europa.eu/project/id/FI2W0128) related to the modelling of radionuclide transport and the collection of the data to describe the physical and chemical processes.

The second 5 year research programme was also marked by the establishment of the first international co-operation agreements with the AECL (Canada), the US Department of Energy and NAGRA (Switzerland). Multilateral collaborations with the NEA/Organisation for Economic Co-operation and Development (OECD) and the International Atomic Energy Agency (IAEA) took place and resulted in the state-of-the-art report on geological disposal of radioactive waste prepared with the NEA in 1983.

Additionally, these international collaborations also studied the possible waste management strategies. In particular, a relative consensus on the 'polluter pays' principle was established and the possibility of disposing of the radioactive waste originating from a third country was ruled out.

Regarding the budget of the programme, it reached overall around 49 million units of accounts of which 25 were spent on the geological disposal activities. About 30–40% of the total cost was covered by the Community funds. Similarly to the first programme, the results were presented in Luxembourg in 1985 during the conference on radioactive waste management and disposal and the proceedings were made available in the report series EUR 10163 (Simon 1996).

1985–94: a decade of *in-situ* experiments in the URL and safety assessments for the future GDR

After the second programme, the R&D community on radioactive waste management agreed on the need for *in-situ* research facilities. The third research programme was then defined in a similar way to the second programme, with a Part A dedicated to the waste management, and a Part B specifically for the construction and/or operation of underground facilities.

The third programme (1985–89) was also marked by open collaborative activities within the Community. An extension was excavated in the HADES Belgian URL with the support of the French WMO ANDRA, which used a specific construction technique (sliding ribs). The collaborative PAGIS project that started under the second programme went on until 1989. Its conclusions were complemented by the PACOMA project (Performance Assessment of Medium Level and Alpha Contaminated Waste; https://cordis.europa.eu/project/id/FI1W0045) and were used for two reference safety assessment studies on generic geological systems related to the three main host rock formations considered in Europe (namely salt, clay and granite host rock formations). In particular, ONDRAF/NIRAS produced the SAFIR I report (Safety Assessment and Feasibility Interim Report) using the results from the PAGIS project. Specific research projects were also launched for the German Asse site and further investigations were carried out in France for a future URL.

The overall budget of the third programme significantly increased in comparison with the second programme and was of 84.5 million units of account, with around 50% covered by the Community contribution. The conference on radioactive waste management and disposal took place in Luxembourg in 1990 and the proceedings were published under the report series EUR 13389.

The fourth programme (1990–94) had similar structure and objectives to the third programme with a Part A related to R&D studies in waste management (e.g. waste characterization, treatment and conditioning, monitoring of packages) and a Part B focusing on the construction and operation of underground facilities open to community joint activities (also known as URLs). In addition to the three identified sites (the Boom clay formation in Mol in Belgium, the Asse salt mine in Germany and the clay formation in France), a new project was launched to identify a suitable site in the UK.

The main projects performed under the fourth programme aimed at improving the understanding of the thermo hydro mechanical and chemical processes in the identified host rock formations in the conditions of geological disposal of the radioactive waste. In particular, it was at that time in 1990 that the PRACLAY project (https://cordis.europa.eu/project/id/FI2W0003) was launched in order to demonstrate the feasibility of the Belgian underground disposal facility concept and its soundness. A disposal dummy gallery was for instance excavated, the heat emitted by high-level waste was simulated by a heating system and the thermo hydro mechanical (THM) behaviour of the surrounding clay and the dummy engineered barrier system (EBS) were monitored over 1 year. Additionally the CERBERUS (Control Experiment with Radiation of the Belgian Repository for Underground Storage; https://cordis.europa.eu/project/id/FI4W950008) project investigated the near-field effects of a Cogema high-level waste canister. These major *in-situ* experiments were also complemented by a number of numerical tools such as DOSEGEO, SOURCE and TEMPRES. Among other major projects were the CACTUS project to study near-field THM couplings in the Boom clay under thermal loading, the BACCHUS project (https://cordis.europa.eu/project/id/603445) to test backfilling materials and the ARCHIMEDE project (https://cordis.europa.eu/project/id/FI2W0117) to investigate the hydro-chemical interactions between the water and the host rock.

Two major safety assessment studies were also launched under the fourth programme and included the SCK•CEN. The first one is the PACOMA that followed the PAGIS project. Its main objective was to evaluate the radiological impact of the geological disposal of spent fuel in the Boom clay. The second is the EVEREST project (https://cordis.europa.eu/project/id/FI2W0017), which aimed at assessing the sensitivity of the radiological impact of the geological disposal of radioactive waste to the different elements in the performance assessment. All three main formations were considered in the project, clay, granite and salt. The project provided a list of the most influential elements for each site

and several recommendations for future research programmes.

Overall, the third and fourth programmes established the essential role of the URLs in evaluating the feasibility and the safety of the future geological disposal repositories. These two programmes were also marked by the first extensive *in-situ* experiments that fed the preliminary safety assessment exercises in the different involved countries.

The total budget for the fourth programme was of 71.2 million units and the Community contribution ranged generally between 30 and 50% of the total costs. Finally, the fourth edition of the European Community Conference on Management and disposal of radioactive waste took place in 1996 in Luxembourg and the contributions were published in the EUR 17543 report (European Commision *et al.* 1997).

1994–2002: from fundamental research activities to objective-oriented joint research projects supporting the national programmes

The Euratom FP4 and FP5 programmes which respectively took place in 1994–98 and 1998–2002 were in fact the fifth and sixth Community programmes. At that time, the programmes started including cross-cutting topics and promoted multidisciplinary synergies. The role of the Joint Research Center of the European Commission grew as well. In addition to the direct actions implemented by the JRC, the indirect actions implemented by the beneficiaries and partially funded by the EC in FP4 covered five research areas and not only radioactive waste management as in the previous programmes:

(A) Exploring innovative approaches (7 million ECU);
(B) Reactor safety (48 million ECU);
(C) Radioactive waste management and disposal and decommissioning (37.8 million ECU);
(D) Radiological impact on man and the environment (50 million ECU).

The FP4 also included one specific research area related to the Chernobyl accident and its consequences:

(E) Mastering events of the past (related to the Chernobyl accident) (12 million ECU).

The Area C dedicated to the management of radioactive waste focused on the testing and demonstration of disposal concepts, the backfilling and sealing of repositories, the long-term behaviour of the SSC (structures, systems and components) and in particular the characterization of groundwater flow and radionuclide transport. Similarly to the two previous programmes, two sub-areas were respectively dedicated to the URLs and to phenomenological research.

In FP5, four research areas were covered:

(A) Operational safety of existing installations (27 million ECU);
(B) Safety of the fuel cycle (37 million ECU);
(C) Safety and efficiency of future systems (6 million ECU);
(D) Radiation protection (6 million ECU).

Research activities related to radioactive waste management and disposal were all included in Area B and were mostly the continuation of the work that started under FP4. The focus of FP4 and FP5 was more inclusive of all research activities in the nuclear field. Still, major achievements were realized by the radioactive waste management research community and in particular, in the HADES URL. The focus of the research activities was on the THM behaviour of the disposal system in representative conditions and on the release and migration of the radionuclides. At that time, several projects were also addressing specific engineering issues for the construction and the exploitation of GDRs. The following projects are illustrations of the work accomplished in FP4 and FP5:

(1) The RESEAL project (https://cordis.europa.eu/project/id/FI4W960025) was launched in 1996 aimed at the testing and the demonstration of the backfilling and the sealing of a 1.4 m-diameter shaft in the HADES facility. The effectiveness of the sealing, in particular to gas, water and radionuclide transport, was characterized. The obtained results were also used to validate the developed numerical transport models. A second project, RESEAL-II (https://cordis.europa.eu/project/id/FIKW-CT-2000-00010), started in 2000 under FP5 and investigated the water, gas and radionuclide migration through the seal of a low-permeability bentonite and the excavation damaged zone (EDZ). Similarly to RESEAL-I, hydro-mechanical models were used for validation purposes.
(2) The CLIPEX project (https://cordis.europa.eu/project/id/FI4W960028) started in 1997 and elaborated an instrumentation programme for the extension of the Belgian URL. Its main objective was to assess the performances of mechanized excavation techniques in limiting the EDZ. The instrumentation included essentially the total stress distribution, the pore water pressure and the deformation measurements around the connecting gallery and in the section to be excavated.
(3) The CORALUS project started under FP4 and addressed the corrosion of alpha active Cogema glasses to be used for the vitirification

of high-level waste when submitted to radiation and heat. A second project, CORALUS-2 (https://cordis.europa.eu/project/id/FIKW-CT-2000-00011), was launched in 2000 under FP5 to investigate the reliability of the predicted performances of the glass in realistic conditions. The glass dissolution and the radionuclide release and migration were measured and the *in-situ* results were compared with the laboratory experiments.

(4) The SELFRAC project (https://cordis.europa.eu/project/id/FIKW-CT-2001-00182) started in 2001 under FP5 and studied the self-healing properties and the EDZ characteristics in clayey host rocks. The project was co-ordinated by ESV EURIDICE GIE, which was established in 2000. In particular, the *in-situ* test 3 and the *in-situ* test 4 were performed in the HADES facility of Mol in Belgium. The first followed up the hydro-mechanical properties within the EDZ that was formed around the gallery after the excavation for a period of 3 years. Fracturation was caused by stress redistribution and could be limited if the excavation and lining techniques were adapted and improved. The fractures were not interconnected. However, the hydraulic conductivity was higher owing to the lower effective stress in the EDZ. The *in-situ* test 4 focused on the self-healing properties. A borehole was drilled, monitoring equipment was installed, creep and other properties of the EDZ were followed up and finally the transmissivity along the borehole was evaluated via hydro testing. Additionally, a fractured clay core was tested and it was demonstrated that fractures seal and seismic parameters recover within several weeks or months.

(5) The past performance assessment exercises identified the radionuclide migration properties as critical safety parameters. The TRANCOM project (TRANCOM-II; https://cordis.europa.eu/project/id/FIKW-CT-2000-00008) was then launched in 2000 and investigated the transport properties of several radionuclides (U, Pu, Se and Am) in Boom clay reducing conditions. In particular, the role of organic matter and the impact of the formation of complexes on the radionuclide release were studied.

In addition to these research projects, two performance assessment exercises started in 2000: SPIN (testing of safety and performance indicators; https://cordis.europa.eu/project/id/FIKW-CT-2000-00081) and BENIPA (bentonite barriers in integrated performance assessment; https://cordis.europa.eu/project/id/FIKW-CT-2000-00015). The radiological impact was evaluated and the values were below the regulatory thresholds and the natural radioactivity baseline, regardless of the considered scenario. More specifically, the results of the performance assessment and research projects were used to complement the Belgian safety assessment and the SAFIR II report was published in 2001.

The total budgets for the FP4 and FP5 programmes were respectively of 33.5 and 32 million ECU. The results were presented during the first editions of the EURADWASTE conference held in 1999 (European Commission *et al.* 2000) and 2004 (European Commission, Directorate-General for Research and Innovation and Davies 2004) in Luxembourg.

2002–13: launch of the ERA, creation of the IGD-TP and integration of the research activities in the Community towards the harmonization of the R&D policies

In 2000, the European Research Area (ERA) was launched with the ambitious objective of creating a single borderless market for research, innovation and technology across the EU. It brought the different countries together by harmonizing their R&D policies and aligning their national programmes.

The FP6 and FP7 Euratom research and training programmes aimed at contributing to the ERA in the field of nuclear energy by improving integration and coordination of nuclear research in Europe. In the early 2000s and after more than 25 years of Community research programmes, there was no official schedule for the exploitation of a Geological Disposal Repository in any of the Member States yet. To this end, FP6 and FP7 were largely oriented towards the integration of waste management organizations and the remaining aspects for the implementation of the geological disposal. A small proportion of the research activities was also dedicated to partitioning and transmutation and the actinide recycling.

More specifically, regarding the management of radioactive waste, the main objective of the FP6 (2002–06) programme was to determine practical ways to reduce radioactivity, contain and safely store radioactive waste. Part of the programme was also dedicated to research in radiation protection to resolve uncertainties and set standards for the wider safe use of radioactive materials.

When it comes to URLs, the programme focused on integrating the research groups and topics and on promoting interactions, networking and co-ordination. The main objectives of the funded research projects were to contribute to a broadly agreed approach to waste management and disposal, and to explore the technical and economic potential of concepts able to make better use of fissile material and generate less waste. The following are some examples of

EC projects related to radioactive waste management that were launched under FP6:

(1) ESRED (https://cordis.europa.eu/project/id/508851) started in 2004, promoted co-operation between the waste management organizations and aimed at further demonstration of the geological disposal feasibility. In particular, the project focused on the buffer design and its construction, the waste canister transfer and emplacement in disposal cells, heavy load emplacement in disposal drifts and the temporary sealing of cells and excavated galleries. The project provided an opportunity for the WMO to collaborate on developing shared solutions and best practices related to geological repositories. In particular, ONDRAF/NIRAS and EURIDICE collaborated on the construction of mock-ups for a backfilling process with grout or a granular material.

(2) FUNMIG (https://cordis.europa.eu/project/id/516514) took over where TRANCOM ended and improved the fundamental understanding of transport and retention properties of radionuclides in the geosphere. The three types of host rocks (salt, clay and granite) were covered and the obtained results fed in the Performance Assessment exercises.

(3) NF-PRO (https://cordis.europa.eu/project/id/2389) was one of the ambitious recent projects led by the SCK•CEN, which aimed at the development of a numerical model that takes into account the phenomenology of the processes at play in the near-field of deep geological repository. The project addresses the different involved systems and components of the near field, first the dissolution of the waste form and the release of the radionuclides, second the chemical processes occurring in the EBS, then THM evolution of the EBS and finally the properties and the evolution of the EDZ. More specifically, the effect of oxidation on Boom clay was studied in the HADES facility. A borehole was drilled using nitrogen and *in-situ* pore water samples were collected and characterized.

(4) The PAMINA project (https://cordis.europa.eu/project/id/36404) focused on safety and performance assessments and aimed at improving and harmonizing methodologies and tools used for different geological disposal concepts and environments. It provided a sound scientific basis and a generic methodology for the safety assessment of a deep geological repository.

Finally, CARD (https://cordis.europa.eu/project/id/36496) was an important initiative that started in 2006 to evaluate the feasibility of a technology platform bringing together the radioactive waste management organizations and other key stakeholders. The project aimed at establishing a framework for co-operation and networking between the WMO who are in charge of the implementation of the disposal facilities. The platform took shape under FP7 in 2009, through support to the secretariat SECIDGD (https://cordis.europa.eu/project/id/249396) and SECIGD2 (https://cordis.europa.eu/project/id/323260), and is today known as the IGDTP Platform (Implementing Geological Disposal Technology Platform; https://igdtp.eu/).

The main challenge for radioactive waste management under FP7 was the actual realization of a deep geological disposal of high-activity radioactive waste and spent fuel. Although some Member States had relatively mature geological disposal programmes and were closer to implementation and realization, some generic issues remained unsolved, such as for example the mechanisms of the gas transport through the engineered barrier system and the host rock over time. The projects and indirect actions under FP7 focused on these issues and included demonstration of technologies to strengthen the safety cases for geological disposal repositories. One of the main objectives was to establish a common European view and one of the main achievements has been the creation of the IGD-TP. The communication between the European Commission and the implementers improved significantly and these key players started getting more involved in the Euratom research programmes. The projects were thus more focused on specific needs, closer to the implementation, less research-oriented and sometimes of interest for only a limited number of participants.

(1) The FORGE project (https://cordis.europa.eu/project/id/230357) started in 2009 and was one of the first that addressed the issue of gas transport throughout the multiple barrier system of a geological disposal repository. It promoted collaboration between the different European stakeholders. A series of laboratory and field-scale experiments, including the development of new modelling tools and methodologies, were carried out in the HADES URL. The Heater Test reproduced in a conservative way the most penalizing conditions in the Boom clay that could occur in a real repository. The Seal Test aimed at evaluating the feasibility of hydraulically cutting off the EDZ of the disposal galleries with a horizontal drift seal. In addition, the Gas Tests were used to evaluate how the seal and its surroundings behave during a gas pressure increase.

(2) MODERN (https://cordis.europa.eu/project/id/232598) was also launched in 2009 and aimed at providing a framework for the development and the implementation of monitoring

techniques for the different phases of the radioactive waste disposal process. The project promoted networking and engagement of the different involved stakeholders and addressed the different specificities of the existing geological disposal concepts. Several monitoring sensor devices were tested in the HADES URL.

(3) PEBS (https://cordis.europa.eu/project/id/249681) started in 2010 and was related to the long-term safety performance of the EBS and in particular of bentonite materials. The project focused on the THM and chemical processes and their coupling within the multibarrier disposal system. The work plan involved extrapolating experimental data into a long-term model and included developing a procedure to validate the modelling of THM and chemical processes. Additionally, the project helped identify the remaining uncertainties related to long-term performance assessment and improved the overall safety of radioactive waste repositories.

(4) In 2011, the LUCOEX (https://cordis.europa.eu/project/id/269905) was launched by a consortium including WMOs that had been involved in experiments in URLs to understand and compare the main parameters for the implementation and the long-term safety of the geological disposal concepts. The project aimed at testing and improving the methods, equipment, technologies, processes and operability related to the different phases of a repository system from construction to closure.

Harmonization of research activities and alignment of national programmes were also further encouraged with the adoption of the Waste Directive in July 2011 (Council Directive 2011/70/EURATOM). It established a Community framework for the responsible and safe management of spent fuel and radioactive waste. In particular, the storage of radioactive waste, including long-term storage, can only be an interim solution and cannot be an alternative to disposal. The Member States are thus obliged to define and implement national programmes for the management of spent fuel and radioactive waste from generation to disposal, including a national research programme to support the implementation. They also have to carry out international peer reviews of their national framework and to report to the European Commission on their national programme at least every 10 years. To this end, collaborative research programmes play an essential role in the implementation of the Directive and the underground research facilities provide the means to address the remaining challenges facing the implementation of GDR.

The EC funding for the FP6 and FP7 programmes was respectively 47.1 and 64.6 million euros. The results were presented during the EURADWASTE '04 (European Commission, Directorate-General for Research and Innovation, and Davies 2004) and EURADWASTE '08 (European Commission, Directorate-General for Research and Innovation, and Davies 2009) conferences in 2004 and 2008 in Luxembourg. In 2013, the EURADWASTE '13 conference took place in Vilnius in Lithuania under the auspices of the Lithuanian Presidency of the EU (European Commission, Directorate-General for Research and Innovation 2015).

2014–20: establishment of the first European Joint Programme on Radioactive Waste Management

In the early 2010s, important steps towards the implementation of high-level waste disposal were reached. The first two licence applications for a deep geological disposal facility were submitted in Sweden in 2011 and in Finland in 2012. Knowledge for the safety case in these two countries was sufficiently mature to go to the next step towards the implementation and the exploitation of an underground disposal facility. However, these two cases highlighted important challenges that the Community faces. First, each underground repository has its own geological and technological specificities and socio-political contexts. Second, there were important differences in the readiness and the maturity of the national programmes from one Member State to another.

These challenges were taken into consideration in the Euratom research and training programme that followed as part of the Horizon 2020 framework. The total budget related to radioactive waste management and decommissioning was of 99.5 million euros. Four different areas were covered. The first area is the geological disposal of radioactive waste (56.59 million euros) which included SITEX-II (https://cordis.europa.eu/project/id/662152) and JOPRAD (https://cordis.europa.eu/project/id/653951), both aiming at establishing a European framework for further collaboration and integration of the R&D efforts related to geological disposal, in addition to other technical and scientific projects such as CEBAMA (https://cordis.europa.eu/project/id/662147), Modern2020 (https://cordis.europa.eu/project/id/662177), MIND (https://cordis.europa.eu/project/id/661880), BEACON (https://cordis.europa.eu/project/id/745942 and DISCO (https://cordis.europa.eu/project/id/755443).

While countries with mature programmes such as Finland, Sweden and France were planning to launch the operational phase of their respective repositories in the next decade, other Member States were in the early stages of establishing their radioactive waste management strategy and they would have to go

through similar research steps to the front-runners. In order to encourage interactions between the Member States, the Euratom H2020 programme played an important role in strengthening the co-operation between the Member States and establishing a network and shared technological platforms. Following the example of the IGD-TP, the two SITEX projects (the first one started in 2011 and the second one in 2014) led to the creation of the Sustainable network for Independent Technical Expertise on radioactive waste management (SITEX Network; https://www.sitex.network/), gathering representatives from the technical safety organizations (TSOs) into one single association. This network aims at supporting networking and research activities of the TSOs, which are in charge of reviewing the safety cases.

Another important achievement towards more integration of the research national programmes that was accomplished under the Horizon 2020 programme was the JOPRAD project (https://cordis.europa.eu/project/id/653951). It was launched in 2015 for 3 years and had the objective of preparing the first Joint European Programme on radioactive waste management via the use of a new contractual instrument: the Joint Programme co-fund. The project involved three colleges consisting of the three R&D communities: the waste management organizations (IGD-TP), the technical safety organizations (SITEX Network) and the research entities (REs). A common vision was established and a strategic research agenda was elaborated for a joint research programme based on the R&D needs and gaps. Eventually, the first European Joint Programme (EURAD, https://www.ejp-eurad.eu/) took shape and was launched mid-2019 for 5 years, including the main stakeholders in research on radiactive waste disposal (WMOs, TSOs and REs) while ensuring their independence.

The other five projects addressed specific technical and engineering issues related to geological disposal. The CEBAMA project started in 2015 and focused on the study of the long-term behaviour of cement-based materials in the context of a geological repository. More than 10 year-old concrete core samples, which were in contact with the Boom clay, were taken from the HADES URL to study their properties, and in particular, the characteristics of the concrete/clay interface. The BEACON project followed in 2017 and investigated the properties of bentonite and its mechanical behaviour over time in representative conditions of a geological repository. MODERN2020 took over where the 2009 MODERN project ended and further investigated the monitoring strategy of the geological repositories. Finally, the MIND and DISCO projects addressed respectively the issues related to microbiological processes in the geological repository and the spent fuel characterization and dissolution over time.

The second area of research covered by H2020 Euratom radioactive waste management programme was related to the predisposal activities and had a total budget of 21.88 million euros. In 2017, the CHANCE project (https://cordis.europa.eu/project/id/755371) was solely about the characterization of conditioned waste while the THERAMIN project (https://cordis.europa.eu/project/id/755480) focused on the thermal treatment techniques, their advantages and drawbacks and the existing facilities in Europe for the minimization, stabilization or immobilization of radioactive waste families. Finally, in 2020, the PREDIS project (https://cordis.europa.eu/project/id/945098) was launched as the sister project of the EURAD programme to investigate the R&D needs and gaps related to predisposal management of radioactive waste.

The third area of research was on the dismantling and decommissioning (D&D) of nuclear installations and had a budget of 21.03 million euros. Among the D&D projects, the Coordination and Support Action SHARE project (https://cordis.europa.eu/project/id/847626) was funded and started in 2019 with the aim of establishing a strategic research agenda and a roadmap for the D&D activities. Finally, the fourth area of research was dedicated to horizontal activities, social sciences, education and training and had a budget of 10.66 million euros. Selecting a location and site for a disposal repository or for an underground research laboratory is a challenging task when it comes to public acceptance and political decision-making. The domain of social sciences and humanities was already included in the Euratom programme since 2000 and various projects were supported to investigate the communication strategy, the stakeholders' engagement, governance aspects and public involvement (e.g. RISCOM-II (https://cordis.europa.eu/project/id/FIKW-CT-2000-00045), TRUSTNET 2 (https://cordis.europa.eu/project/id/FIKR-CT-2000-20070), OBRA (https://cordis.europa.eu/project/id/36473), ARGONA (https://cordis.europa.eu/project/id/36413), IPPA (https://cordis.europa.eu/project/id/269849) and InSOTEC (https://cordis.europa.eu/project/id/269906)). These projects produced guidelines and general recommendations on how to manage communication and the engagement of stakeholders, including representatives from civil society.

Euratom research and training projects, education, training, training schemes, mobility, infrastructures, technology platforms and international co-operation are being capitalized

As illustrated here above, with the implementation of HADES URL in Mol, in Belgium, and other URLs in

Europe, the European Atomic Energy Community (Euratom) Research and Training framework programmes are benefitting from a consistent success in pursuing excellence in research and facilitating Pan European collaborative efforts – together with EU Member States – across a broad range of nuclear science and technologies, nuclear fission and radiation protection. Euratom R&D programmes also contribute to fulfilling the key objectives of maintaining high levels of nuclear knowledge and competence and building a more dynamic and competitive European industry. It is promoting EU added value through Pan-European mobility of researchers implemented by co-financing transnational access to unique research infrastructures and joint research activities through Research and Innovation and Coordination and Support Actions' funding schemes. Establishment by the research community of European technology platforms, e.g. IGDTP, SNETP (https://snetp.eu/) and MELODI (https://melodi-online.eu/), is being capitalized. Mapping of research infrastructures and education and training (E&T) capabilities is allowing a closer co-operation within the European Union and beyond, benefiting from multilateral international agreements and from closer co-operation between Euratom, OECD/NEA, IAEA and international fora. 'Euratom success stories' in facilitating Pan-European E&T collaborative efforts through Research and Training framework programmes show the benefits of research efforts in key fields, of building an effective 'critical mass' and implementing European MSc curricula, of promoting the creation of 'Centres of Excellence' with an increased support for 'Open access to key research infrastructures', exploitation of research results, management of knowledge, dissemination and sharing of learning outcomes (Fig. 1).

Dedicated Euratom Fission Training Scheme co-ordination actions aimed at structuring higher university education Master of Science training and career development benefitting from a European Credit Transfer and Accumulation System initiated by the Bologna Process in 1999 for higher academic education. The European Credit System for Vocational Education and Training launched in Copenhagen in 2002 is also promoted today for lifelong learning in the field of nuclear and successfully tested across a wide range of industrial sectors. It is further promoting transparency, mutual trust, continuous professional development based on a modular course approach and recognition of learning outcomes that refer not only to knowledge but also to management of skills and competences.

Through H2020 (2014–20), within Euratom Fission Research and Training programmes, an estimated workforce of around 8000 persons was involved, estimated at 200 scientific managers (2%), 5000 experienced researchers (63%), 500 researchers recruited (6%), 800 PhDs partially or full time in a project (10%) and 1500 others (engineers, technicians, administrative support) (19%). The type of organizations participating in Euratom Fission projects within H2020 are similar to those in FP7: research organizations, 40%; private entities, 24%; higher or secondary education establishments, 30%; public (excluding research organizations and higher or secondary education establishments), 3%; and other, 3%.

All of the above illustrates the positive and high impact achieved between Member States' institutes, research centres, academia, industry and Euratom by

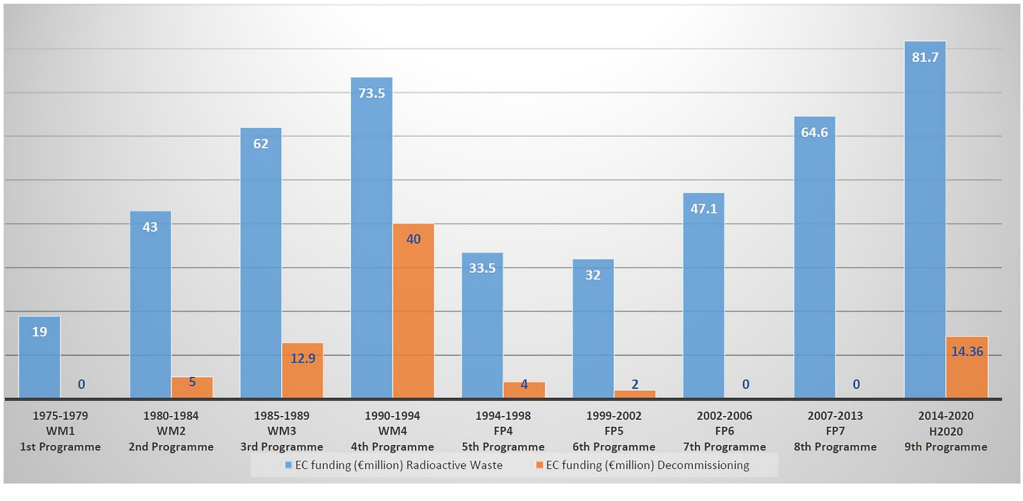

Fig. 1. Budgets allocated for radioactive waste management and decommissioning over the past nine Euratom Framework Programmes.

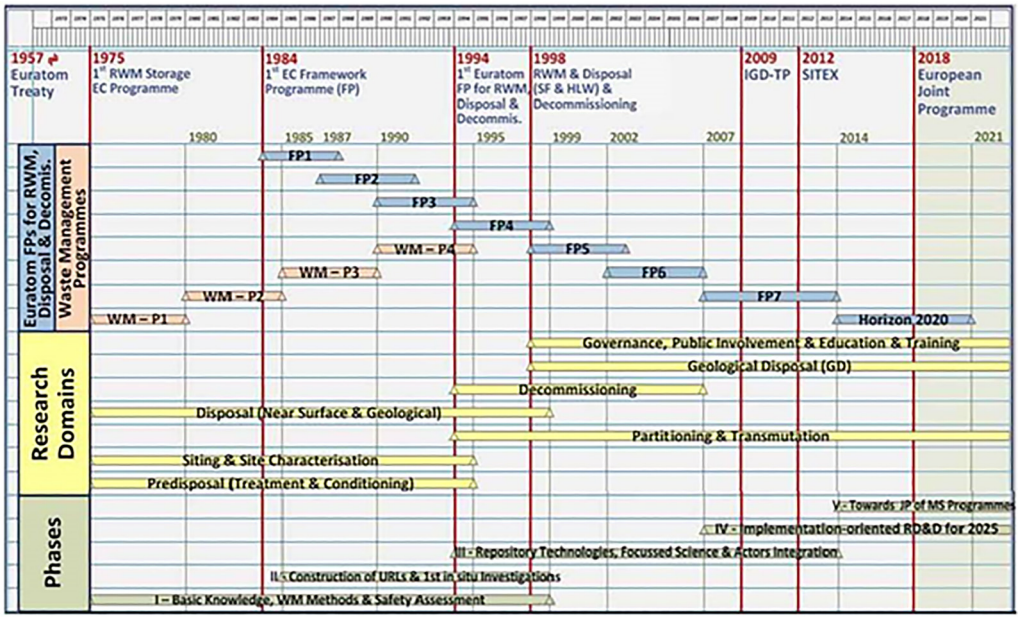

Fig. 2. Evolution of the Research and Training Euratom programmes of the European Commission in the radioactive waste management domain over the past.

closely collaborating at European level towards common broad scientific and technological research challenges and opportunities, innovation, development and demonstration goals (as further illustrated within the latest JRC's Taxonomy report (European Commission *et al.* 2021)):

- Research activities improve the performance of European research, in particular through the networking and co-ordinated implementation of national programmes; networking centres and areas of excellence in the public (in particular university) and private sectors in the Member States; carrying out large-scale targeted research projects, particularly in the field of industrial research.
- Research and innovation, start-ups and small and medium-sized enterprises (SMEs) strengthen technological innovation capacities in the EU, in particular by supporting research for and in SMEs, dissemination, transfer and take-up of knowledge and technologies, exploitation of research results and the setting-up of technology businesses
- Research infrastructures strengthen the European research infrastructure by implementing a European policy in this area, taking into account questions concerning access, operation and construction, and also covering the question of large-capacity networks for research.
- Human resources support the development of a knowledge-based economy, strengthening Europe's human resources in science, technology and innovation, in particular by increasing transfrontier mobility, developing European careers, increasing the participation of women in research and making the scientific professions more attractive to young people and Europe more attractive to researchers from third countries.
- Science, society and citizens establish on a European scale a new contract between science and society, as well as the social and ethical consequences of scientific and technological progress.
- All require international co-operation and open sharing of data and information. While individual experts are often responsible for communicating key scientific results and providing science advice, they must be guided by clear common principles and supported by scientific institutions, international organizations, European Technology platforms, Fora and networks across the globe, e.g. among others EU/Euratom, OECD/NEA and the IAEA.

Conclusions

Over more than 45 years of joint research efforts and nine successive R&T programmes, the Euratom Community covered all of the R&D phases required for the management of radioactive waste: decommissioning, pre-disposal operations, fuel cycle, policy and waste management strategy, public perception

and acceptance and, finally, the disposal phase. The concept of geological repositories went a long way from a plausible disposal solution to its actual construction and authorization by the regulatory bodies. Over these four last decades, URLs have played an essential role in the realization of the first deep geological repositories (Fig. 2).

In particular, the site for the first URL, which would later be known as the present HADES facility, was identified in the Boom clay formation in Belgium under the first Community research programme in 1975. During the first two research programmes (1975–84), the research effort focused on the siting, the feasibility study and the construction of such an underground laboratory. Already early at that time, the first safety performance assessments and radionuclide migration studies were carried out. The HADES facility had a pioneering role not only in implementing the initial phases for a geological repository (e.g. siting, safety assessment studies) but also in the first research studies related to radionuclide migration and chemical and hydric processes in representative conditions.

The following decade of research programmes (1985–94) saw the emergence of other host rock formations for URLs and geological repositories in Germany, the UK and France. The research programmes related to radiaoctive waste management greatly promoted collaborations within the Euratom Community and with other international partners. The HADES facility further implemented research studies related to the THM and chemical processes in the representative conditions of the Boom clay and a number of comparative studies were launched to better assess the safety of such facilities.

The research projects under FP4 and FP5 (1994–2002) investigated specific technological and engineering issues related to the excavation and the construction of geological disposal facilities. To this end, the URL gave the Community the opportunity to carry out various *in-situ* tests and experiments. The projects were also more objective-oriented and pursued the previous studies on the chemical processes in the different host rocks and the release of the radionuclides to the biosphere. More specifically, the first studies on the characteristics of the EDZ and the self-healing properties of the Boom clay were launched. Additionally, the results of the programmes were used for complement the Belgian safety assessment published in the SAFIR-II report.

The FP6 and FP7 programmes (2002–13) focused on further integration of the Community research efforts. The programmes were more inclusive of the national waste management organizations. One important achievement at that time was the creation of the IGD-TP in 2009, which helped promoting the co-operation between WMOs and the harmonization of best practices and guidelines between Member States. These aspects were further strengthened by the EC Waste Directive in 2011. It was also at that time, in 2011 and 2012, that the first two licence applications for a geological repository were submitted in Finland and in Sweden. The URLs and in particular the HADES facility continued their work in refining the safety assessment studies and optimizing the geological disposal concepts for its future construction. Finally, the first edition of the EURADWASTE conference was successfully organized at the end of the FP6 programme in Luxembourg to present the results of the Euratom projects.

In 2014, the Horizon 2020 Euratom Research and Training programme was launched for 5 years with a 2 year extension. The scope of the radioactive waste management programme included four main areas: decommissioning, predisposal activities, disposal, and social sciences and humanities. The programme pursued its efforts in promoting integration, co-operation between the Member States and the engagement of the stakeholders. The SITEX Network was established in 2018 for the TSO similarly to the IGD-TP for the WMO and the first European Joint Programme on Radioactive Waste Management, EURAD, was launched in 2019. More importantly, the H2020 programme aimed at establishing a knowledge management strategy to ensure that knowledge, best practices, expertise and competences are maintained for future generations, and shared between countries at an advanced stage of the implementation of their RWM strategy and early-stage Member States.

Through the many collaborations and involvements of the SCK•CEN, ONDRAF/NIRAS and EURIDICE in the Euratom research programmes, the HADES URL continues today to contribute to the science behind the geological disposal of radioactive waste. It is in this context that the 9th Euratom Horizon Europe framework programme started in 2021. It will have the important challenge of defining and launching the second European Joint Programme, EURAD-2, to pursue the efforts of the last four decades of joint research by the Euratom Community. Finally, the 10th edition of the Euratom research and training conferences on fission safety of reactor systems (FISA 2022) and radioactive waste management (EURADWASTE '22) supported by the European Commission together with the Commissariat à l'Energie Atomique et aux Energies Alternatives, under the auspices of the French Presidency of the Council of the EU, took place on 30 May to 3 June 2022 in Lyon, France. FISA 2022 technical sessions covered progress of the research carried out through 60 projects and included the topic of decommissioning of nuclear facilities (European Commission, Directorate-General for Research and Innovation 2022*a*). EURADWASTE'22 aimed at taking stock of what kind of research the Commission had funded during Horizon 2020 and open-up

exchange and discussions on future collaborative research of EU added-value. The proceedings include written contributions from invited presentations and posters, session summaries and panel reports (European Commission, Directorate-General for Research and Innovation 2022*b*).

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