Deliverable 9.12: A review of past and present studies and plans for developing shared solutions for radioactive waste management in Europe

Work Package 9 (ROUTES)

Task 6 (Sub-task 6.1)

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Executive Summary

The objective of this report is to summarise studies and plans for developing shared solutions and technologies for radioactive waste management in Europe. The report concentrates on European solutions, but other shared solutions are also identified (e.g., in IAEA studies) where relevant. The materials that were reviewed for this report were questionnaire answers for ROUTES (IRSN, 2020 a), ROUTES workshop (WS) exercise results (See Appendix A) and discussions, reviews of the newest (2000 onward) EC projects (including SAPIERR, SAPIERR II, CHANCE, THERAMIN), IAEA studies on the topic and national programmes that refer to shared solutions (if they were available in English).

This deliverable summarises the knowledge and approaches regarding the sharing of technology and facilities between countries in different steps of the waste lifecycle. Based on the materials found, geological disposal has been the most investigated step, but shared research and development work and the use of technologies and facilities for characterisation, treatment, storage and disposal have also been explored.

Some collaboration examples from the wider nuclear field that are applicable to waste management purposes are also used.

One of the topics discussed during ROUTES' 1st workshop in Athens was the classification of the solution types that could be called 'shared' solutions. Three sharing methods that were identified from the questionnaire responses and discussed during the WS are described below. One way of describing the methods is on the basis of how commercial they are:

- Free of charge transfers;
- Shared costs or exchanges of information;
- Commercial services.

Commercial solutions were not originally in the scope of the project, but a variety of them have been included in the report for future stages of the project, after having been identified by the members.

The content within this report is firstly organised by the sharing type and then by stage of waste management cycle, including also ownership and construction of facilities of waste disposal. Indeed, it was determined in the WS as a topic of interest for later work in this task.

The questionnaire responses (IRSN, 2020 a) have shown the interest of many countries for shared research projects and information exchange. Many countries acknowledged the benefit from further information exchange and collaboration with other states regarding the various aspects of radioactive waste management, e.g. development and sharing of technologies, methodologies, approaches, education/exchange of personnel etc. Also, some countries have provided information on facilities that could be available for sharing.

Joint research projects in various forms are currently the favoured way for collaboration, but some small inventory countries are also interested in shared facilities. However, in some countries, this option is not feasible due to the legislation in place.

The shared facilities option has been more modest, despite early proposals for major multinational fuel cycle centres and the implementation of large shared facilities for enrichment and reprocessing. The fuel cycle centre initiatives concluded that most of the proposed arrangements were technically feasible and economically attractive, but they all failed for a variety of political, technical and economic reasons.

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Glossary

ACSEPT	Actinide recycling by SEParation and Transmutation
ARAO	Agency for radioactive waste management in Republic of Slovenia
AT	Austria
AU	Australia
BE	Belgium
BG	Bulgaria
BR3	Belgian Reactor 3, pressurised water reactor in Mol
CARBOWASTE	Treatment and disposal of irradiated graphite and other carbonaceous waste
CATT	Co-operation and technology transfer on long-term radioactive waste management for Member States with small nuclear programmes
CEA	French Alternative Energies and Atomic Energy Commission
CH	Switzerland
CHANCE	Characterisation of conditioned nuclear waste for its safe disposal in Europe
CND	Co-ordination network of decommissioning of nuclear installation
COMPAS	Comparison of alternative waste management strategies for long-lived radioactive waste
CY	Cyprus
CZ	Czech Republic
DE	Germany
DGR	Deep Geological Repository
DOE	Department of Energy
DSRS	Disused Radioactive Sealed Sources
EC	European Commission
EDO	European Development Organisation
ENEN	European Nuclear Education Network
ENSREG	European Nuclear Safety Regulators Group
ERDO-WG	European Repository Development Organisation Working Group
ES	Spain
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
EURADScience	A network of research organisations for radioactive waste science in Europe
Eurochemic	European Company for the Chemical Processing of Irradiated Fuels
EURODIF	European Gaseous Diffusion Uranium Enrichment Consortium
EUROPART	EUROpean research programme for the PARTitioning of minor actinides and some long-lived fission products from high active wastes arising from the reprocessing of spent nuclear fuels

FAIRFUELS	Fabrication, irradiation and reprocessing of fuels and targets for transmutation
FI	Finland
FORATOM	European Atomic Forum
FR	France
GENIORS	GEN IV integrated oxide fuels recycling strategies
GR	Greece
HEP	Hrvatska elektroprivreda, Croatian state-owned energy company
HTR	High Temperature Reactor IAEA International Atomic Energy Agency
IC	Intergovernmental commission
IER	Ion Exchange Resin
IFNEC	International Framework of Nuclear Energy Cooperation
IGD-TP	Implementing Geological Disposal – Technology Platform
INF3	International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code) Class INF 3 ship - Ships which are certified to carry irradiated nuclear fuel or high-level radioactive wastes and ships which are certified to carry plutonium with no restriction of the maximum aggregate activity of the materials.
INSIDER	Improved nuclear site characterisation for waste minimisation in dismantling and decommissioning operations under constrained environment
IT	Italy
JAVYS	Slovakian company which operates, maintains and decommissions of nuclear facilities and manages radioactive waste *(Jadrová a vyraďovacia spoločnosť)*
JP	Japan
KBS-3	Nuclear fuel safety, method for final disposal of the spent nuclear fuel (*Kärnbränslesäkerhet)*
LILW	Low and intermediate level waste
LT	Lithuania
MA	Minor actinides
MICADO	Measurement and instrumentation for cleaning and decommissioning operations
MNA	Multilateral Nuclear Approach
MOX	Mixed oxide fuel
MS	Member-States
NEK	Krško Nuclear Power Plant (*Nuklearna Elektrarna Krško)*
NEWPART	New partitioning techniques
NL	The Netherlands
NPP	Nuclear Power Plant
OECD-NEA	The Nuclear Energy Agency (NEA) within the Organisation for Economic Co-operation and Development (OECD)

ONDRAF/NIRAS	Belgian National Agency for Radioactive Waste and enriched Fissile Material (Dutch: *Nationale instelling voor radioactief afval en verrijkte Splijtstoffen*, French: *Organisme national des déchets radioactifs et des matières fissiles enrichies)*
PETRUS	Towards a European training market and professional qualification in geological disposal
PL	Poland
Posiva Oy	an expert organisation responsible for the final disposal of spent nuclear fuel in Finland
PT	Portugal
Pu	Plutonium
PUMA	Plutonium and Minor Actinide Management in Thermal High-Temperature Gas-Cooled Reactors
PYROREP	Pyrochemistry for cost-effective nuclear waste management
PYROSMANI	PYROchemical processes Study for Minor ActiNIdes recycling in molten salt chlorides and fluorides
RE	Research Entities
RED-IMPACT	Impact of P and T and Waste Reduction Technologies on the Final Nuclear Waste Disposal
RO	Romania
ROSATOM	State Atomic Energy Corporation in Russia
ROUTES	Waste management routes in Europe from cradle to grave
RR	Research Reactor
RTD	Research and Technological Development
RU	Russia
RW	Radioactive Waste
RWM	Radioactive Waste Management
SACSESS	Safety of ACtinide Separation processes
SAPIERR	Support action: pilot initiative for European regional repositories
SAPIERR II	Strategy action plan for implementation of European regional repository - stage 2
SCK.CEN	Belgian nuclear research centre (Dutch: *Studiecentrum voor Kernenergie*; French: *Centre d'Étude de l'énergie Nucléaire*)
SE	Sweden
SECIGD	Secretariat of the Implementing Geological Disposal of Radioactive Waste - Technology Platform
$SECIGD_2$	Secretariat of the Implementing Geological Disposal of Radioactive Waste - Technology Platform - Phase 2
SFDS	Spent Fuel Dry Storage Facility
SFRY	Socialist Federal Republic of Yugoslavia

SI	Slovenia
SITEX	Sustainable network of Independent Technical EXpertise of radioactive waste disposal
SITEX-II	Sustainable network for Independent Technical EXpertise of radioactive waste disposal - Interactions and Implementation
SK	Slovakia
SKB	Swedish Nuclear Fuel and Waste Management Company, (*Svensk Kärnbränslehantering Aktiebolag*)
SNSA	Slovenian Nuclear Safety Authority
SRA	Strategic Research Agenda
SRPA	Slovenian Radiation Protection Administration
SSM	Swedish Radiation Safety Authority (StrålSäkerhetsMyndigheten)
STREP	Specific Targeted Research Project
THERAMIN	Thermal treatment for radioactive waste minimisation and hazard reduction
TRIGA	Training, Research, Isotopes, General Atomics, a class of nuclear research reactor
TRU	Transuranic
TSO	Technical Support Organisation
UA	Ukraine
UK	the United Kingdom of Great Britain and Northern Ireland
Urenco	A nuclear fuel company operating several uranium enrichment plants in Germany, the Netherlands, the United States, and the United Kingdom
US	The United States of America
USA	The United States of America
VKTA	Radiation Protection, Analysis & Disposal Rossendorf e. V. *(Verein für Kernverfahrenstechnik und Analytik Rossendorf)*
WAC	Waste Acceptance Criteria
WENRA	Western European Nuclear Regulators' Association
WMO	Waste Management Organizations
WS	Workshop
ZA	South Africa

1. Introduction

The preamble of the 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 acknowledges that: "*Some Member States consider that the sharing of facilities for spent fuel and radioactive waste management, including disposal facilities, is a potentially beneficial, safe and cost-effective option when based on an agreement between Member States concerned*".

In Article 4 (General principles) of the Directive, this translates into the following legal requirements: "*Where radioactive waste or spent fuel is shipped for processing or reprocessing to a Member State or a third country, the ultimate responsibility for the safe and responsible disposal of those materials, including any waste as a by-product, shall remain with the Member State or third country from which the radioactive material was shipped."*

And more specifically for disposal: "*Radioactive waste shall be disposed of in the Member State in which it was generated, unless at the time of shipment an agreement, taking into account the criteria established by the Commission in accordance with Article 16(2) of Directive 2006/117/Euratom, has entered into force between the Member State concerned and another Member State or a third country to use a disposal facility in one of them*."

Prior to the shipment to a third country, the exporting Member State shall take reasonable measures to be assured that:

- *the country of destination has radioactive waste management and disposal programmes with objectives equivalent to those established by this Directive;*
- *the disposal facility in the country of destination is authorised for the radioactive waste to be shipped, is operating prior to the shipment, and is managed in accordance with the requirements set under the radioactive waste management and disposal programmes.*

In the report (European Comission, 2015) the EC observes that "*The majority of Member States acknowledge their responsibility to dispose of radioactive waste generated on their territory in line with Article 4 of the Directive, and no Member States have currently notified to the Commission agreements for the use of disposal facilities in third countries*"... "*Half of Member States are considering the possibility of shared solutions for disposal either as a preferred or as an alternative option (the 'dual track' approach). However, none of the Member States' programmes or reports set out concrete milestones or measures towards the implementation of such a solution. While the Directive allows shared disposal solutions to be developed, a policy based only on this option, without a clear path towards implementation, cannot be regarded as being in line with the aims of the Directive. The Commission sees important challenges in putting shared solutions into practice."*

Moreover, in the last report (European Commission , 2019) it is mentioned *"While a few countries consider the option of a shared solution for disposal, in particular for high-level waste and spent fuel, no significant development has been observed in practice in the last three years. The viability of this option is limited by a legal ban of import of radioactive waste in about half of the Member States".*

The development of shared solutions for disposal are still in their feasibility phase, only one agreement for disposal of small amounts of institutional waste (from Luxemburg to Belgium) has been notified and two Member States (Slovenia and Croatia) were working towards a common disposal solution for spent fuel and radioactive waste generated by the shared nuclear power plant and an agreement on a common solution was expected by 2023. However, it is reported in the second national report that a mutually satisfactory common solution was not achieved.

On the other hand, hundreds of transboundary shipments of spent fuel and nuclear waste are authorized each year. These materials are imported and exported in MS with available capacities for processing or reprocessing in Europe. Sweden and Germany reported the majority of shipments, while the following nine Member States did not report any authorised shipment on their territory in the period 2015-2017: Croatia, Cyprus, Estonia, Greece, Ireland, Latvia, Luxembourg, Malta and Portugal. Among them, six Member States did not report any authorised shipments of radioactive waste on their territory since the beginning of reporting obligations under the present Directive (2009): Croatia, Cyprus, Estonia, Greece, Malta and Portugal (European Commission, 2019)

An alternative option for import and export (return) could be the development of shared solutions or facilities, immobile or mobile. Although the development of shared solutions could rise some issues related to the acceptance by the Civil Society, the development of such a shared solution treatment and conditioning facilities could be of both interest:

- For countries with small or medium-sized inventories and
- For some categories of problematic radioactive waste of quite small amounts

In these two situations, the majority of waste producers have a fairly small volume (e.g. batteries, solvents and pyrochemical waste), which would make the development of treatment capability at each site disproportionately expensive per unit volume.

Individual member states may not be able to afford a solution, but an EC wide approach could potentially be implemented to develop effective processes. This would avoid the construction of a treatment or conditioning facility for only a very small amount of radioactive waste.

The management of challenging waste in Small Inventory Member States (SIMS) is out of this deliverable scope. This issue is specifically addressed in the deliverables developed under ROUTES' task 2.

Within the framework of ROUTES and more specifically in task 6, the conducted work offers an opportunity for partners to assess the feasibility of developing further European shared solutions for waste management from cradle to grave, on the basis of their past experience and lessons learnt. ROUTES and task 6 are briefly described below.

Waste management routes in Europe from cradle to grave (ROUTES) - WP9 - is one of the work packages of the European Joint Programme on Radioactive Waste Management (EURAD). The objectives of ROUTES are to:

- Provide an opportunity to share experience and knowledge on waste management routes between interested organisations (from different countries, with programmes at different stages of development, with different amounts and types of radioactive waste to manage).
- Identify safety-relevant issues and their R&D needs associated with the waste management routes (cradle to grave), including the management routes of legacy and historical waste, considering interdependencies between the routes.
- Describe and compare the different approaches to characterisation, treatment and conditioning and to long-term waste management routes, and identify opportunities for collaboration between MS.

The work of ROUTES is organized under the following 8 tasks:

- Task 1 – S/T coordination, State-of-the-art and training material;
- Task 2 – Identify challenging wastes to be collaboratively tackled within EURAD;
- Task 3 – Description and comparison of radwaste characterisation approaches;
- Task 4 – Identification of WAC used in EU Member-States for different disposal alternatives in order to inform development of WAC in countries without WAC/facilities;
- Task 5 – RWM solutions for small amounts of wastes;
- Task 6 – Shared solutions in European countries;
- Task 7 – Interactions with Civil society;
- Task 8 – ROUTES Extension on the evaluation of the possible disposal solutions for Member States without WAC and with small inventories (SIMS).

The work under ROUTES has started with a joint questionnaire for all tasks in order to assess topics and to find common areas of interests for further work. The implementation of joint workshops including different tasks of ROUTES, and projects dealing with the same topics, are important to further collaborate and expand the findings of the questionnaire.

This deliverable was originally planned for the first year of the project, but due to some reworking it was delayed.

The task 6 objectives are to:

- Describe and assess knowledge and approaches to sharing technology and facilities between Member-States.
- Provide an overview of the interest and experience with sharing technology/facilities in the different steps of waste management.
- Identify gaps and define needs for R&D, strategic priorities and opportunities for collaboration between Member States, as applied to challenging wastes as defined in Task 1 and early stage RWM programmes and Small Inventory Programmes.

The task 6 is divided in 3 subtasks and include the submission of three deliverables, entitled as follows:

1. Studies and plans for developing shared solutions for radioactive waste management in Europe
2. Case studies of shared development and use of technologies and facilities
3. Report on the feasibility of developing further European shared solutions for waste management from cradle to grave

The objective of this report is to summarise studies and plans for developing shared solutions and technologies for radioactive waste management in Europe. The report concentrates on European solutions, but other shared solutions are also identified (e.g., in IAEA studies) where relevant. The materials that were reviewed for this report were questionnaire answers for ROUTES (IRSN, 2020 a), ROUTES workshop (WS) exercise results (See Appendix A) and discussions, reviews of the newest (2000 onward) EC projects (including SAPIERR, SAPIERR II, CHANCE, THERAMIN), IAEA studies on the topic and national programmes that refer to shared solutions (if they were available in English).

This deliverable summarises the knowledge and approaches regarding the sharing of technology and facilities between countries in different steps of the waste lifecycle. Based on the materials found, geological disposal has been the most investigated step, but shared research and development work and the use of technologies and facilities for characterisation, treatment, storage and disposal have also been explored.

This report also includes inputs gathered from the questionnaire responses (IRSN, 2020 a) and discussions during the ROUTES Workshop held in March 2020. A specific session was organized during the workshop in order to discuss the answers given by participants to the questionnaire (IRSN, 2020 b) and some challenges were identified during discussions. One issue raised involved a consistent definition of waste types. At the highest level, this could lead to some radioactive materials not appearing in a national waste inventory. Indeed, not every country considers spent fuel, depleted uranium or metal scrap as waste types, since they can also be treated as recyclable raw materials. It may be useful to keep such material in separate categories where opportunities for multinational cooperation can be sought. At a more detailed level, it would be valuable to have some consistency or commonality in the description and specification of waste streams arising from nuclear plant operations, facility decommissioning or nuclear applications in medicine, industry and research. At a minimum, each country should clearly define the national approach to waste management, the classification of its waste streams and the specific terminology used.

Another challenge raised from the questionnaire responses is the lack of all European countries representation in ROUTES. Additionally, the questionnaire does not necessarily cover all the aspects of waste management for the represented countries. Depending on which organisations from each country are participating, the coverage varies from country to country. In some cases, answering the questionnaire was coordinated within a country, and inputs were also integrated from organisations that were not participating in ROUTES. However, this was not always the case and the incomplete nature of information in the questionnaire responses makes this current literature review important, checking EU and IAEA projects, and national programmes, in order to identify as many collaboration topics as possible.

Some collaboration examples from the wider nuclear field are also used, if they could be applied for waste management purposes.

2. Definition of a shared solution

Considerations of shared solutions in the nuclear waste cycle have certain common factors, regardless of what part of the waste cycle is dealt with. These cross-cutting factors extend beyond the technology issues and include various aspects such as economics, assurances of supply, legal and institutional arrangements, non-proliferation and security issues, training, education, knowledge management and stakeholder interactions. Many of these factors are rather "national", and differ based on historical, cultural and socioeconomic differences among Member States. These specific issues have been left out of the objective of the report and are addressed in task 7 and more specifically in deliverable 9.16, whose objective is to highlight societal and public acceptance issues related to the development of shared solutions. Of course, collaboration in these fields would also be beneficial, especially since they are quite often preconditions which need to be addressed in order to go forward with shared facilities. They could be a topic for a new project. Also, the IAEA already gave some examples of these topics in its report (IAEA, 2006).

The content within this report is firstly organised by the sharing type and then by stage of waste management cycle, including also ownership and construction of facilities of waste disposal. Indeed, it was determined in the WS as a topic of interest for later work in this task.

Topics identified in the questionnaire, or during the workshop, but outside the objective of this report (or difficult to position by the definitions used here), are included in Appendix A (as long as the handwriting in the WS exercise was understandable).

2.1 Shared solutions identified in the WS

As mentioned in the introduction, although Member States consider sharing solutions and facilities as an interesting option, very few, if none, examples of shared solutions or facilities have been actually implemented.

One of the topics discussed during ROUTES' 1st workshop in Athens was the classification of the solution types that could be called 'shared' solutions. Three sharing methods that were identified from the questionnaire responses and discussed during the WS are described below. One way of describing the methods is on the basis of how commercial they are:

- Free of charge transfers;
- Shared costs or exchanges of information;
- Commercial services.

In some cases, information, knowledge or expertise has been provided without charge, as support to a less advanced or economically challenged organisation or country, or as part of information sharing between countries at different stages of their waste management practice. As beneficial as this was, it was on a small scale (e.g., sharing information or plan), and is unlikely to be the starting point for a shared solution in terms of a major facility.

Different ways of cooperation were also identified, and joint projects took many forms, ranging from in-kind contributions, to shared costs, to the information exchange between organisations (e.g., two different topics, but shared results). As expected, much of this cooperation has taken place (and is still taking place) in the context of jointly funded **EU projects.** While these joint projects **do not lead directly to joint facilities** (e.g., research on safety assessment of geological disposal), they are listed here but not discussed further.

Then, purely commercial solutions were identified, where the supplier provided the product or services on a commercial basis.

Although such solutions could not be considered shared solutions, information of this sort of activity, both identified in a questionnaire or found in the literature can be useful for the later stages of this project when trying to identify solutions for challenging waste potentially leading to sharing facilities.

In this framework, three types of commercial activities can be mentioned:

- Existing facilities treating or having treated foreign nuclear waste.
- Shared solutions (by different operators) inside a country. They have been considered, when information was available, because if a solution can be shared, it could also be shared across borders and this information will be useful in the later phases of task 6.
- Commercial solutions more easily shareable, such as mobile facilities.

2.2 IAEA's multilateral approaches

In its report, the IAEA expert group on Multilateral Nuclear Approaches (MNAs) identified three types of options for the Nuclear Fuel Cycle (p. 102 in (IAEA, 2005)):

- Assurances of services not involving ownership of facilities (either by suppliers, International consortia or IAEA).
- Conversion of existing national facilities to multinational facilities.
- Construction of new joint facilities.

The report discusses the pros and cons of multilateral approaches, such as non-proliferation strengthening with cooperation and cost effectiveness (pros) and limitation of state sovereignty and independent ownership (cons). There were some examples of these cases in the report, and these are briefly described in the next chapter, but mostly, these options or their variations were discussed theoretically. The report (p. 136 in (IAEA, 2005) gave five suggested approaches to MNAs:

1. Reinforcing existing commercial market mechanisms
2. Developing and implementing international supply guarantees with IAEA participation
3. Promoting voluntary conversion of existing facilities to MNAs
4. Creating, through voluntary agreements and contracts, multinational and regional MNAs for new facilities
5. Development of a nuclear fuel cycle with stronger multilateral arrangements and for broader cooperation

These approaches could also be applied to waste management MNAs. **The mechanisms to implement shared solutions depend both on the type of multilateral options (as identified by IAEA) but also on the type of chosen technical solution, i.e. a shared (jointly developed) mobile facility will be probably implemented more easily and rise less concerns about acceptability than a facility thermally treating nuclear waste.**

Although such considerations are beyond the scope of this report, they provide a guideline for further work in ROUTES.

3. Examples of EC-funded projects and International initiatives

This paragraph provides an overview of the EC-funded projects and the initiatives promoted by International Organisations (IAEA, NEA etc...) in the field of nuclear waste management listed by waste management cycle.

3.1 Characterisation

The work conducted under ROUTES has clearly pointed out characterisations as a fundamental step for the management of challenging waste, especially for legacy or dismantling waste; to this end, the EC has launched several projects on characterisation of radioactive waste. The following paragraph aims to give an overview of the existing project of interest for ROUTES. The specific issues related to the characterisation of challenging waste is addressed in ROUTES task 3.

CHANCE, Characterisation of conditioned nuclear waste for its safe disposal in EUROPE is still an ongoing project (2017-2022). Partners of the project are from FR, IT, DE, BE, UK, FI, RO and PL. CHANCE aims to address the characterisation of conditioned radioactive waste. The characterisation of fully or partly conditioned radioactive waste is a specific issue because unlike for raw waste, its characterisation is more complex and needs non- destructive techniques and methodologies. Characterisation issues within CHANCE encompass both physico-chemical characterisation and radiological characterisation. The first objective of the CHANCE project is to establish at the European level a comprehensive understanding of current conditioned radioactive waste characterisation and quality control schemes across the variety of different national radioactive waste management programmes, based on inputs from end-users members such as Waste Management Organizations and storage operators. The second objective of CHANCE is to further develop, test and validate techniques already identified that will improve the characterisation of conditioned radioactive waste, namely those that cannot easily be dealt with using conventional methods. (EC, 2020 a)

The goal of the on-going **MICADO** project (Measurement and instrumentation for cleaning and decommissioning operations) is to propose a cost-effective solution for non-destructive characterisation of nuclear waste, implementing a digitalization process that could become a reference standard facilitating and harmonizing the methodologies used for in-field waste management and dismantling and decommissioning operations. The project partners are from IT, FR, DE, CZ and BE. The absence of a consistent and straightforward solution to characterise all types of materials, along with the lack of an integrated solution for digitizing the enormous amount of data produced, is a critical issue. The decontamination and decommissioning of nuclear infrastructures still rely on an independent operator's process and on manually entering notes of nuclear waste management steps in a database. In addition to these variables, the information systems used do not provide analyses of past information within the same system, much less allowing sharing of data among operators. The MICADO project is setting up a standardised process that will allow full traceability of waste material and database sharing. The full digitalisation of the process will introduce procedures that reduce costs, ensure better safety procedures and protect staff from exposure. (EC, 2020 d).

The **CND** (Co-ordination network of decommissioning of nuclear installation) project participants were CH, CZ, DE, ES, IT, NL, SK and UK. The purpose of the project was to organise, develop and operate a network with organisations from the EU and candidate countries, involved in decommissioning activities. (EC, 2009 c)

INSIDER (improved nuclear site characterisation for waste minimisation in dismantling and decommissioning operations under constrained environment), is also recently closed project (2017-2021) involving FR, DE, UK, UA, ES, BE, HU, DE, CH and CZ. (EC, 2020 e). Decommissioning and dismantling (D&D) operations are dependent on the facilities' history and the inventory of radionuclides. The D&D processes are a significant source of radioactive waste and their management is a major challenge. These challenges are subject for further optimisation and the aim of the INSIDER project is to contribute to this. The envisaged project outcomes will enable building of a fit-for-purpose representation of the radiological status of facilities (or components), at a relevant accuracy and precision level, allowing decision-making concerning different D&D scenario options. The project will study interlaboratory comparisons on matrix-representative reference samples and benchmarking. Selected industrial partners, in cooperation with major EU R&D organisations, will develop conclusions formalised in guidelines, recommendations and elements for pre-standardisation initiatives. These will be validated and disseminated to the broad D&D community and beyond. (EC, 2020 g)

Some EU-projects, e.g. **Large waste assay** (NL, BE, FR, IT, UK, CZ, FI) (EC, 2002 a) which was developing NDA procedures for the QA/QC characterisation of large volume radioactive waste packages, **DACAPO** (DE, IT, AT) (EC, 2002 b) developing and automating of chemical analytical procedures for the determination of non-gamma emitting radionuclides in radioactive waste and **INTERLAB-ANALYSIS** (ES, BE, FR, DE, IT, UK, NL, FI) (EC, 2017 a) interlaboratory radiochemical analysis comparison on a primary waste flux, also had operational aspects on them. They were all EU research projects and they were related to QA/QC procedures and their harmonization.

The **ERDO-WG** initiated a joint project on characterisation of legacy waste, which includes collecting, from participants and the literature, information on problematic legacy wastes and trying to derive minimum WAC, which could be used in a joint facility. The project does not include development of methodologies – only information exchange and literature survey.

IAEA established the International Network of Laboratories for Nuclear Waste Characterisation (**LABONET**) to enhance sharing internationally in the application of proven, quality assured practices for the characterisation of low and intermediate level radioactive waste and waste packages. Their objectives are listed in their webpage as follows (IAEA, 2021):

- *To support organizations or Member States with less advanced nuclear programs for characterisation of radioactive waste;*
- *To develop an expanded range of training and demonstration activities;*
- *To facilitate sharing and exchange of knowledge and experience amongst organizations with characterisation facilities in operation;*
- *To create a forum in which experts' advice and technical guidance may be provided.*

Several ROUTES participants are also involved in the above-mentioned project(s), nevertheless during one of a ROUTES WS (IRSN, 2020 b), two other examples in this field were identified:

- IAEA (+SP) had collaboration in management and characterisation issues with CY, BG and LT. This was done through information exchange between already established disposal facilities to harmonize procedures (SP);
- Radiochemical analyses of metal samples from Greece (U, Pu, Sr-90, Fe-55, Ni-63) was performed by VKTA in Dresden (D).

3.2 Treatment and conditioning

As many graphite-moderated nuclear reactors in Europe will soon be at the end of their operational lives, solutions are needed for the radioactive waste raised from decommissioning. **CARBOWASTE** 'Treatment and disposal of irradiated graphite and other carbonaceous waste' participants from DE, UK, FR, ES, IT, LT, RO, BE, NL, SE and ZA addressed these needs. The principal investigations in CARBOWASTE ensured that acceptable technologies are identified for characterisation, retrieval, treatment, reuse/recycling and disposal of irradiated graphite (both legacy waste and waste foreseen in the future). It is considered that sufficient understanding of i-graphite has now been gained to conclude with confidence that graphite waste can be safely disposed in a wide range of disposal systems and a process for the evaluation and comparison waste management options was developed. The project created a European-wide collaboration on this special topic, which has now expanded to global cooperation through the International Atomic Energy Agency (IAEA). The work undertaken achieved a better understanding of graphite waste management options through combining results and findings from different groups and has started to make a practical difference to national plans and actions in managing graphite. (EC, 2014)

More recently two EC funded projects address issues of fundamental interest to ROUTES. They tackle issues specifically related to the developpement of technologies and processes for the management of problematic waste: **THERAMIN** and **PREDIS**.

Thermal treatment in an optimised waste management lifecycle can provide significant waste volume reduction, waste passivation and organics destruction, with benefits for waste storage and safety cases for geological disposal. **THERAMIN** (partners FI, FR, UK, DE, LT, BE and SK) aimed at using the relevant technologies, such as in-container vitrification, gasification, plasma treatment and hot isostatic pressing. THERAMIN provided an EU-wide strategic review and assessment of the value of thermal technologies applicable to a broad range of waste streams, compiled an EU-wide database of thermally treatable wastes, will document the strategic benefits of thermal treatment, and identify the opportunities, synergies, challenges, timescales and cost implications to improve radioactive waste management. The project evaluated the applicability and the achievable volume reduction of the technologies through full-scale demonstration tests and assessed the disposability of residues. The project benefited from the investments made by partners in thermal treatment R&D facilities. THERAMIN established a pan-European network of expertise on thermal treatment, provided for cross-European technology transfer and identified prospects for sharing of facilities between countries facing similar problems. (EC, 2020 c).

In order to support delivery of the UK Nuclear Decommissioning Authority (NDA) 2016 Strategy, a **Problematic Waste Integrated Project Team (IPT)** was established in May 2016 (IRSN, 2020 a). Its objective is to develop a co-ordinated and improved approach to the industry-wide management of challenging radioactive waste (termed “problematic waste” in the UK). The IPT is being led by LLW Repository Ltd and Radioactive Waste Management (RWM) on behalf of the NDA and includes engagement with a range of stakeholders. IPT has developed a network to provide support to waste owners and invited overseas organisations to join. They have exchanged information with France via a discussion between the ONR and the IRSN.

In March 2020, the PW IPT completed a 3-year programme of work (known as the “tactical phase” of the IPT) to improve the inventory of problematic radioactive waste, identify and develop treatment solutions for priority waste groups. These were prioritised through discussions with a Community of Practice (CoP) comprising waste owners with declared problematic waste inventories (PWIs) from across the whole UK’s Nuclear Industry. This included projects to identify specific treatment technologies that may be suitable for the treatment of oils and oily wastes, ion exchange materials, sludge, mercury, uranics and filters, as well as assembly of useful information from the supply chain and other NDA-funded projects.

Treatment technology datasheets have been made available in a Problematic Waste Toolkit (https://ecosystem.org.uk/groups/problematic-waste/pages/pw-toolkit) on the NDA’s Knowledge Hub. The toolkit also includes treatment facility datasheets that describe a range of commercially available and site-specific treatment facilities, including:

- Incinerators (https://ecosystem.org.uk/docs/DOC-2010)
- Supercompactors (https://ecosystem.org.uk/docs/DOC-24509)
- Laboratory testing facilities (https://ecosystem.org.uk/docs/DOC-14726) .

These datasheets are based on information contained in: L. Hunter-Smith, M. Dickinson and C. Laughey, Potential Treatment Options for Higher Activity Wastes and Problematic Wastes, Report no. NDA/RWM/PWIPT/18/001, LLWR/NWP/REP/185, Issue 2, February 2019 (unpublished), available on the Hub here: https://ecosystem.org.uk/docs/DOC-15907. Access can be requested from Mark Cowper of RWM (mark.cowper@nda.gov.uk).

Following the decision to extend the lifetime of the PW IPT to March 2023, it is moving into an “implementation phase”, during which it aims to start treating problematic wastes, including mercury and asbestos.

The **PREDIS** project is the outcome of the EURATOM NFRP-2019-2020-10 RIA call “Developing pre-disposal activities identified in the scope of the European Joint Programme in Radioactive Waste Management” (September 2019). The four-year, 47-partner project started on 1 September 2020. The PREDIS project develops and increases the Technological Readiness Level of treatment and conditioning methodologies for wastes for which no adequate or industrially mature solutions are currently available (e.g. metallic materials, liquid organic waste and solid organic waste). PREDIS also develops innovations in cemented waste handling and pre-disposal storage by testing and evaluating. PREDIS specifically targets Radioactive Waste Producers (RWP) as a separate group within the radioactive waste management process. The consortium is supported by a strong End User Group (EUG) representing a broad European and international interest. PREDIS encompasses the wider European Community, allowing cross-fertilisation and interaction between different national programmes. Numerous dissemination activities, including with Nugenia, IAEA and NEA, will be undertaken to maximize PREDIS’ impact to all the identified stakeholders in the field.

3.3 Disposal

Shared solutions in preparation for deep geological disposal of radioactive waste have provided the most extensive information in the recent literature reviewed for this report. In Europe, there are many cooperative research projects on the long-term safety of geological disposal. The more detailed names and durations of these projects are given in Appendix B. While a few of them specifically aimed at shared solutions, even though research efforts and results are shared.

Some EU projects have dealt specifically with shared repository concepts, e.g., **SAPIERR** (EC, 2008 a) and **SAPIERR II** (EC, 2013), which led to the formation of the **ERDO-WG** and recently **ERDO Association**. The SAPIERR and SAPIERR II projects were specifically focussed on small inventory countries, where a national geological repository may not be the most practical solution. However, there can also be economic and environmental benefits in shared solutions for countries that could implement a national solution. The prospect that countries could work together to explore regional solutions is raised in the EC radioactive Waste Directive. SAPIERR was a pilot initiative to help the EC to begin to establish the boundaries of the issue, collating and integrating information in sufficient depth to allow potential regional options to be identified and the new RTD needs to be scoped. SAPIERR II continued the work with feasibility studies into a practical implementation strategy and organisational structures that could enable a formalised, structured organisation to be established for working on shared EU radioactive waste storage and disposal activities. The principal goals were as follows (EC, 2013):

1) Development of an organisational framework and project plan to facilitate debate on the establishment of a modestly sized, self-sufficient European Development Organisation (EDO) that can work in parallel with national waste agencies;

2) Further studies of key issues related to economics, design, public and political attitudes and the safety and security of shared storage and disposal facilities.

The main tasks within the project were as follows:

1) Preparation of a management study on the legal and business options for establishing an EDO;

2) A study on the legal liability issues of international waste transfer within Europe;

3) A study of the potential economic implications of European regional repositories;

4) First considerations of the safety and security impacts of implementing regional repositories;

5) A survey of public and political attitudes towards regional repositories and of approaches to involving communities in decision making;

6) Development of a Strategy and a Project Plan for the work of the organisation, EDO.

The project fulfilled its goals and the ERDO-WG was established. Progress was slower than expected, but ERDO members are now working together in two specific projects (deep borehole disposal concepts and legacy waste characterisation) and have recently established a new organisational form of co-operation (association), which will be more capable of starting and funding new projects.

EU projects **SECIGD** (EC, 2019 c) and **SECIGD$_2$** (EC, 2016 b) led to the formation of the IGD-TP by waste implementers (WMOs) in Europe to promote the implementation of geological disposal. The mission of the IGD-TP is to support confidence-building in the safety and implementation of deep geological disposal solutions. IGD-TP is also a platform where information is shared and joint projects aiming for geological disposal are planned, at EU-level or as internal IGD-TP projects.

IGD-TP is concentrating on geological disposal implementation, but the EU (and ENSREG, WENRA, NEA, IAEA) has also supported initiatives for regulatory authority purposes, especially in a view of scientific review of safety cases. This work was done, e.g., in EU projects **SITEX** (EC, 2015) and **SITEX-II** (EC, 2017 b), which led to the formation of the SITEX network.

The SITEX network, IGD-TP and EURADscience have important roles in EURAD, guiding the EU-funded research projects. Whilst they are not specifically aiming at promoting shared solutions, they are enhancing R&D and Expertise co-operation between countries.

The **CATT** project (Co-operation and technology transfer on long-term radioactive waste management for Member States with small nuclear programmes) was complementary to the SAPIERR projects, because it assumed only national disposal solutions. Participants came from the UK, SI, BE, DE, SE, BG and LT. The purpose of the CATT project was to investigate the feasibility of small nuclear programmes implementing deep disposal of radioactive waste within their national borders, through collaboration or technology transfer with those who have advanced disposal concepts. The project explored a number of technology transfer options, all of which might lead to the creation of a national repository in the country where the waste originated. A CATT-type technology transfer has the potential to reduce the costs of national waste management facilities for long-term storage, encapsulation for disposal. However, differences in fuel type and disposal geology mean that some national development work will always be necessary. Where two or more countries have similar fuel types and similar disposal environments, significant cost savings may also be possible through the creation of a shared encapsulation facility. Alternatively, where a Member State has decided that SF is to be exported for reprocessing, cost savings could be made by the customer (and added value created for the reprocesser) if the reprocessing plant were to offer encapsulation as an additional service. A number of possible collaboration scenarios was developed. (EC, 2008 b)

The status of international developments on shared repositories was recently thoroughly reviewed by ONDRAF/NIRAS (Cornelis, 2019) and here it is only summarised. The concept of developing multinational geological disposal facilities has been discussed for decades, often via initiatives taken by the International Atomic Energy Agency (IAEA). Shared disposal facilities are currently topical, both due to the high costs of geological repository programmes and the security concerns of fissile materials being widely distributed across the world.

The main concrete initiatives across the globe since the early 1970s aimed at developing shared geological repositories are listed in Table 1 (after (Cornelis, 2019) They are grouped by potential scenarios — introduced in 2004 by the IAEA (p. 16 in (IAEA, 2004):

- The *add-on scenario*, in which a host country complements its national inventory of waste for disposal by waste imported from other countries;
- The *cooperation scenario*, also called *partnering scenario*, in which a shared repository programme is developed by a group of partner countries for later implementation in one of them, which becomes the host country;

- The *international or supranational scenario*, in which a shared repository would be fully in the hands of an international or supranational body. In 2004, this scenario was judged the least feasible by the IAEA, due to the political sensitivity to the transfer of sovereignty requirement (IAEA, 2004). Since then, international bodies have not developed concrete plans for international repositories and the Table 1 does not list any of this type of shared option projects.

Since this report, there has been additional emphasis placed on a “service provider” scenario in which the multinational repository is implemented by a private or governmental developer as a commercial venture. This was the thrust of the Pangea and South Australian projects mentioned in Table 1 and is also a focus of the IFNEC work on this topic.

SCK.CEN (BE) and ARAO (SI) had bilateral collaboration in planning of disposal performance and safety assessment methodology for LILW in SI. (IRSN, 2020 b). Multilateral collaboration with CEA, SCK.CEN and Los Alamos National laboratory (FR, BE, US) to select and characterise the site for a future RO near surface facility was also identified. (IRSN, 2020 b)

A good example of bilateral R&D co-operation is between the Swedish Nuclear Fuel Co. (SKB) and Posiva Oy in Finland, as described in IAEA’s case study (p. 63 in (IAEA, 2006)). They have together developed the KBS-3 concept for the deep geological disposal of spent nuclear fuel. In 2001, an agreement of collaboration was signed to:

- Avoid conducting duplicate work and enhance the cost effectiveness;
- Enhance the usage of resources; and
- Contribute to the public information and acceptance of the geological disposal.

SKB and Posiva have established procedures for planning and coordinating the joint activities. "Joint projects" are selected based on common areas of interest, the costs are shared, the personnel of both companies participate in projects and R&D facilities in both countries (and elsewhere in Europe) are used jointly. The experiences made were positive and the cooperation continues to this day. Over time, the areas of interests have changed, and in the future, when programmes in both countries progress, new topics might be included. The most important findings in recent years have been published in a joint publication series, reaching its 10th publication in 2019 (Björck, 2019).

Table 3-1 *Shared repository projects: their status and type.* (Cornelis, 2019).[1]

Name	Status	Type	References
IAEA’s suggestion to South-Africa	Terminated (1990s)	Add-on scenario	(Berkhout, 1997)
China	Terminated (1993-2000)	Add-on scenario	(Wen, 2001) (Wikipedia, Orchid Island, 2020)
Marshall Islands	Terminated (1994-2000)	Add-on scenario	(Breckenridge, 1997) (Feiveson, 2011)
Pangea project	Terminated (1997-2000)	Add-on scenario	(McCombie C. , 1999) (Tazaki, 2012) (Wikipedia, Pangea Resources, 2020)
US non-proliferation trust and Russian Federation	Terminated (1998-around 2003)	Add-on scenario	(IAEA, 2004) (Tazaki, 2012)
Kazakhstan	Terminated (2001-2006)	Add-on scenario	(World Nuclear News, 2014)
Mongolia	Terminated (2010-2011)	Add-on scenario	(Langley, 2011) (WISE, 2012)

[1] Ljubljana initiative (McCombie C. , 2004) was short lived and its participants joint SAPIERR project, so it is not listed separately here.

Russian Federation	Ongoing (1991-)	Add-on scenario	(Feiveson, 2011)
South-Australia	Ongoing (2015-)	Add-on scenario	(Commonwealth of Australia, 2017) (Government of South Australia, 2016)
IAEA: International project on innovative nuclear reactors and fuel cycles group	Ongoing (2015-)	Add-on scenario	(McCombie C. C., One for all?, 2018)
Belgium and Grand Duchy of Luxembourg	Ongoing (2016-)	Add-on scenario	
OECD/NEA	Terminated (1987)	Cooperation scenario	(Berkhout, 1997)
IAEA: Regional Nuclear Fuel Cycle Centres	Terminated (1975-1977)	Cooperation scenario	(Meckoni, 1977) (Berkhout, 1997)
IAEA: Expert Group	Terminated (1994-1995 and 2001-2002)	Cooperation scenario	(IAEA, 1998)
IAEA; Multinational Nuclear approaches Expert Group	Terminated (2004-2005)	Cooperation scenario	(ElBaradei, 2003) (IAEA, 2005)
IAEA; Preparation and publication of various reports			(IAEA, 2011) (IAEA, 2013) (IAEA, 2016)
International Working Group	Terminated (1995-1996)	Cooperation scenario	(IAEA, 2004)
EC: SAPIERR and SAPIERR II projects	Completed (2003-2005 and 2006-2009)	Cooperation scenario	(Stefula, 2006) (Verhoef, 2009) (Chapman, 2008)
ARIUS	Ongoing (2002-)	Cooperation scenario	(Arius, sd) (McCombie C. C., 2015) (McCombie C. C., Progress with Initiatives for Multinational Disposal of Radioactive Wastes. AEA-CN-242, 2016)
ERDO Working Group, presently ERDO Association	Ongoing (2009-)	Cooperation scenario	(Verhoef, 2009) (ERDO-WG, 2011 a) (ERDO-WG, 2011 b)
EC-backed initiatives	Ongoing (2003-)	Cooperation scenario	(European Commission , 2017)
IFNEC	Ongoing (2010-)	Cooperation scenario	(IFNEC, 2014) (IFNEC, 2016) (IFNEC, 2017 a) (IFNEC, 2017, b)

4. Examples of facilities having possibility to treat or having treated foreign waste

The introduction mentioned the authorization every year of hundreds of transboundary shipments of radioactive waste among member states for treatment and conditioning and eventually their return to the country of origin. There are also some mobile solutions where the treatment facility is moved to the place where the waste is produced. Some of these mobile solutions are discussed below.

4.1 Examples of commercial facilities

4.1.1 Waste Storage

There are currently no shared multinational storage facilities. Storage of spent fuel will cover longer periods of time than originally expected, and storage up to 100 years is being discussed now. The IAEA continues to work on the concept of regional spent fuel storage. The objective and scope are similar to those of geological repositories. The IAEA has presented to the MNA Expert Group preliminary findings of a study it has carried out on technical, economic and institutional aspects of regional spent fuel storage facilities, which is a valuable contribution for the assessment of such multinational arrangements. (IAEA, 2005)

4.1.2 Recycling, treatment and processing

Eckert & Ziegler provides purely commercial solutions e.g. for sealed sources a complete product and service cycle. For sealed sources, it includes the worldwide distribution of their sources. After their use, spent radioactive sources may be returned to the Environmental Services segment (this also includes sealed radioactive sources that have been manufactured and/or distributed by the company's legal predecessors). All sources returned are checked for reuse in order to feed the radioactive material back into the production cycle. They also offer services for waste processing and treatment without transfer of the waste ownership to Eckert & Ziegler. These services include waste transport services, volume reduction by compaction or incineration, packaging and conditioning of waste in approved containers, or intermediate storage of conditioned waste packages. (Eckert & Ziegler, sd)

AT, RO and NL have used Cyclife (SE) for scrap metal melting (IRSN, 2020 b). Cyclife, in Studsvik Sweden has been providing waste treatment services to domestic and international customers for 40 years. Metal treatments include: segmentation, decontamination, melting, clearance and recycling of produced metal ingots, characterisation and conditioning of secondary waste for return to customer. Treatment is always carried out in customer-specific campaigns. Cyclife also provides other services, such as thermal treatment of organic waste by incineration or pyrolysis, material and waste characterisation, disposal of sealed sources and other radioactive materials, Cyclife also performs re-loading of sealed sources in some industrial equipment (in the customer's facility). (Cyclife Sweden, 2020). More information about Studsvik can be found in ROUTES deliverable 9.16: Implementation of ROUTES action plan first place (JSI [EIMV], 2021).

In order to meet the needs for recycling materials from the nuclear industry and to mitigate the limited availability of interim and final disposal facilities for radioactive waste, Siempelkamp (D) developed options to recycle contaminated metals from operation and decommissioning of nuclear facilities. Their melting plant CARLA has been in operation since 1989 and services are also offered to international customers. The metal is recycled for new applications both within and outside the nuclear industry. (Kluth, 2009). The second melting facility GERTA, delivers melting services for mercury and/or NORM contaminated metals from oil- and gas industries. This unit is going step by step out of operation by a commercial and strategical decision of the company owners (T. Kluth, personal communication, September 1, 2020).

Slovak WMO JAVYS has quite rich skills in RAW processing. Since 2013, JAVYS has been providing its services for RAW processing from abroad (Czech Republic, Germany, Italy), especially incineration plant capacities, both for the needs of nuclear industry and for the processing of institutional RAW. (IRSN, 2020 b). More information about Studsvik can be found in ROUTES deliverable 9.16: Implementation of ROUTES action plan first phase (JSI [EIMV], 2021).

Belgoprocess in Belgium has facilities to treat and condition all types of radioactive waste, plasma thermal technologies and they provide services for dismantling of obsolete nuclear installations. (IRSN, 2020 a), (Belgoprocess, 2021)

4.1.3 Reprocessing

This is a specific aspect and mentioned here for completeness sake, it will not be further developed in this deliverable. Orano La Hague in France does provide reprocessing and recycling services of spent fuel, e.g. the Netherlands, Germany, Japan, Switzerland, Belgium and Italy have used their services. (IRSN, 2020 a), (Orano Group, 2021). Another known reprocessing facility in Sellafield in the UK is closing down, but it used to reprocess 9000 tonnes of spent fuel during its operation. (Government of the UK, 2021) (IRSN, 2020 a)

4.1.4 Transport

There is no multinational collaboration in this field identified by members, either in the ROUTES questionnaire or the WS. This was quite surprising considering the number of transboundary shipments authorized each year, as mentioned in the introduction. However, one example was found from Sweden in the literature. SKB International makes available SKB's special purpose vessel *m/s Sigrid* at times when it is not involved in SKB's programme. The *m/s Sigrid* is a transport ship with INF3 classification, allowing transports of the highest class of radioactive cargo. This is an example of a purely commercial option. (SKB, 2016) (SKB, 2019)

4.2 Mobile facilities

Mobile facilities are easily shareable and potentially more acceptable from a public perspective than local facilities. A review of the existing mobile techniques and examples of facilities is given in the IAEA Report (IAEA, 2014). A list of the existing mobile solutions and technologies developed by European countries and identified both through the ROUTES Questionnaire/Workshop and literature review are summarised in the Appendix C.

Hinneburg is a company that can offer melting services at the customer's premises. Belgian nuclear installation BR3 contracted Hinneburg three times to manage contaminated lead. The project was carried out by on-site melting using heating blankets. (OECD NEA, 2017)

In France, the Mercure mobile equipment operated by Cyclife France conditions IERs (Ion Exchange Resin) into epoxy resin matrix. It is a commercial solution, and well known in France since this machine travels the whole country from a NPP to another in order to condition IERs (LILW) in epoxy resin in a concrete container with a steel radiological shield. This waste package complies with the French LILW repository WAC and is in accordance with transport regulations. So far, the machine has been used only in France, but the services could also be provided abroad. (Andra, 2021), (Cyclife, 2021)

In the ROUTES WS, Germany identified several mobile facilities for different treatment purposes: e.g., drying evaporates, super compaction of mixed wastes, pumping resins, cutting core elements underwater, drying core parts coming from the reactor, conveyor belt clearance measurement device, drying pellets from supercompaction (IRSN, 2020 b). Due to their mobile nature, they would be suitable for shared use in different countries; so far, they have been in use in Germany.

5. Experiences in sharing facilities

5.1 Ownership and construction of facilities

There are practical examples from the front end of the nuclear cycle of joint facilities, e.g., the uranium enrichment plants Urenco and EURODIF (both from an ownership and construction point of view) and a nuclear power plant in Slovenia. Similar arrangements as used in these cases (e.g., commercial/industrial management, governmental joint committee or bilateral agreement) could also be used for sharing waste management facilities. Joint construction was also the focus of the IAEA's 1975–1977 Regional Nuclear Fuel Cycle Centre study, but in the context of reprocessing, and is therefore of general interest here. (p. 146 in (IAEA, 2005)

Urenco is the most complex of these organizations. It has enrichment facilities in the three following countries: Germany, the Netherlands and the United Kingdom. Based on the Treaty of Almelo, Urenco owns and operates enrichment facilities in these three countries, helps to coordinate research and development, assures equal access to developments in centrifuge technology by any of the members, and executes contracts for the sale of services to third countries. The main driving force behind the setting up of the Urenco organization in the early 1970s was commercial. The three governments also believed that the type of international organization that could be established — with multinational organization and management, together with trinational political oversight and control rights — would prevent the proliferation of technology and materials. (p. 60 in (IAEA, 2005))

EURODIF was founded by five participating countries — Belgium, France, the Islamic Republic of Iran (Iran), Italy and Spain — owning one enrichment facility, located in France. EURODIF was intended to serve the domestic fuel requirements of its members. The level of investment of each member reflected its percentage share of the product, and sensitive barrier technology was held by only one member: France. While excluding the transfer or sharing of sensitive technology, EURODIF did provide European participants with an assurance of supply, and an equity share in a production enterprise utilizing proven advanced technology. (p. 61 in (IAEA, 2005)

Another historical example of a multinational arrangement is the European Company for the Chemical Processing of Irradiated Fuels (Eurochemic), created in 1959 by 13 European countries with the support of the OECD/NEA. Eurochemic was initially seen by its member countries as a way to pool financial and intellectual resources, and to gain national expertise in an expensive but promising industry. Its facility at Mol, Belgium, reprocessed civilian power reactor fuel from 1966 to 1975. Eurochemic was terminated in 1974. Eurochemic was established to serve as a training centre in which reprocessing technologies could be acquired, various fuel types and techniques explored, and industrial experience developed. Eurochemic encompassed this goal. Eurochemic facilitated and launched the basis for industrial capability in a new technological field (Wolf, 1996) and (Scheinman, 2004) as cited in (IAEA, 2005)

A FORATOM (European Atomic Forum) recommendation to rationalize investment in order to establish a 'viable industry' in Europe led to the "International reprocessing initiative United Reprocessors Gesellschaft (UNIREP) creation in October 1971 by British, French and Germans. It aimed to divide the European reprocessing market between the British and French plants until their capacity was saturated. At this point, a large German plant would take over. However, in the end, UNIREP never built a plant, but the plans were enough to affect on the fall of Eurochemic (p. 79 in (IAEA, 2005))

The Slovenian Krško nuclear power plant (NPP) is located in the south-eastern part of Slovenia near the border with Croatia. The Krško NPP was built as a joint venture between Slovenia and Croatia in the period 1974 – 1981. The operating company Nuklearna elektrarna Krško (NEK) is co-owned (50:50) by the Slovenian state-owned company Gen-Energija and the Croatian state-owned company Hrvatska elektroprivreda (HEP). The electricity generated by the Krško NPP is equally shared between the two countries. (IRSN, 2020 a)

The agreement between the Government of the Republic of Slovenia and the Government of the Republic of Croatia on the "Regulation of the Status and Other Legal Relations Regarding the Investment, Exploitation and Decommissioning of the Krško NPP (Intergovernmental Agreement)" has been in force since 2003. The agreement inter alia states that management of radioactive waste (RW) and spent fuel (SF) are a joint responsibility of the contracting parties to ensure an effective joint solution for the management of RW and SF from an economic and environmental protection perspective. In July 2015, it was decided that the construction of a spent fuel dry storage facility (SFDS) at the Krško NPP site to be used until the cessation of the NPP's operation is part of a joint solution for spent fuel disposal and in accordance with Article 10 of the Intergovernmental Agreement. Slovenian national strategy included in "Resolution on the National Programme for Managing Radioactive Waste and Spent Nuclear Fuel 2016-2025", definition of the construction of the low- and intermediate-level waste (LILW) repository for Krško NPP LILW and the disposal of LILW inventory in the repository. The strategy considers two scenarios: the baseline scenario involving thedisposal of only half of the waste generated at the Krško NPP and all Slovenian LILW not generated at the Krško NPP; and the extended scenario in which an agreement is reached between Slovenia and Croatia on joint LILW disposal in accordance with Intergovernmental Agreement on the Krško NPP. (IRSN, 2020 a)

Some shared activities, less well referenced, and more examples of information exchange rather than actual shared operations, were identified during the ROUTES workshop. They were facility designs provided by the Netherlands to Denmark, Spain and Italy, research visits to disposal facilities in order to get ideas for El Cabril (Spain) site and EU support for Ukraine for new safe confinement-, DSRS storage- and near surface disposal facility buildings (IRSN, 2020 b).

5.2 Operation of facilities

Slovenia and Croatia also provide a clear example of a shared option, but only for one power plant, which is operated on the basis of an agreement between the governments of Croatia and Slovenia. An Intergovernmental Commission (IC) was formed by the contracting parties (governments) to monitor implementation and to initiate further activities in accordance with the agreement. A Supervisory Board and Assembly was established with representatives of the owners to provide direct supervision of the management of Nuklearna elektrarna Krško (NEK). The contracting parties are equally responsible for ensuring all material conditions, whereas the regulation and supervision of nuclear and radiation safety for NEK is the sole responsibility of the Republic of Slovenia Radiation.Nuclear safety is regulated by the Slovenian legal system and a comprehensive set of regulations and decrees is based on its Atomic Act. The Slovenian Nuclear Safety Authority (SNSA) and Slovenian Radiation Protection Administration (SRPA) are the principal regulators. (IRSN, 2020 b)

Spain has examples of information exchange in relation to the operation of already established disposal facilities, in order to harmonize procedures in Spain. (IRSN, 2020 b)

6. Miscellaneous/ Crosscutting issues

Although European co-operation in the RWM field has always been close, the European Commission launched in 2019 the EURAD project, representing a new step in European collaboration for the safe management of radioactive waste, including its disposal, through the development of a science, technology and knowledge management programme that supports RWM activities. EURAD supports the implementation of the Waste Directive in EU Member-States, taking into account the various stages of advancement of national programmes. National RWM programmes across Europe cover a spectrum of stages of development and level of advancement, particularly with respect to their plans and national policy towards implementing geological disposal. Programmes differ significantly, depending on the national waste inventory, from small to large volumes and different types of waste (from medical and research waste to nuclear power and waste defence programme). (EURAD, 2019 a)

EURAD brings together Waste Management Organisations (WMOs), Technical Support Organisations (TSOs) and Research Entities (REs) which have together produced the EURAD Vision, Strategic research Agenda (SRA) and Roadmap. EURAD activities consist of RD&D activities aiming at developing and consolidating the S/T knowledge of the SRA and the EURAD Roadmap. Complementing RD&D and supporting the implementation of Member States' national programmes, the strategic studies provide an opportunity for participants and contributing experts to network on difficult methodological and strategic issues that are common to various national programmes and that are closely linked to scientific and technical issues. In addition to RD&D and strategic studies, EURAD will consolidate its efforts in knowledge management –including access to existing Knowledge (State-of-Knowledge), guiding the planning and implementation of a RD&D plan for the national RWM programme, and developing training/mobility based on core competencies. (EURAD, 2019 b)

An earlier overarching EU project, COMPAS, proposed the creation of a thematic network for the evaluation and comparison of alternative long-term strategies for the management of long-lived radioactive waste that have been considered in EU member states and candidate countries. The focus was on strategies for the management of spent fuel for direct disposal, long-lived ILW and HLW generated from reprocessing and transmutation. COMPAS was a forum for discussion, promoting the exchange of information and expertise. National differences influencing the selection of strategies and key factors in of national policies formulation were reviewed, with the aim of reaching a common understanding of the differences between current strategies. Participants were from the UK, FR, ES, DE, CH, NL, FI, SE and SK. (EC, 2003)

In the WS, some additional topics were identified (IRSN, 2020 b), they can be seen in Appendix B.

7. Concluding comments

The objective of this report was to review past and current studies and plans for developing shared solutions for radioactive waste management in Europe. The review shows that for the last two decades much work has been done on the shared development of methodologies for the characterisation and treatment of various waste streams and that intensive efforts continue in these areas.

The questionnaire responses (IRSN, 2020 a); see table in Appendix D for summary, have shown the interest of many countries for shared research projects and information exchange. Many countries acknowledged the benefit from further information and collaboration with other states regarding the various aspects of radioactive waste management, e.g., development and sharing of technologies, methodologies, approaches, education/exchange of personnel etc. Also, some countries have provided information on facilities that could be available for sharing.

Joint research projects in various forms are currently the favoured way for collaboration, but some small inventory countries are also interested in shared facilities. However, in some countries, this option is not feasible, due to the legislation in place.

The shared facilities option has been more modest, despite early proposals for major multinational fuel cycle centres and the implementation of large shared facilities for enrichment and reprocessing. The fuel cycle centre initiatives came to the conclusion that most of the proposed arrangements were technically feasible and economically attractive, but they all failed for a variety of political, technical and economic reasons. The main reason was that the parties could not agree on the non-proliferation commitments and conditions that would entitle participation in the multilateral activities. Also, differences of views on whether or not to reprocess or recycle plutonium prevailed between countries (IAEA, 1977), (IAEA, 1980), (IAEA, 1982) and (IAEA, 1985)as cited in (IAEA, 2005).

The efforts on multilateral mechanisms faded by the end of 1980s and remained weak until the IAEA's 1997 international symposium on the nuclear fuel cycle and reactor strategies. One of the most important conclusions of this symposium was that previous initiatives had failed due to different priorities. For governments, the priorities were political legitimacy and public support; for industry, they were technical feasibility and commercial viability. (IAEA, 1997) as cited in (IAEA, 2005)

Through a serie of meetings in 2001 and 2002, the focus on multilateralization of the fuel cycle was broadened to include repositories for spent fuel and nuclear waste. Again, while political and institutional issues have been the main obstacles to the establishment of these facilities, technical and economic considerations have favoured them. The meetings led to the development of a seminal IAEA publication on developing multinational radioactive waste repositories. (IAEA, 2004).

In the next task 6 report, case studies of some of the joint efforts identified in this report will be described in more details.

Appendix A. Athens WS exercise results - Ways and phases of sharing identified during the workshop (IRSN, 2020 b)

	Free*	Shared^	Commercial~
Construction and ownership	NL to DK, SP, IT facility designs provided Research visits to disposal facilities in order to get ideas for El Cabril site (SP)	EU supported projects in UA New safe confinement-, DSRS storage- and near surface disposal facility	
Operation & Quality	Exchange info already established disposal facilities to harmonize procedures (SP)	NPP Krško ownership SI& Cro	
Transport			
Characterisation	IAEA (+SP) collaboration in management and characterisation issues with CY, BG, LT Exchange info already established disposal facilities to harmonize procedures (SP) RO in EU project CARBOWASTE: learn to characterise irradiated graphite		Radiochemical analyses from GR metal samples (U, Pu, Sr-90, Fe-55, Ni-63 by VKTA Dresden (D)
Treatment			JAVYS (SK) various RAW, various countries Drying evaporates, mobile facility (D) by FAVORIT, GNS Supercompaction mixed waste mobile facility FAKIR, GNS (D) Mobile facility for pumping resins NEWA/PUSA & FAFNIR, GNS (D) Cutting core elements underwater (D) by BZ/UWS, GNS Mobile facility for drying core parts coming from the reactor KETRA, GNS (D) Mobile facility conveyor belt clearance measurement device FREMES (D) Mobile facility for drying pellets from supercompaction PETRA, GNS (D) Incineration and melting of contaminated RW from SI, RO NPP operations in SE (SNSA, 2013)
Conditioning			Sealed source conditioning with IAEA help (SI (Železnik, 2003)) Reprocessing of UA SNF in RU, returned as vitrified waste Reprocessing NL NPP waste in France, returned as vitrified waste

Storage	TRIGA RR fuel to USA (DOE) from Slovenia (Ravnik, 2006)		
Decommissio-ning			Dismantling of large components at ZLW Greifswald (D)
Recycling			Shielded sources from GR recycled in Eckert & Zieggler (D) AT, RO, NL used Cyclife (SE) for scrap metal melting Melting NL metal scrap in Siempelkamp (D) Mobile facility for metal scrap melting Hinneburg (D)
Disposal	Planning of disposal PA/SA method. For LILW by SCK.CEN (BE) to ARAO (SI) (Železnik. N., 2003) Bilateral collaboration with CEA, SCK.CEN and Los Alamos National laboratory (FR, BE, US) to select and characterise the site for RO future near surface facility. RO in EU project CEBAMA: learn how to study the RW sorption diffusion on concrete RO in EU project FORGE: learn how to treat the gas transport through bentonite	SAPIERR, SAPIERRII, ERDO-WG ERDO-WG projects (Cost, Legacy waste, deep borehole disposal) IGD-TP cooperation projects (Climate, KINA) RW+SF management SI+HR SE+FI cooperation in KBS-3 method (horizontal implementation, canister welding and other R&D activities) Exchange info already established disposal facilities to harmonize procedures (SP) EU supported projects in UA roadmap for DGR	DGR in SK providing research/studies by UJV Rez CZ
The rest	DGR in SK training support by BE gov. AT knowledge sharing via IAEA technical visits (multiple countries) SSM (SE) +NO provide support for projects on safety (Eastern Europe) SP, PT, CZ Exchange of students in PETRUS and ENEN programmes, technical visits with hands on jobs. Exchange info already established disposal facilities to harmonize procedures (SP)	EU supported projects in UA (Documents): guidelines, drafts of regulations, etc. EU supported projects in UA: new RW classification NO support to UA: regulations, general safety provisions (predisposal and disposal) Radioactive materials transported to Russia for reprocessing or storage.	

* Given with no payment or exchange in return
^Work (in-kind) or costs are split
~Bought or sold services

Appendix B. EU joint research projects - Some EU-projects with a scope on RD&D from 2000 onwards, their scopes and participants

Projects are arranged in alphabetical order according to their topic.

Name	Scope	Duration	Countries involved	Topic	Funding Scheme
CHANCE	Characterisation of conditioned nuclear waste for its safe disposal in EUROPE	2017-2022	FR, IT,DE, BE, UK, FI, RO, PL	Characterisation of conditioned waste	Research and innovation action
PARTNEW	Partitioning: new solvent extraction processes for minor actinides	2000-2003	FR, ES, SE, DE, IT, UK	Chemical separation (partitioning)	Cost-sharing contracts
PYROREP	Pyrometallurgical processing research programme	2000-2003	FR, UK, JP, ES, DE, IT, CZ	Chemical separation (partitioning)	Cost-sharing contracts
CND	Co-ordination network of decommissioning of nuclear installation	2005-2008	CH, CZ, DE, ES, IT, NL, SK, UK	Decommissioning	Coordination action
INSIDER	Improved nuclear site characterisation for waste minimisation in DD operations under constrained environment	2017-2021	FR, DE, UK, UA, ES, BE, HU, DE, CH, CZ	Decommissioning & dismantling	Research and innovation action
MICADO	Measurement and instrumentation for cleaning and decommissioning operations	2019-2022	IT, FR, DE, CZ, BE	Decommissioning	Innovation action
BAMBUS II	Backfill and material behaviour in underground salt repositories	2000-2003	DE, FR, NL, ES, US	Disposal	Cost sharing contracts
BEACON	Bentonite mechanical evolution	2017-2020	SE, SZ, FI, FR, CH, ES, UK, DE, BE, LT	Disposal	Research and innovation action
BELBaR	Bentonite erosion: effects on the long-term performance of the engineered barrier and radionuclide transport	2012-2016	SE, FI, ES, CZ, DE, UK, RU,	Disposal	Small or medium-scale focused research project
BIOCLIM	Modelling sequential biosphere systems under climate change	2000-2003	FR, ES, DE, CZ, UK, BE	Disposal	Cost sharing contracts
BIOMOSA	Biosphere models for safety assessment of radioactive waste disposal based on the application of the reference biosphere methodology	2001-2003	DE, BE, ES, UK, SE, HU,	Disposal	Cost sharing contracts

BORIS	Building confidence in deep disposal	2000-2002	UK, RU, BE, DE, FR, ES, US	Disposal	Cost sharing contracts
CAST	Carbon-14 source term	2013-2018	UK, RO, CH, FR, BE, NL, DE, IT, JP, CZ, ES, FI, UA, SE	Disposal	Collaborative project
CATCLAY	Processes of cation migration in clayrocks	2010-2014	FR, CH, DE, BE, NL	Disposal	Small or medium-scale focused research project
CEBAMA	Cement-based materials, properties, evolution, barrier functions	2015-2019	DE, FR, ES, UK, NL, RO, JP, BE, CZ, FI, CH	Disposal	Research and innovation action
CLUSTER URL 2	Club of underground storage, testing and research facilities for radioactive waste disposal	2001-2002	BE	Disposal	Preparatory, accompanying and support measures
CROCK	Crystalline rock retention processes	2011-2013	DE, ES, SE, CZ, RU, FI	Disposal	Small or medium-scale research project
CROP	Cluster repository project – a basis for evaluating and developing concepts of final repositories for high level radioactive waste	2001-2004	SE, BE, ES, DE, CH, FR, CA, FI, US	Disposal	Coordination of research actions
DISCO	Modern spent fuel dissolution and chemistry in failed container conditions	2017-2021	SE, ES, UK, FI, DE, BE, FR, CH	Disposal	Research and innovation action
DOPAS	Full scale demonstration of plugs and seals	2012-2016	FI, FR, DE, CH, UK, CZ, SE, NL	Disposal	Collaborative project
ECOCLAY II	Effects of cement on clay barrier performance - phase II	2000-2003	FR, UK, BE, SE, ES, DE, CH, FI	Disposal	Cost-sharing contracts
ESDRED	Engineering studies and demonstrations of repository designs	2004-2009	FR, ES, DE, BE, CH, UK, NL, FI, SE	Disposal	Integrated project
FEBEX-II	Full-scale engineered barriers experiment in crystalline host rock phase II	2000-2004	ES, FR, SE, CZ, BE, DE, CH, FI	Disposal	Cost-sharing contracts
FIRST-nuclides	Fast / instant release of safety relevant radionuclides from spent nuclear fuel	2012-2014	DE, HU, ES, BE, CH, FR, SE	Disposal	Small or medium-scale focused research project
FORGE	Fate of repository gases	2009-2013	UK, RO, SE, BE, FR, ES, DE, CH, FI, CZ, LT	Disposal	Large-scale integrating project

FUNMIG	Fundamental processes of radionuclide migration	2005-2008	DE, ES, FR, SE, FI, HU, DK, BE, CH, RO, UK, CZ, SK, CY, NL	Disposal	Integrated project
GASNET	A thematic network on gas issues in safety assessment of deep repositories for nuclear waste	2001-2004	UK, ES, DE, BE, CH, FR, FI, SE	Disposal	Thematic network contracts
Heater experiment	Rock and bentonite thermos-hydro-mechanical (THM) processes in the near field	2001-2004	DE, ES, CH	Disposal	Cost-sharing contracts
IN CAN PROCESSES	Rates and mechanisms of radioactive release and retention inside a waste disposal canister	2000-2003	UK, SE, FI	Disposal	Cost-sharing contracts
JOPRAD	Towards a joint programming in radioactive waste disposal	2015-2017	FR, BE, CZ, UK,CH	Disposal	Coordination and support action
LUCOEX	Large underground concept experiments	2011-2015	SE, FR, CH, FI	Disposal	Large-scale integrating project
MICADO	Model uncertainty for the mechanism of dissolution of spent fuel in a nuclear waste repository	2006-2009	FR, ES, DE, BE, SE, CH, UK	Disposal	Coordination action
MIND	Development of the safety case knowledge base about the influence of microbial processes on geological disposal of radioactive wastes	2015-2019	SE, UK, BE, FI, CH, ES, DE, UK, CZ	Disposal	Research and innovation action
MoDeRn	Monitoring developments for safe repository operation and staged closure	2009-2013	FR, ES, DE, BE, CH, UK, NL, FI, CZ, JP, US, SE	Disposal	Small or medium-scale focused research project
Modern2020	Development and demonstration of monitoring strategies and technologies for geological disposal	2015-2019	FR, ES, CZ, DE, IT, CH, BE, UK, NL, JP, SE	Disposal	Research and innovation action
NET.EXCEL	Network of excellence in nuclear waste management and disposal	2002-2004	SE, ES, DE, BE, CH, FR, FI, UK	Disposal	Thematic network contracts
NF-PRO	Understanding and Physical and numerical modelling of the key processes in the near-field and their coupling for different host rocks	2004-2007	BE, FR, ES, DE, SE, UK, CH, NL, FI, CZ	Disposal	Integrated project

	and repository strategies				
OMNIBUS	Development of the tools and interpretations techniques for ultrasonic surveys to monitor the rock barrier around radioactive waste packages	2001-2004	UK, FR	Disposal	Cost-sharing contracts
PAMINA	Performance assessment methodologies in application to guide the development of the safety case	2006-2009	DE, ES, FR, BE, UK, NL, CZ, CH, FI, SE	Disposal	Integrated project
PEBS	Long-term performance of engineered barrier systems (EBS)	2010-2014	DE, CH, SE, ES, FR, CN, JP	Disposal	Small or medium-scale focused research project
PROTOTYPE REPOSITORY	Prototype repository-full scale testing of the KBS-3 concept for high-level radioactive waste	2000-2004	SE, ES, DE, JP, FI, UK	Disposal	Cost-sharing contracts
RECOSY	REDOX phenomena controlling systems	2008-2012	DE, FR, SE, ES, FI, BE, CZ, CH, AT, HU, CY, LT, NL, RU, UK	Disposal	Collaborative project
REDUPP	Reducing uncertainty in performance prediction	2011-2014	SE, FI, UK	Disposal	Small or medium-scale focused research project
RESEAL II	A large scale in situ demonstration test for repository sealing in an argillaceous host-rock	2000-2007	BE, ES, FR,	Disposal	Cost-sharing contracts
RETROCK	Treatment of geosphere retention phenomena in safety assessments	2001-2004	FI, ES, CH, SE	Disposal	Coordination of research actions
SECIGD	Secretariat of the implementing geological disposal technology platform	2010-2012	FI, SE, FR, DE	Disposal	Support actions
$SECIGD_2$	Secretariat of the implementing geological disposal of radioactive waste	2013-2015	FR, UK, FI, BE	Disposal	Support actions
SELFRAC	Fractures and self-healing within the excavation disturbed zone in clays	2001-2004	BE, FR, BE, CH	Disposal	Cost-sharing contracts
SPIN	Testing of safety indicators	2000-2002	DE, BE, CH, ES, NL, CZ, FI	Disposal	Cost-sharing contracts

THERESA	Coupled thermal-hydrological-mechanical-chemical processes for application in repository safety assessment	2007-2009	SE, DE, NL, ES, UK, FI, FR	Disposal	Specific targeted research project
TIMODAZ	Thermal impact on the damaged zone around a radioactive waste disposal in clay host rocks	2006-2010	BE, CH, DE, NL, ES, CH, FR, CZ, UK,	Disposal	Specific targeted research project
TN on MONITORING	Thematic network on the role of monitoring in a phased approach to disposal	2001-2003	UK, BE, DE, ES,CH, FR, NL, FI, CZ, SE	Disposal	Thematic network contracts
TRANCOM-II	Migration case study: transport of radionuclides in a reducing clay sediment	2000-2003	BE, FR, UK, BE	Disposal	Cost-sharing contracts
SITEX	Sustainable network of independent technical expertise for radioactive waste disposal	2012-2013	FR, BE, DE, CZ, LT, SK, SE, NL, CA, CH,	Disposal (regulatory functions)	Coordination of networking action
SITEX-II	Sustainable network for independent technical expertise of radioactive waste disposal	2015-2017	FR, LT, BE, FR, SK, CA, HU, NL, DE, SE, BG, CH, CZ	Disposal (regulatory functions)	Coordination and support action
EB	Engineered barrier emplacement experiment in opalinus clay	2000-2003	ES, DE, CH,	Disposal (repository technology)	Cost-sharing contracts
SAPIERR	Support action: pilot initiative for European regional repositories	2003-2005	SK, CH	Disposal strategy	Specific support action
SAPIERR-2	Strategy action plan for implementation of European regional repository – stage 2	2006-2009	NL, SI, CH, LT, IT, ES, SK, UK	Disposal strategy	Coordination action
Novel ligands for extraction	Novel calixarene ligands for the selective extraction of F-group elements from radioactive pollutants	2002-2004	DE, RU, FR	Extraction	
CARD	Co-ordination of research, development and demonstration (RD&D) priorities and strategies for geological disposal	2006-2008	UK, BE, CZ, FI, FR, DE, SI, ES, CH, SE	Geological disposal, networking	Coordination action
SACSESS	Safety of actinide separation process	2013-2016	FR, SE, ES, CZ, IT, PL, BE, DE, UK, CH, NL, JP	P&T, waste amount reduction	Collaborative project

ACSEPT	Actinide recycling by separation and transmutation	2008-2012	FR, PT, ES, NL, CZ, IT, DE, PL, BE	Partitioning for recycling	Collaborative project
EUROPART	European research program for the partitioning of minor actinides and some long-lived fission products from high active wastes issuing the reprocessing of spent nuclear fuels	2004-2007	FR, AU, UK, JP, ES, CZ, SE, BE, IT, DE, PL, NL	Partitioning for transmutation or conditioning	Integrated project
PUMA	Plutonium and minor actinides management by gas-cooled reactors	2006-2009	NL, PL, BE, IT, FR, US, SE, UK, DE	Pu and minor actinide incineration	Specific targeted research project
DACAPO	Development and automation of chemical analytical procedures for the determination of non-gamma emitting radionuclides in radioactive waste	2000-2003	DE, IT, AT	Quality checking of waste packages	Cost-sharing contracts
INTERLAB-ANALYSIS	Interlaboratory radiochemical analysis comparison on a primary waste flux	2000-2002	ES, BE, FR, DE, IT, UK, NL, FI	Quality checking on waste packages	Cost-sharing contracts
Large waste assay	Development of NDA procedures for the QA/QC characterisation of large volume radioactive waste packages	2000-2003	NL, BE, FR, IT, UK, CZ, FI	Quality checking of large waste packages	Cost-sharing contracts
RED-IMPACT	Impact of P and T and waste reduction technologies on the final nuclear waste disposal	2004-2007	SE, BE, UK, RO, ES, FR, DE, CZ, SK	Reduction of waste generation	Specific targeted research project
FAIRFUELS	Fabrication, irradiation and reprocessing of fuels and targets for transmutation	2009-2015	NL, SE, ES, UK, BE, FR	Reprocessing	Large-scale integrating project
GENIORS	GEN IV integrated oxide fuels recycling strategies	2017-2021	FR, SE, ES, CZ, PL, BE, DE, UK, IT, NL, UK	Reprocessing & recycling	Research and innovation action
CARBOWASTE	Treatment and disposal of irradiated graphite and other carbonaceous waste	2008-2013	DE, UK, FR, ES, IT, LT, RO, BE, NL, SE, ZA	Treatment / disposal	Collaborative project
CATT	Co-operation and technology transfer on long-term radioactive waste management for member states with small nuclear programmes	2006-2007	UK, SI, BE, DE, SE, BG, LT	Waste management steps e.g. encapsulation and conditioning	Specific support action

COMPAS	Comparison of alternative waste management strategies for long-lived radioactive waste	2001-2003	UK, FR, ES, DE, CH, NL, FI, SE, SK	Waste management strategies	Thematic network contracts
THERAMIN	Thermal treatment for radioactive waste minimisation and hazard reduction	2017-2020	FI, FR, UK, DE, LT, BE, SK	Waste treatment	Research and innovation action

Appendix C. Some mobile facilities identified in the WS or in the literature review.

Company	Name	Process	Type of waste	Site	Reference
Cyclife France	MERCURE	Embedding in an epoxy resin matrix	Ion exchange Resins	France - Centrales	(IRSN, 2020 a) (Andra, 2021) (Cyclife, 2021)
Cyclife France	Mobile Unit	Cementation	Sludge	France - Centrales	(IRSN, 2020 a) (Andra, 2021; Cyclife, 2021)
WESTINGHOUSE	MOSS	Cementation	Liquid waste/resins/sludges	USA – Hanford Europe	(Boucay, 2019)
Hinneburg		Melting	Metals		(OECD NEA, 2017)
GNS group	See with the type of waste	See with the type of waste	Drying evaporates, mobile facility by FAVORIT Super compaction mixed waste mobile facility FAKIR Mobile facility for pumping resins NEWA/PUSA & FAFNIR Cutting core elements underwater by BZ/UWS Mobile facility for drying core parts coming from the reactor KETRA Mobile facility conveyor belt clearance measurement device FREMES Mobile facility for drying pellets from supercompaction PETRA Incineration and melting of contaminated RW from NPP operations in FAFNIR	Germany	(GNS, 2021)

Appendix D. ROUTES questionnaire (and national programmes) summary of past projects and future interests

	History in international collaboration	Ways of collaboration interested in	Topics of interests	Could provide assistance in	Legalities or policies to consider
Austria (IRSN, 2020 a)	Taking part in Conferences, Technical Meetings and Networks (Regional, EU-wide and international). Examples include: IAEA Technical Meetings and Networks and the ERDO-WG. Use of the commercial available European facilities for metal melting and encourages recycling of DSRS at producer's sites.	In the "Disposal Program" international co-operations with other EU member states are specifically mentioned for the exchange of experiences Technical exchanges	Especially final disposal for SIMS	Host technical meetings and shares its experiences (e.g. tours of its premises and also consultation work).	Follow the "dual-track approach" and is looking to establish a national solution Radioactive waste treatment for other countries is prohibited
Belgium (IRSN, 2020 a)	Processing of foreign waste Expedition of waste to be processed abroad Acceptance of foreign waste by ONDRAF/NIRAS Sharing of competences	International programmes Exchange meetings/exchange platforms Bilateral meetings (formal and informal).	Legal aspects Aspects with respect to responsibilities over longer time period Technical guidance related to the implementation of disposal Social aspects and ethical issues Stakeholders participation Physical/chemical characterisation of CW Identification and management of uncertainties The definition of preliminary WAC in the absence of a disposal solution.	Waste from abroad can be treated in Belgium and sent back to the country of origin Belgoprocess shares its competences in the field of plasma incineration (Switzerland, Bulgaria)	Shared repositories are not excluded

	History in international collaboration	**Ways of collaboration interested in**	**Topics of interests**	**Could provide assistance in**	**Legalities or policies to consider**
Bulgaria (IRSN, 2020 a)	International collaboration e.g. in EU projects	Involvement of Bulgarian R&D organisations as partners in international projects, seminars, conferences, etc	In all aspects of the RAW management area The option of disposing of SNF from Bulgaria in Russia is developed currently with agreement between the both countries		An import of RAW is not allowed
Croatia (Republic of Croatia, 2018)			Disposal of spent nuclear fuel high level waste (HLW) in deep geological formation at a location in the Republic of Croatia or the Republic of Slovenia (or in an eventual international repository in the EU)		
Cyprus (IRSN, 2020 a)(Ministry of labour welfare and social insurance, 2018)	International collaboration e.g. in EU projects (ROUTES)	Attend relevant courses and visit relevant facilities	The correct handling/management of LLW and DSRS storage/reuse/recycling/disposal		Shared solutions are not covered by the in-force legislation, however it is not prohibited. Shipments of radioactive waste are governed by legislation in harmonization with Euratom Directive 2006/117
Czech Republic (IRSN, 2020 a)	Large international collaboration through platforms (e.g. SITEX.Network, IGD-TP, Club of Agencies,..), NEA RWMC, IAEA, URF, WENRA etc.) and bilateral collaboration Involvement in the Joint research programmes, EJP (eg. EURAD, MELODI,..)	Involvement in the international projects, getting data, information, international reviewers Discuss issues, share data, results, information, seminars	In all areas of radioactive waste management		The import of RAW is prohibited by Section (§) 7, paragraph 3 of the Act No.263/2016 Coll. – Atomic Act. No shared disposal facilities can be sited in Czech Republic The use of shared facilities abroad is not forbidden, it has to follow restrictions defined in 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

	History in international collaboration	**Ways of collaboration interested in**	**Topics of interests**	**Could provide assistance in**	**Legalities or policies to consider**
Denmark (IRSN, 2020 a)	Cooperation in the form of knowledge management takes place through a.o. Club of Agencies, ERDO-WG, the EURAD programme and bilaterally (mainly Norway, Sweden and the Netherlands) Some waste incinerated in Sweden on a commercial basis, and we are assessing the opportunity of melting metallic waste and re-use of spent sources ERDO projects	Both multilaterally – as in the ERDO framework – and bilaterally, on knowledge sharing and specific sharing of methods, technology, services etc.	Cooperation and knowledge sharing on characterisation, waste descriptions/waste inventories, RD&D-projects, WAC, safety analysis, repository concepts etc. Also sharing of methods, technology (e.g. mobile equipment) and competences		In the Danish Parliamentary resolutions from 2003 and 2018 it is specifically mentioned, that an international solution for 233 kg of spent research reactor fuel – the only fuel in the Danish waste inventory – should be sought
Finland (MEE, 2015)	Participation in international cooperation regarding nuclear waste research. Active in the OECD (NEA) and its working groups and (WPDD) (IAEA) work on safety standards Bilateral collaboration especially with SKB			Several consultancy companies selling consultancy services in research, design and safety assessment field (especially DGR)	No import or export of waste is allowed, some exceptions

	History in international collaboration	Ways of collaboration interested in	Topics of interests	Could provide assistance in	Legalities or policies to consider
France (IRSN, 2020 a)	Incineration of a small amount of Italian wastes in Centraco (Cyclife, plant of Marcoule) Waste packages (vitrified fission products, compacted fuel cladding…) issued by the treatment of foreign spent full in La Hague plant (Orano), stored in La Hague storage facilities (Orano) and awaiting for takeover in the country of provenance of the spent fuel for further storage or disposal			Nuclear characterisation lab of Marcoule (CEA) specialised in U, Pu and LL-β emitters Nuclear characterisation lab of CIME (Orano) specialised in U, Pu, bearing waste Particular spent fuel treatment in the plant of La Hague (Orano) Incineration plant of Centraco (Cyclife) for LLW and VLLW and effluents Melting of LLW and VLLW metals in the plant of Centraco (Cyclife) IERs conditioning in epoxy resin matrix by Mercure mobile equipment (Cyclife) WM routes strategies and methods (Orano) Conditioning technologies for sludges, IERs and effluents (EDF, Orano) Conditioning technologies for organic solvents and contaminated oils (CEA, Orano) Storage concepts and methods of IL and HL wastes (CEA, EDF, Orano) Disposal concepts and methods for VLL-, LL-, IL- and HL- wastes (Andra)	Entrance of foreign wastes for characterisation and treatment is permitted as long as the wastes themselves and induced wastes, are eventually sent back to their country of provenance Storage of foreign wastes is permitted in France Disposal of foreign wastes is forbidden

	History in international collaboration	Ways of collaboration interested in	Topics of interests	Could provide assistance in	Legalities or policies to consider
Germany (IRSN, 2020 a)	Reprocessing of SNF Treatment and conditioning of LILW using mobile solutions of GNS Joint work for dismantling of experimental nuclear reactor DIORIT Joint research programmes	Joint research programmes as well as bilateral informational exchange.	Long-term stability of SNF Radionuclide transport in the environment Characterisation, treatment and conditioning of problematic nuclear wastes Development of waste management concepts Sustaining competence in nuclear waste management	e.g. GNS mobile solutions	There is a law in Germany that no nuclear waste originating from German nuclear facilities can be sent abroad, but has to be treated and disposed of in Germany No shared solution is applicable in case of disposal.
Greece (IRSN, 2020 a)	EU-projects, use of commercial facilities outside Greece	Funding from the EU for the development of a mobile lab for this issue would be helpful	For predisposal management, for example incineration, conditioning of sources of category 1 and 2, super compaction A country with larger amounts can develop a specific facility and then, this country can accept waste from other countries for treatment and conditioning	There are needs for treatment of waste i.e. incineration of liquid waste, super-compaction of metals, melting of activated and contaminated lead, possibly dismantling of high activity disused sources Furthermore, after the development of the technique for characterisation, sorting and segregation of raw historical waste we can share this solution with others	According to the Presidential Decree 122/2013, shared solutions , including disposal, could be feasible
Hungary (IRSN, 2020 a)					No shared program in Hungary

	History in international collaboration	**Ways of collaboration interested in**	**Topics of interests**	**Could provide assistance in**	**Legalities or policies to consider**
Italy (Italian government, 2018)	Participation in EU and IAEA projects Active in ERDO-WG		Promote the development of a shared disposal		
Lithuania (IRSN, 2020 a)	Lithuania has no shared competences, methods, technologies and/or facilities of radioactive waste treatment, storage or disposal (or something else related to radioactive waste management), with other states		The disposal of spent nuclear fuel (SNF) from Lithuania in geological repository in other country		According to Lithuanian Law on Radioactive Waste Management the import of RAW and SNF from the other countries is not allowed
Netherlands (IRSN, 2020 a)	Witrification of SNF in France and UK Siempelkamp and Studsvik for metal melting International collaboration through organisations (e.g. IGD-TP, ERDO, NEA, IAEA) and bilateral collaboration (e.g. Spain, Denmark…) European joint projects Regulatory authorities have shared knowledge related to radioactive waste management with other countries	Continue as so far, sharing research capacity and results through international platforms	Option for shared GDF On-going operation with France in reprocessing and pre-cycling EPZ fuel There are several on-going joint research projects through different platforms e.g. EURAD, ERDO	The Netherlands is also willing to help other countries in waste treatment	A dual-track strategy, a national route towards disposal will be developed and the possibility of collaboratiion with other European Member States in establishing a disposal location will not be excluded
Poland (IRSN, 2020 a)	European research programmes	Sharing the knowledge, education, exchange of information, participation in joined programmes, international initiatives	Construction of repositories, development of waste management schemes, characterisation of waste, as well as social activities for the acceptance of new solutions		

	History in international collaboration	**Ways of collaboration interested in**	**Topics of interests**	**Could provide assistance in**	**Legalities or policies to consider**
Portugal (IRSN, 2020 a) (COMRSIN, 2018)	European research programmes Research reactor fuel returned to the USA	Exchange of students, researchers, trainers, technical personnel, others Scientific improvement, better technical solutions and sharing of experiences and human resources training	Solutions already used by other advanced countries can be beneficial Some radioactive wastes could be managed by other countries with more technical support		Shared solution not allowed
Romania (IRSN, 2020 a)	Expedition of solid and organic RW generated by Cernavoda NPP operation to be processed at an European operator European research programmes	Only at the R&D level Common R&D programmes	Developing treatment/conditioning technologies for the RW categories specified at Q11 (SIERs with high C-14 content, aluminium &beryllium waste, irradiated graphite, long-lived disused sealed sources)		Shared solution not allowed
Slovak republic (IRSN, 2020 a)	Slovak WMO has quite rich skills in processing of RAW from abroad (Czech Republic, Germany, Italy)	Slovak DGR program is in its initiation phase Memorandum of Understanding between SÚRAO (Czech WMO) and the JAVYS (Slovak WMO) gives a possibility to Slovak WMO utilize capacities of underground research facility Bukov (Bukov URF**)** and as well to share JAVYS skills in decommissioning	In case of research for DGR there are no sufficient national capacities and it will be fully recommended to provide shared research in common areas with countries with similar nuclear programme (e.g. Czech republic and Hungary in case of SNF)	WMO provide services - waste treatment on commercial basis	Only possible to dispose of radioactive waste which has been produced on its own territory - with some exemptions Any import of radioactive waste is prohibited - with some exemptions The disposal of radioactive waste in another member state or third country, is possible on the basis of an international treaty Monitoring dual-track

	History in international collaboration	Ways of collaboration interested in	Topics of interests	Could provide assistance in	Legalities or policies to consider
Slovenia (IRSN, 2020 a)	Krško NPP constructed jointly by Slovenia and Croatia now operated jointly Spent fuel from TRIGA research reactor was shipped to the US Krško NPP is regularly using services of RW incineration in Studstvik Recently the RW was sent for melting With IAEA several TC activities were implemented : covering the needs on PA/SA, planning, R&D activities, treatment of RW from small producers (Co sources, radium applicators, smoke detectors, …)	Joint RD&D programmes for small or early stage disposal programmes for HLW and SF would be beneficial Already established cooperation on the basis of waste management organisations, where regular technical meetings are organised, should be expanded and enhanced between WMO, RD&D and TSO community with cooperation and exchange of knowledge or use of services for RW and SF management	Sharing of treatment and conditioning facilities for LILW from nuclear or non-nuclear applications and sharing of encapsulation plant capabilities is also one of the sharing options that can be followed by potential regional disposal in one of the EU countries		Management of radioactive waste (RW) and spent fuel (SF) Krško NPP are joint responsibility Concept of shared facilities and regional cooperation in waste management, including the dual-track approach is implemented Export of the SNF and HLW is an acceptable solution
Spain (Ministerio de Industria, Turismo y Comercio, 2006)	At international level there is close collaboration in the field of R&D, both through the EU Framework Programmes – and specifically within EURATOM – and through bilateral or multinational agreements	Maintain a presence in suitable international forums, with preferential attention to the NEA and the EU, in the generic aspects of mapping out and making arrangements for these projects			

	History in international collaboration	Ways of collaboration interested in	Topics of interests	Could provide assistance in	Legalities or policies to consider
Sweden (SSM, 2015)	Active in multilateral and bilateral collaboration projects Member of the IAEA and OECD/NEA, involved in WENRA, HERCA, INRA Industry has a long tradition of active international technical cooperation in the form of exchanging experiences, contributing to development of international regulatory frameworks, and taking part in international work Joint research projects in SKB's underground laboratory at Äspö SKB's cooperation with Posiva in Finland comprising projects on disposal and canister technology as well as site investigations			Cyclife facility for waste treatment Transport ship Studsvik Nuclear AB (SNAB) provides professional services within waste management, consulting in addition to fuel and materials technologies to the international nuclear power industry	
Ukraine (IRSN, 2020 a)	Mainly as international cooperation and technical support projects from IAEA, European Union, Norway, etc. in three categories: - facilities - activities - documents Return of vitrified HLW from reprocessing of spent nuclear fuel of Ukrainian NPPs with WWER-type reactors in Russian Federation	Ukraine would obtain potential benefit from further information and collaboration with other Member States as regards various aspects of radioactive waste management	e.g. development and sharing of technologies, methodologies, approaches, including those for management of challenging waste		National regulations are fully applicable to the shared solutions. The regulatory framework of Ukraine does not allow disposal of non-Ukrainian RW in Ukraine

	History in international collaboration	Ways of collaboration interested in	Topics of interests	Could provide assistance in	Legalities or policies to consider
UK (IRSN, 2020 a)	NDA works closely with a number of international committees such as the IAEA and the OECD/NEA and also other decommissioning and waste management companies in France, the US and Japan, among others Conducted reprocessing on behalf of other countries, returning equivalent activity amounts to the country of origin. The thermal oxide reprocessing plant (THORP) ceased operating in 2018 and the Magnox reprocessing plant (both at Sellafield) ceased operating in 2020 Participation in EC projects	The Problematic Waste IPT developed numerous studies and gained experience in the challenging waste topic. The group is moving towards an implementation phase where it hopes to enable new or current routes to manage problematic waste. The group has a lot of information to share and will also benefit from other countries' experience	Sharing of information and lessons learned (e.g. characterisation and treatment of mercury, thermal treatment of LILW, including asbestos).	Two-way knowledge is transferred for the development of new waste treatment facilities in the UK, including: • Problematic waste • Thermal treatment of low and intermediate level waste	Disposal of UK radioactive waste overseas is not allowed, but transport to another country for treatment is allowed and waste has been transported from the UK to Sweden and the US for treatment The same regulations specific to the use of processing or management facilities for UK nuclear materials or wastes (There is government policy in place regarding activity substitution in the case of commercial reprocessing (e.g. an equivalent amount of HLW from reprocessing can be returned instead of returning ILW and LLW generated as a result of reprocessing activities) would apply

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