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Innovative solutions for the management and safety of radioactive waste

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Radioactive waste is generated by all activities associated with nuclear energy production, including nuclear power plants and the fuel cycle, as well as research and development activities. In addition, smaller but significant amounts of radioactive waste come from other areas, such as medical diagnosis and treatment, production quality control and scientific research. In Italy, radioactive waste is classified according to its physical state and radioactivity levels, as defined by the Decree of 7 August 2015. Each category of waste requires specific treatment and conditioning processes to minimize its volume and make it suitable for short, medium or long-term storage, final disposal or disposal in accordance with legal standards. The management of this waste requires careful attention to protect workers, the public and the environment from radiological risks. At the national level, waste management is regulated by Legislative Decree no. 45/2014 and Legislative Decree no. 101/2020 and its amendments, together with the ISIN Technical Guide no. 33. This work aims to explore the key technological, regulatory and safety aspects of the management of radioactive waste. It will cover current practices and innovative solutions for waste management.

Keywords: Radioactive waste, waste management, nuclear medicine, radioprotection, waste conditioning

1. Introduction

Radioactive waste is mainly generated from all activities associated with nuclear energy production, including nuclear power plants and the fuel cycle. Smaller but still significant amounts of them are produced in other areas such as medical, industrial and research. In Italy, most of the radioactive waste comes from the country's past nuclear program and is stored in four nuclear power plants, permanently closed in the 1980s (Trino, Garigliano, Latina, and Caorso) and in the decommissioned facilities of Saluggia, Trisaia and Casaccia. Besides these sites, other facilities that use radioactive substances every day generate considerable amounts of radioactive waste. It is important to note that while "energy-related" radioactive waste will decrease once all plants are decommissioned, the production of healthcare-related radioactive waste will continue for many years. This waste requires ongoing management to ensure public safety, protect the environment, and shield workers and future generations from radiological risks, involving several risk and safety issues.

This work will explore the key technological, regulatory, and safety issues involved in managing radioactive waste produced in hospitals, industries and nuclear plants. It will review current waste classification practices, innovative treatment technologies, volume reduction methods and the requirements for safe storage or disposal.

2. Radioactive waste management: risk and safety issue

Assessing and managing the impact of radioactive waste produced in hospitals, industries and nuclear plants is fundamental for the general public, workers and environment protection. In hospitals, the management of radioactive waste involves collection, disposal, identification, segregation within a controlled and restricted area, monitoring and labelling for the activity level. For radioactive waste produced in industries and nuclear plants, risk and safety issue concern the identification of long-term storage solutions for some radioactive that remains hazardous for thousands of years, avoiding that harmful radiation does not escape into the environment. Monitoring potential contamination of soil, water, and air, containment and isolation are essential to prevent the release of harmful radiation into the environment. This requires robust containers and storage facilities designed to withstand natural disasters and other hazards. Radioactive waste is stored in specially designed containers made of materials like stainless steel, concrete and lead. These containers are engineered to withstand radiation, corrosion and physical damage. Before being placed in containers, radioactive waste is often treated and packaged to stabilize it and minimize its volume. Containers are placed in storage facilities that incorporate multiple layers of barriers, such as walls, liners and backfill materials to provide additional protection against leaks and contamination. Isolation ensures that radioactive waste remains separated from the environment and living organisms over long periods. One of the safest long-term storage solutions is deep geological repositories. These are underground facilities located in stable geological formations, such as salt beds or clay layers, that can naturally contain and isolate waste for thousands of years. For shorter-term storage, waste can be kept in secure, monitored facilities above ground. Both containment and isolation require rigorous safety measures, including:

- Regular Monitoring: continuous monitoring for signs of leaks or structural integrity issues. This includes using sensors and inspection techniques to detect radiation levels and environmental conditions.
- Maintenance and Inspections: periodic maintenance and inspections to ensure that all containment and isolation systems remain effective.
- Emergency Preparedness: developing and implementing plans for responding to potential emergencies, such as natural disasters or accidental releases of radiation.

Moreover, transporting radioactive waste to storage or disposal sites poses risks, including potential accidents and the need for secure transportation methods to prevent theft or sabotage. Developing and implementing advanced technologies for safe treatment, storage, and disposal is an ongoing challenge, with innovations needed in waste processing and containment methods. Ensuring compliance with national and international regulations is essential, including adherence to safety standards set by organizations like the International Atomic Energy Agency [1].

3. Management and processing of radioactive waste in Italy

In Italy, Legislative Decree no. 101/2020 [2] sets safety standards to protect individuals from the risks of exposure to ionizing radiation across various sectors, including industry, medicine, research, and exposure to specific natural radiation sources. It also governs the safety of nuclear plants, installations, and activities involving radioactive materials, as well as the management of spent fuel and radioactive waste. The national program about the management of the spent fuel and radioactive waste is established according to the Legislative Decree no. 45/2014 [3] (Italian reference for the Directive 2011/70/EURATOM [4]).

Radioactive waste generated from the operation and decommissioning of nuclear facilities, as well as from the use of radionuclides in industry, medicine, and research, is classified under the Italian Ministerial Decree of 7 August 2015 [5]. The classification is based on the type, the amount of radioactivity present and waste final destination according to five categories: Very Short-Lived Waste (VSLW), Very Low-Level Waste (VLLW), Low-Level Waste (LLW), Intermediate-Level Waste (ILW), and High-Level Waste (HLW) [5]. Each category has distinct management and disposal methods. To ensure safe disposal, radioactive waste must be processed. This processing involves treatment (mechanical, thermal, or chemical) and conditioning (such as immobilization). Any secondary waste generated during these processes must also be handled safely and efficiently. The main objective is to minimize both the quantity and volume of radioactive waste through treatment and to convert it into a form suitable for disposal, or for long-term storage. The choice of processing methods and technologies should consider the waste's characteristics and the requirements for its subsequent management, including transportation, storage and disposal. IAEA Safety Standards set out fundamental safety principles, objectives and requirements for protecting people and the environment, alongside guidance on how to comply with these standards. At the national level, the Technical Guide (TG n.33) [6] defines the safety and radiation protection criteria for the proper and safe management of radioactive waste. The guide follows a graded approach, considering the nature and radiological risks of different waste types, and sets minimum requirements for the packaging of radioactive waste, ensuring its safe management in storage facilities at production sites, as well as in its future transfer to surface disposal facilities or long-term storage at the National Repository.

In Italy, Sogin, a state-owned company, is responsible for decommissioning Italy's nuclear plants and managing radioactive waste, including that produced by industrial, research and medical activities. Sogin is also tasked with the planning, design, construction, and operation of the National Repository and the Technology Park, which are dedicated to the long-term storage and disposal of radioactive waste.

4. Management of radioactive waste produced in hospital

Medical uses of nuclear physics are categorized based on whether they involve sealed (used in radiotherapy applications) or non-sealed (used for diagnostic and therapy in nuclear medicine) radioactive sources.

The 2022 Inail guidelines "Design of a Site for Handling Unsealed Sources and Producing Radiopharmaceuticals" provide practical recommendations, in compliance with Legislative Decree no. 101/2020, for the design of nuclear medicine units, including radiation protection aspects related to contaminated waste.

While managing disused radioactive sources is a key concern in radiotherapy, the production of radioactive waste that requires disposal is typically associated with nuclear medicine. A nuclear medicine unit is divided into therapeutic and diagnostic sections. Diagnostic procedures, such as PET/CT and SPECT/CT scans, require the use of specific radiopharmaceuticals. A nuclear medicine technician, guided by a physician's prescription, prepares the correct dosage of the radiopharmaceutical. After administration, patients wait in a designated room within the nuclear medicine unit for a period aligned with the radiopharmaceutical's pharmacokinetics. During this time, both patients and healthcare workers generate waste, which may be contaminated by common radioisotopes or by radio-activated substances (e.g., induced radioactivity from cyclotrons). The isotopes most used in diagnostic settings include ^{18}F, ^{68}Ga, and ^{99m}Tc, with half-lives of 1.83 hours, 1.13 hours, and 6 hours, respectively. These isotopes are stable enough to not easily evaporate, and their disposal (whether solid, liquid, or gaseous) typically follows a regulatory framework that considers the non-radiological relevance criterion. This criterion is met when the practice is justified, risks to individuals are negligible, and the practice is inherently safe, ensuring no significant chance of non-compliance. Specifically, the non-radiological relevance criterion holds when the effective dose to any member of the public is 10 μSv or lower in all realistic scenarios. Due to their short half-lives (less than 60 days), solid waste contaminated with these isotopes can be stored in a dedicated facility until the radiation concentration decays to safe levels, as determined by a Radiation Protection Expert. This waiting period ensures compliance with the non-radiological relevance criterion. Before disposal, solid waste should be measured with suitable equipment, such as a contamination monitor or gamma spectrometer, to confirm proper waste management procedures. Compact systems that combine contamination monitoring with weight measurement can also be used. A significant challenge arises with liquid waste contaminated by isotopes with very long half-lives (e.g., radioinduced activity from cyclotron use or pharmaceutical synthesis). These isotopes cannot be safely stored for short periods to meet regulatory requirements. In such cases, when the non-radiological relevance criterion cannot be met or the decay time is too long, the waste should be managed by a specialized operator responsible for the transportation and disposal of radioactive materials and waste. Gaseous waste is particularly relevant in facilities with medical cyclotrons for radioisotope production. In such installations, an air monitoring system is necessary to ensure that potential contamination does not release into the environment. The system should have pre-alarm and alarm thresholds to ensure that radioactivity in the exhaust air (after filtration) complies with the non-radiological relevance criterion. If alarm thresholds are exceeded, the air inside the facility must be contained until the activity levels fall below the authorized limit. In a typical diagnostic ward, gaseous contamination is less common. Any airborne contaminants are filtered by high-efficiency filters (e.g., HEPA or activated carbon) installed in the manipulation cells and chimneys, with filters replaced regularly and disposed of once the residual radioactivity has decayed.

Nuclear medicine therapy is a medical specialty that utilizes radiopharmaceuticals to treat various diseases, primarily cancer. ^{131}I, which became widely used in clinical practice during the 1950s and 1960s, remains the main radionuclide in nuclear medicine therapy. In recent decades, new radiopharmaceuticals labelled with radionuclides emitting alpha or beta particles, such as ^{177}Lu, ^{223}Ra and ^{225}Ac, have been introduced. The growing interest in alpha particles is due to their ability to deliver high energy over short distances, which can break both DNA strands and produce a stronger cytotoxic effect on tumour cells. In accordance with Legislative Decree no. 101/2020, if the administered activity of ^{131}I exceeds 600 MBq, the patient must be hospitalized in a protected room, and radioactive fluids must be collected. For all other therapeutic radiopharmaceutical administrations, hospitalization is decided individually by the medical specialist, following consultation with the medical physicist and radiation protection expert. A nuclear medicine therapy unit must provide adequate facilities for both patients and healthcare workers. This includes protective rooms with bathrooms connected to the radioactive waste collection system, spaces for waste storage and decay, radiation monitoring systems for patients and staff, and sufficient shielding. Radioactive waste generated in a nuclear medicine therapy unit primarily includes solid waste (such as waste from patient hospitalization, radiopharmaceutical preparation, biological waste from patients, and surface decontamination), liquid waste (residues from radiopharmaceuticals), and gaseous effluents. Solid and liquid waste from nuclear medicine therapies is typically classified as biological and infectious waste, but it also contains radioactive substances when packaged. Proper separation and collection of waste based on the characteristics and half-life of the radioactive materials are essential.

Solid waste can be stored temporarily before disposal as regular hospital waste, following the authorization guidelines. Alternatively, the waste can be managed by a specialized operator in radioactive materials/waste logistics, who ensures compliance with requirements like labelling or proper packaging. A special register for radioactive waste must be maintained, and includes details of the waste disposal, such as the list of radionuclides in the waste, the activity levels of each radionuclide at disposal time, and the weight of the waste. During hospitalization, patient excreta are collected and stored in decay tanks before being released into the public sewer system. The tank size must be calculated based on the expected isotope quantities and workload. After sufficient decay, spectrometric analysis ensures that activity levels meet regulatory limits, allowing safe discharge into the public sewer system via an automated sampling process.

Legislative Decree no. 101/2020 also mandates the assessment of the effective dose to the representative individual from the release of radioactive waste into the environment. Environmental impact assessments are conducted using models that consider all potential pathways through which radioactive substances might return to humans [16], [17]. The disposal formula is calculated by estimating the released activity and applying screening factors for each release route to ensure non-radiological relevance. Generally, nuclear medicine therapy does not produce significant gaseous radioactive effluents that would challenge compliance with non-radiological relevance. Air exhaust systems in high-risk areas are equipped with high-efficiency or activated carbon filters to trap any gaseous emissions. These filters are regularly replaced and disposed of safely after the decay of residual radioactivity. The unit's rooms are also monitored with environmental radioactivity systems that trigger alarms if radioactivity levels exceed safe thresholds. In some cases, precautionary estimates may be used to demonstrate compliance with radiological non-relevance by following the discharge formula. Recently, alternative waste collection solutions have been introduced, such as toilets with high-efficiency filters designed for ^{177}Lu, offering up to 99.95% filtration. These filters are lead-shielded and can be stored until the decay period is complete, ensuring compliance with the non-radiological relevance standard. This system can be integrated with existing waste storage tanks, offering an efficient solution when the volume and decay time of existing tanks are insufficient due to an increase in radiopharmaceutical therapies.

5. Management of Radioactive Waste in Industrial Activities

Industrial activities generate a range of radioactive waste types that require specific treatment and disposal methods to ensure environmental safety. Key sectors involved include the nuclear industry, which produces waste from facility decommissioning, including metallic parts, resins, sludge, and liquid waste. Fuel reprocessing plants also contribute, creating high-activity liquid waste and solid materials. The oil and gas industry generates naturally occurring radioactive materials (NORM), such as sludge and scale, while industries involved in quality control and food sterilization produce waste from the use of radioactive sources for product irradiation. Additionally, other industrial sectors, such as electronics manufacturing, produce waste from devices containing small radioactive sources. This waste is typically collected, treated, and temporarily stored until a final disposal solution is found. Nuclear industry is a major source of radioactive waste, generated at various stages of the nuclear fuel cycle and during decommissioning activities. This waste includes solids, liquids, and gases, each requiring specific management strategies. A large portion of radioactive waste in the nuclear sector arises from the decommissioning of nuclear power plants, particularly contaminated metal components and irradiated concrete. After decontamination and treatment, some of these materials may be recycled or classified as "normal waste" through a clearance process [18], while radioactive components are conditioned and disposed of according to their activity levels. Waste from reprocessing plants and fuel manufacturing, which is predominantly HLW, may also be treated for recycling, including materials like depleted uranium used in other radioactive applications [19].

The oil and gas industry [20] is another significant producer of radioactive waste, generated both by the use of radioactive sources for industrial purposes and by managing naturally occurring radioactive materials (NORM). This waste can include solids, liquids, and

sludges, each requiring specialized handling and disposal. A primary source of radioactive waste in this sector is the maintenance and decontamination of infrastructure, particularly scale deposits and sludges contaminated with NORM that accumulate during hydrocarbon extraction and transportation. These materials contain radionuclides such as ^{226}Ra, ^{228}Ra, ^{210}Pb, and ^{210}Po, which require specific treatment for safe disposal. Additionally, sealed radioactive sources (such as ^{192}Ir, ^{137}Cs and ^{241}Am-Be) used in industrial radiography and well-logging must be safely disposed of once depleted. Unsealed sources, including radiotracers and radioactive markers, generate contaminated waste that requires careful management. In cases of maintenance or accidents, additional radioactive waste may be produced, which is treated, conditioned, and disposed of according to strict safety standards.
The management of radioactive waste from mining and milling [21] presents significant challenges due to the large volumes of material involved and the presence of long-lived radionuclides, such as those associated with uranium and thorium ores. This waste includes processing residues (tailings), mineralized rocks, process water, and radon and dust emissions. Waste management strategies typically include disposal in surface or underground facilities with low-permeability barriers, engineered covers to limit infiltration, and stabilization techniques such as cementation for ILW and vitrification for HLW. These measures aim to limit radionuclide dispersion and reduce environmental impact and health risks over time. The quality control and food sterilization industries use sealed radioactive sources [22] for product safety and to extend shelf life. Gamma irradiation, often performed using radioactive isotopes like ^{60}Co, eliminates microorganisms and parasites in food products. Once these sources are depleted, they are classified as ILW or LLW depending on their residual radioactivity. The disposal of these sources requires specific management protocols, including shielding and disposal in authorized facilities to minimize risks to both the environment and public health. Radioactive waste in electronics and various other industrial sectors, though often underestimated, poses environmental and health risks. In some instances, electronic devices, medical waste processing materials, and industrial instruments containing radioactive sources have been recycled without proper precautions, leading to contamination [23]. Items like smoke detectors (^{241}Am), emergency exit signs (tritium), and old luminous watches may contain small amounts of radioactive material. While production of such devices has decreased in recent years, older items may still pose a risk, especially if improperly disposed of. The main challenge in managing these wastes is identifying the radioactive sources, as not all are easily detectable. Many were disposed of as regular waste, creating orphaned sources. Once identified, these materials can be decontaminated and treated appropriately to ensure safe disposal.
In summary, industrial radioactive waste comes from a wide range of activities, and each type requires specific treatment and disposal methods to minimize its impact on human health and the environment. Proper identification, handling, and management are key factors to ensuring safety and compliance with environmental regulations.

6. Treatment and conditioning of radioactive waste

The primary goal in managing radioactive waste is to minimize the volumes requiring disposal through effective treatment and decontamination processes when is possible. This involves applying appropriate techniques to reduce the amount of waste generated, followed by conditioning the final waste forms to ensure a safe disposal [7][8] . Each type of radioactive waste follows different processes before the disposal, depending mainly on its nature. Treatment consisting in the preparation of waste to the conditioning phase and/or disposal, reducing the volume with many different techniques [9]:

- *Chemical decontamination techniques.* The objective is to remove contamination on surfaces using water and steam (to dissolve chemical species by eroding and flushing loose debris), strong mineral acids, acid salts, organic/weak acids, alkaline salts, complexing agents, redox agents, organic solvents, detergents and surfactants. Waste removed can be further treated using ion exchange resins (to trap radionuclides) or evaporative processes (to separate liquids from radioactive sludge that is reconcentrated).
- *Mechanical decontamination techniques*. The remotion of contamination is made with techniques such as water flushing, steam cleaning, dusting, CO_2 blasting, wet ice blasting, hydroblasting, ultra-high-pressure water, shot blasting, scrubbing, scarification, drilling and spalling. Also in this case, residual liquid waste can be processed, while solid waste is ready for the conditioning.
- *Other decontamination techniques.* Some techniques categorized differently from the others are the electropolishing, ultrasonic cleaning and vibratory finishing.
- *Cutting and dismantling techniques.* Sometimes, there are big volumes of waste that must be reduced using cutting techniques, for example thermal cutting and hydraulic cutting in combination with mechanical techniques.
- *Remote control techniques.* In some cases, workers cannot operate directly on the waste, and this is due to high level of dose rates. For this reason, there is the possibility that some decontamination techniques can be managed by remote techniques

using robots, drones, remotely operated vehicles (that operate in confined environments under negative pressure) and mechanical manipulators (installed on the hot cells).

After the treatment, before the conditioning, radioactive waste can be additional reduced mainly using two techniques:

- *Compaction.* This is the most used techniques[10], and consists in pressing the waste by minimizing its volume
- *Incineration.* Organic radioactive waste can be burned transforming it in a more stable waste (ashes)[11]. This technique is not accepted by all the countries.

When waste cannot be minimised any further, last step is the conditioning phase. Residual radioactive waste can be immobilized following three methods[12]:

- *Cementation.* This is the widely used method[13], and consists of encapsulation of waste in cementitious matrices to provide structural stability and limit radionuclide migration
- *Bituminization.* Radioactive waste is embedded in bitumen[14], which acts as hydrophobic barrier and limiter of radionuclides migration
- *Vitrification.* Radioactive waste is converted into a glassy matrix through high-temperature processes[15], providing long-term durability and chemical stability. This process is used mainly for HLW radioactive waste.

After the conditioning process, radioactive waste can be disposed following the properly route.

7. Research and innovation in radioactive waste management

Directive 2011/70/EURATOM establishing a community framework for the responsible and safe management of spent fuel and radioactive waste. It explicitly requires that "Member States shall ensure that the national framework require all parties to make arrangements for education and training for their staff, as well as research and development activities to cover the needs of the national programme for spent fuel and radioactive waste management in order to obtain, maintain and to further develop necessary expertise and skills". Dedicated R&D programmes and Knowledge Management activities are usually initiated by the relevant stakeholders at the national level and in addition to this, the Euratom Research and Training Programme has been implemented by the European Commission, under the provisions of the European Atomic Energy Community (Euratom) Treaty, to supplement and coordinate the Member State programmes to perform joint cutting-edge research and to support knowledge generation and preservation. A 5-year framework programme (with a 2-year extension) is implemented via annual or biannual work programmes publishing calls for proposals which are evaluated by independent experts. The selected research projects are then funded up to a duration of five years. As example, Sogin is participating to different EU Research funded projects and among the others the following two are focused on R&D activities for Radioactive Waste Management:

- PREDIS (Predisposal Management of Radioactive Waste): 4 years project ended in August 2024, aimed at identifying, developing, and improving innovative technologies in predisposal of low and intermediate level radioactive waste. The project targeted metallic wastes, liquid and solid organics and concrete waste packages long term monitoring.
- EURAD-2 (European Partnership on RWM): started on October 2024, it is a 5 years project that gathers 120 organisations from across 21 European countries and 23 International partners. EURAD-2 is supporting the Member States in developing and implementing their national RD&D programmes for the safe long-term management of their full range of radioactive waste considering the various stages of advancement of national programmes. EURAD-2's vision is deployed into a set of 18 Work Packages and covers all phases of the Waste Management programme, including predisposal and disposal, through the development of a robust and sustained science, technology and knowledge management programme that supports timely implementation of RWM activities and serves to foster mutual understanding and trust between Joint Programme participants.

In addition to the EU Research funded projects, to solve some specific issues and find solutions for the safe management of specific waste streams existing in some of the Sogin sites, dedicated R&D activities have been conducted on-site, and innovative solutions have been internally developed such as a multiphase (oil/water/sludge) radioactive liquid waste solidification with polymer and cement 0 and the application of direct cementation system for small volume of alpha contaminated aqueous waste 0. Multiphase radioactive liquid waste, characterized by the presence of three different stratified phases (oil, water and sludge), poses significant challenges to waste management because in many cases, due to the presence of hazardous and non-standard components, doesn't exist a suitable treatment and disposal route. To enhance the safe waste management on site and to fulfil the criteria for the future transport to the National Repository for final disposal, a specific test program was developed. It was based on the use of two different solidifying agents: NocharTM polymer for the oily phase and cement for the aqueous one. The design and realization of the mixing system was included in the project. The liquid waste to be managed (approx. 800 l) were produced during past activities conducted in the plant and consisted in a heterogeneous mixture of:

- Organic phase (on average 15% by volume) consisting of exhausted mineral oil stratified above and partly dispersed in the aqueous phase below in the form of an emulsion
- Aqueous phase of cloudy appearance (on average 55% by volume)
- Bottom deposit (sludge) consisting of organic and inorganic particulate, partly dispersed also in the aqueous phase (on average 30% by volume)

The test program conducted at Sogin site, involved the application of high technology polymers manufactured by NocharTM, Inc. (Indiana, USA) to immobilize, by absorption in a solid form, the oily phase of the liquid waste streams and the subsequent solidification of the aqueous phase by using cement powder. The experimental program was developed in three different phases:

- Laboratory tests by using simulated waste (non-radioactive materials)
- Laboratory verification and formula optimization with the real waste stream
- Full-scale trials (non-radioactive materials)

Sogin designed and developed also mixing system that provided the solidification process directly into 220 litres drums preloaded with a fixed amount of liquid waste by using a removable impeller. The final product obtained at the end of the solidification process is a monolithic solid material that can be managed as a solid radioactive waste ready to be conditioned and qualified (both with real tests and numerical evaluations) for the final disposal according to acceptance criteria to the final disposal to the National Repository. Another challenge is to manage small volume of alpha contaminated liquid waste during the pre-disposal and disposal phases. In the Sogin Casaccia Plutonium Plant (IPU) are stored about 310 l of alpha contaminated aqueous liquid wastes (ILW) arose from the past activities conducted in the Plant: REBA Project (that involved TESEO Process and PUREX Process) and from other laboratory activities. Followed by a preliminary evaluation of the possible technical and strategical options to be applied, Sogin selected the on-site direct cementation as the best one. Due to the limited amount of waste a dedicated processing plant has been designed to implement both the treatment and conditioning process in a small volume process system inside a glove box. The design of the drum to be coupled with the cementation system has been included within the project. The characterization of the waste evidenced the presence of two main streams: acidic stream (about 70 l) and alkaline stream (about 240 l). A laboratory scale testing program has been carried out to select the treatment and conditioning materials and to define the main process parameters. The stability and durability of the cemented waste form have been verified through a specific qualification program. A final full-scale mock-up test has been conducted to complete the process and waste form qualification activities. The innovative treatment and conditioning system are realised with equipment and components installed in a small volume process system inside a glove box. The system allows, in an enclosed alpha-sealed environment, to perform semi-automatic handling operations aimed at cementing alpha contaminated aqueous liquid waste and consists in the simplification and reduction of components and equipment normally used in large industrial plants. It offers the nuclear decommissioning sector a solution to treat and condition small volumes of liquid waste without having to build complex industrial plants that involve long authorization procedures, environmental impacts and significant construction and management costs. The process components and the process operation scheme have a great flexibility to be adapted for treatment and conditioning of different type of liquid radioactive waste and the full system has been designed to be easily decontaminated to be reused for future conditioning campaign and finally easily dismantled.

8. Conclusions

The management of radioactive waste requires economic investments and technological innovation in order to guarantee public safety, the protection of the environment, workers and future generations from radiological hazards. Effective containment and isolation are essentials. Optimizing worker protection and safety measures involve: using remote handling and shielded equipment for waste disposal when needed; managing the work environment to minimize the risk of accidents and their potential impact; reducing the need for maintenance in supervised and controlled areas. Additionally, contamination must be controlled and prevented as much as possible. Advances in monitoring technologies, such as remote sensing and automated inspection systems, are improving the ability to detect and address potential issues. Technologies and practices for radioactive waste management are well advanced, but further optimisation can bring more economical, sustainable and environmentally friendly waste processing practices. In addition, some challenging waste streams (e.g. graphite, organic waste, reactive metals and future generation wastes, like molten salt reactors) have not yet a mature and consolidated treatment technologies and RD&D activities are needed to develop solutions for such problematic waste management. Research should be aimed at developing, in a short time, concrete solutions to demonstrate the feasibility of appropriate treatment processes and the possibility of adapting techniques used at industrial level on conventional waste to the nuclear field should be considered.

The needs for R&D are, in most of the cases, common to many countries and the sharing of experiences between countries with more advanced programs and countries that have limited quantities of waste and less advanced nuclear programs should be encouraged. Modifications will be soon introduced in the radioactive waste management program, according to the requests of the European Commission (ref. doc n.2020/2266).

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