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Recent radiation protection activities related to nuclear facilities on the Iberian Peninsula

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A B S T R A C T

Part of the radiation protection in Spain and Portugal is focused on the protection of workers, public and environment due to the influence of nuclear facilities present in their territory (Spanish case) or nearby. Radiation protection is in a process of continuous improvement, with the participation of nuclear facilities, companies and researchers in numerous research projects funded in Spain by the Nuclear Safety Council or other international organizations. This article presents some of the projects in which Spanish working groups have participated. In addition, specific examples of activities related to radiation protection and environmental radiological monitoring carried out in Spain in recent years are shown. Among them are: the development of methods of analysis of environmental samples in case of emergency, real-time monitoring networks for measuring radiation, environmental dosimetry in the environment of nuclear facilities, programs and models of radiation dispersion in case of accident, and the treatment and management of radioactive waste for its clearance.

1. Introduction

Since the early days of Nuclear Fission technology for civil uses, the fundamental safety objective is to protect people an environment against harmful effects of ionizing radiation, as established by the International Atomic Energy Agency (IAEA, 2006). This objective must be achieved assuring the proper operation of the nuclear facilities. To do so, it is necessary to control population radiation exposure and radioactive material releases to the environment in normal or abnormal operational conditions, and also to mitigate the radiological consequences in case of an accidental situation. Governments, facility owners and other organizations must be involved to assure these actions are undertaken.

In Spain, the *Consejo de Seguridad Nuclear* (CSN) (https://www.csn.es) is the regulatory authority in radiation protection (RP). Its primary mandate is to ensure the safeguarding of workers, public, and environment against the harmful effects of ionizing radiation. The CSN is responsible for supervising the safe operation of nuclear and radioactive facilities by licensees and establishing preventive and corrective measures for radiological emergencies, regardless of their source. To accomplish this mission, the CSN conducts evaluations of the safety and radiation protection measures installed in nuclear and radioactive facilities, along with conducting inspections throughout their operational phases. Additionally, the CSN assesses and inspects any activities involving handling, processing, storage, and transportation of nuclear and radioactive materials or any processes that could entail a risk of ionizing radiation exposure. Furthermore, the CSN continuously monitors and controls radiation levels both within and outside of these facilities, including air, water, soil, food, and other mediums, in order to assess their impact on individuals and the environment.

These activities must be undertaken during all the installation's life

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cycle, since the beginning of the nuclear power plant (NPP) operation. Both in normal operation and in the event of accidental situations the radioactive material must be monitored and controlled, until the dismantling phase, that involves different activities with a non-neglected risk of radiation exposure. In Spain there are two reactors in dismantling and one in cold shutdown with authorization for dismantling and with the necessary radiological protection activities for each dismantling task programmed. Moreover, Spain has other nuclear facilities, nuclear power plants, a fuel manufacturing facility and a radiological waste management facility, where the control of radiation is necessary.

The case of Portugal is different because there are no nuclear power plants in its territory. There is only a civil nuclear reactor in the country that nowadays is in cold shutdown. This reactor was operated by the *Instituto Superior Técnico* of the University of Lisbon and is located in its Technological and Nuclear Campus in Bobadela, a few kilometers from Lisbon. The reactor ended its operations in 2016 and all the nuclear fuel (fresh and irradiated) was transferred to the United States of America in 2019. However, it is under the supervision of the *Agencia Portuguesa del Ambiente* (APA) (www.apambiente.pt), which is in charge of the legislative, regulatory and organizational framework in the field of nuclear safety in Portugal.

Despite not having nuclear power plants (NPPs), different Portuguese organizations work on activities related to the environmental surveillance of nuclear facilities in case of emergencies, due to the neighbor NPPs located in Spain. For example, the Spanish NPP of Almaraz (Extremadura, Spain) is on the Tagus river and not far from the Portugal border (about 100 km). Thus, Portugal participates in the RENEB network, for research and large scale radiological and nuclear emergency situations (Monteiro Gil et al., 2017). Moreover, other research groups are working on the development of portable radiation detection systems (Marques et al., 2023) and unmanned aerial vehicles (UAV) (Ramos Pinto et al., 2021) with detectors that allow the measurement of gamma and/or neutron contamination due to a possible accident at a nuclear facility or a terrorist attack using dirty bombs. Moreover, if a medical assessment of the population is necessary, Portugal is also prepared for an emergency thyroid monitoring (Monteiro Gil et al., 2019).

Due to the lack of nuclear facilities in Portugal, the paper is mainly focused on the Spanish activities related to radiation protection. The main research and development projects financed by the CSN or other international institutions, and other routine activities involved in the radiological protection of Spanish nuclear installations are summarized in this paper.

1.1. The Spanish national platform for R&D in radiological protection (PEPRI)

In Spain, there is a long tradition in research and development in the field of radiation protection, which has been carried out both in centers devoted to this specific purpose, or by research workgroups from universities or other institutions. Until 2014, these groups mostly worked individually with little coordination among them, mainly channeled through the Spanish Society for Radiological Protection (SEPR) (https://www.sepr.es) and the Spanish Society of Medical Physics (SEFM) (https://www.sefm.es).

Since 2014 radiation protection research in Spain has been coordinated through the National Platform for R&D in Radiological Protection (PEPRI) (https://www.pepri.es), a platform devoted to the coordination of R&D activities in radiation protection, which involves public and private organizations with interests and research capacity in the field.

Before the constitution of PEPRI, from 2009 to 2014, the total amount of resources dedicated to R&D in radiation protection in Spain was 62.7 M€, including Spanish and European funds. These funds were distributed among different research areas, as shown in Table 1 (PEPRI, 2016). The output of these R&D activities consisted of more than 1,100 publications, 5 patents and other products such as computer programs, courses, etc.

Table 1
Spanish Funding distribution in radiation protection R&D (2009–2014).

Research area	Funding distribution
Detection and measurement of radiation	20 %
Radiobiology and epidemiology	17 %
Radiological protection of the public and the environment	16 %
Radiation protection in medicine	13 %
Radiation protection in emergency exposure situations	9 %
Non-ionizing radiation	8 %
Radiation protection in existing exposure situations	8 %
Radiation protection in planned exposure situations	5 %
Education, training and social aspects	3 %
Radioactive waste management	1 %

PEPRI was established in 2014, promoted by the SEPR and the CSN. PEPRI has the general objective of promoting R&D activities aimed at protection against ionizing radiation, as well as knowledge and minimization of its effects. The specific objectives are the following:

- To promote the growth of the scientific and technological base of radiation protection, by promoting the participation of PEPRI members in R&D activities and training courses.
- To constitute an entity for the coordination of R&D initiatives at national level, which allows the development of knowledge and new technologies, methodologies and tools applied to radiation protection.
- To make suggestions to the National R&D Plan regarding the scientific-technological priorities of PEPRI members.
- To constitute an advisory and coordination committee at national level that facilitates the participation of PEPRI members in international R&D programs related to radiation protection.

Nowadays, PEPRI has a hundred members, including universities, technological and research centers, healthcare institutions and nuclear and radioactive industries, as shown in Table 2.

2. Recent R&D projects on radiation protection carried out in Spain

2.1. Projects with CSN funding

The CSN is one of the main sources of funding for radiation protection research in Spain, it funds research projects with an annual budget of 3 M€, approximately. Among the general objectives that the CSN pursues with its R&D activities, those aimed at improving the monitoring and control of exposure of workers, the public and the environment stand out. Likewise, CSN pursues to have the necessary knowledge to assess the risks associated with future facilities and activities, to carry out innovation tasks aimed at improving its relationship with society, to preserve and to implement available expert knowledge and to better disseminate it.

The CSN Research and Development Plan (CSN, 2022), constitutes the tool to organize the lines of research funded by the CSN, according to

Table 2
PEPRI composition by sector of activity.

Sector of activity	Percentage of members
Universities and research centers	40 %
Health care institutions	22 %
Engineering and service companies	16 %
Equipment manufacturers	9 %
Industry and energy	8 %
Regulators	1 %
Others	4 %

its interests. The CSN approves this plan for a period of five years and establishes the strategic priorities, as well as the most relevant lines of research. For its subsequent execution, the CSN funds various research projects to be carried out by prestigious research entities. In the current R&D Plan, which comprises years 2021–2025, the main strategic lines regarding radiation protection research are the following:

- Radiological protection in planned exposure situations.
- Radiological protection in existing exposure situations.
- Environmental radiological surveillance.
- Radiological protection of the public and the environment.
- Emergency management.
- Dismantling of facilities and site restoration.
- Metrology and dosimetry.
- Radiobiology.
- Radiological protection of the patient.
- Development of computer codes related to radiological protection.
- Radioactive waste management and disposal.
- Security of facilities.

The following sections summarize different examples of the specific projects funded in recent years by the CSN, through the research lines established in the R&D Plan.

2.1.1. RP projects related to the surveillance of the environment and the public

The following projects were focused on improving the radiological surveillance of the environment to assure the RP of the public:

- **Development of software for the deconvolution of liquid scintillation spectra. PR-017–2019 (2019–2021):** carried out by the *Universitat de Barcelona*, with the aim of developing the software DECLAB, for liquid scintillation spectra deconvolution for fast and simultaneous measurement of alpha and beta emitters.
- **Development of common procedures for the laboratories attached to the CSN Environmental Radiological Monitoring Network. PR-037–2021 (2021–2023):** carried out by the University of Seville. It aims to the development of common procedures for the laboratories attached to the Spanish Environmental Radiological Monitoring Network, in any special circumstance which is not necessarily associated with a nuclear emergency. The procedures have a common structure for all the laboratories, and will allow the achievement of a better coordination among them, as well as the provision by the CSN of better information for its decision-making process.
- **IA2-RACOHN project: Analysis of the radiocarbon content in samples of human consumption close to Spanish nuclear power plants. PR-074–2022 (2022–2025):** The University of Cadiz is analyzing the C-14 content of eight plant samples and one animal sample in agrifood facilities close to Spanish NPPs. The sampling will be carried out in a group of 3–4 different locations for each of the power plants, as well as a remote area for the control group.
- **Regulation of the Environmental Radiological Impact Assessment in ecosystems. PR-050–2021 (2021–2024):** carried out by the University of Extremadura. The main objective of the project is the development of methodologies to carry out environmental radiological impact assessments for geoclimatic environments such as those prevailing in Spain, so that it is applicable to sites of nuclear or radioactive facilities (Hernández et al., 2023).
- **XENRAD project: Exposure to ionizing radiation in amphibians: evaluation of international radiation protection frameworks. PR-053–2021 (2021–2024):** carried out by the University of Oviedo. It is framed in the International Commission of Radiation Protection (ICRP) initiative for the Reference Animal and Plants Group. The purpose of XENRAD Project is the study of continuous exposure to low radiation doses (realistic in an exposure context in case of accidental release of radiation into the environment) for amphibians. The interest of this study is especially relevant early in the life cycles of organisms, i.e., embryonic or juvenile stages, more susceptible than adults to radiological damage.
- **Study of the behavior of Lanthanum Bromide gamma spectrometers and adaptation for continuous sampling of particles in air (by direct measurement and on a paper filter). Application of methods for the stabilization of spectra and determination of isotopic activity concentrations. BOE 178, 26th July 2012 (2012–2015):** Carried out by the *Universitat Rovira i Virgili*. It was framed on the R&D projects related with radiological protection. The main objective of the project was to study the behavior of the lanthanum bromide gamma spectrometers in different measuring configurations (direct measurement and on paper filter) for real time gamma spectrometry analysis. This study was motivated by the better resolution and efficiency of these detectors than the given by the NaI(Tl) detectors.

2.1.2. RP projects related to emergency situations

The objective of these projects is the improvement of the emergency response and the RP.

- **Development of emergency procedures for environmental radiological surveillance with plastic scintillators. PR-033–2020 (2020–2022):** This collaboration agreement signed by the CSN, the *Universitat Politècnica de València* and the *Universitat de Barcelona* aimed to the development of procedures for environmental radiological surveillance with plastic scintillators to reduce the quantification time of pure alpha and pure beta radionuclides present in accidental situations in NPPs, where a radiochemical separation is needed to isolate each element for their quantification.
- **ADARVE project: Virtual Reality for training in radiological emergencies. PR-044–2021 (2021–2024):** carried out by the Complutense University of Madrid. This project intends to use a combination of technological advances in the field of computer-assisted learning (virtual reality, stress response modeling, and data capture/analysis) to develop an educational and training tool for the staff in radiological emergencies.
- **MEYER project: Preparation of a National protocol for the evaluation of the I-131 in emergencies. PR-042–2021 (2021–2023):** carried out by Center for Energy, Environmental and Technological Research (CIEMAT) and TECNATOM, S.A., with the aiming to develop a National Protocol for I-131 evaluation in emergency situations. This project is based on the output of the European project on Child and Adult Thyroid Monitoring After Reactor Accident (CAThYMARA, Broggio et al., 2019).

2.1.3. RP projects related to dismantling and site restoration

An increasing number of R&D projects are focused on nuclear decommissioning management, such as:

URACAM project: Mobile laboratory for uranium characterization. PR-071–2022 (2022–2025): The CIEMAT is carrying out this project. Its main objective is to build a measurement system prototype that allows the fast and reliable characterization of materials from activities corresponding to the initial phase of the process of obtaining uranium ore concentrate. In Spain, the activities corresponding to the process of obtaining uranium ore concentrate have been carried out for more than 50 years and consisted of separating the uranium from the rest of the elements by physical and chemical methods, breaking the radioactive equilibrium between the uranium and its descendants. This project aims to build a prototype able to measure uranium in very large amounts of soil and debris, through the measure of the alpha or beta emission of its descendants in a reliable way. In this way, areas with disturbed materials can be detected and their corresponding treatment can be carried out for the final restoration of the uranium mine site.

2.1.4. RP projects related to the exposure assessment and dosimetry

These are some examples of the projects related to the workers and public exposure, and the improvement of their characterization by TLD dosimetry.

- **EDOCI project: Estimation of occupational doses to the eye lens in medical and research centers. PR-015–2019 (2019–2022):** This project was developed by the *Universitat Politècnica de Catalunya* (UPC) and the Foundation for Biomedical Research of San Carlos Clinical Hospital, with the aim to define a methodology and to stablish criteria to estimation of eye lens dose.
- **CALIDOSIS project: Methodology for the characterization and calibration of individual dosimetry systems in terms of $H_p(3)$. PR-075–2022 (2022–2024):** developed by the UPC. CALIDOSIS Project is intended to establish a methodology for the calibration of individual dosimetry systems in terms of $H_p(3)$, based on ISO 4037–3 (2019). As well as to develop a protocol for the characterization of these eye lens dosimeters.
- **DOPEN project: Establishment of a national personal neutron dosimetry laboratory based on trace detectors. PR-028–2020 (2020–2022):** carried out by CIEMAT with the aim to establish a personal neutron dosimetry laboratory based on trace detectors.

2.1.5. RP projects related to radiobiology

Radiobiology is also an important area in radiation protection because it focuses on the study of the biological effects of ionizing radiation on living organisms. In Spain, different groups are working in projects related to this topic.

- **Finding of new biomarkers in biological dosimetry. PR-011–2018 (2018–2021):** This project is framed in the Multidisciplinary European Low Dose Initiative (MELODI) platform (https://www.melodi-online.eu). It was developed by the Autonomous University of Barcelona, with the aim of finding biomarkers that, in biological dosimetry, can be used more quickly and efficiently than classical biomarkers which require cell culture (e.g., dicentric chromosomes) (Lopez et al., 2022; Młynarczyk et al., 2022).
- **Obtaining information on the genetic-molecular bases of the response of cells to low-dose expositions. PR-012–2018 (2018–2021)**: This project is framed in the MELODI platform, and was developed by the Autonomous University of Madrid, the Autonomous University of Barcelona and the *Universitat Rovira i Virgili*, with the aim of obtaining information on the genetic-molecular bases of cells response to low-dose expositions of ionizing radiation (López et al., 2023; Rodriguez-Muñoz et al., 2021a).
- **Analysis of the individual susceptibility to radiation associated with age. PR-030–2020 (2020–2024)**: developed by the Autonomous University of Barcelona, the project analyzes the individual susceptibility to radiation associated with age. It aims to study the risks associated with low and moderate doses of radiation, considering possible individual differences caused by age (Anglada et al., 2020; Rodriguez-Muñoz et al., 2021b).
- **PRONADB project: Preparation of a national protocol on biological dosimetry. PR-076–2022 (2022–2025):** This project is being carried out by *La Fe* Hospital Research Foundation, with the purpose of preparing a National Protocol on Biological Dosimetry. The objective is to coordinate all the Spanish research teams and laboratories that work with the different biological dosimetry techniques applied to ionizing radiation, in order to establish a national interactive rapid response network in the frame of a National Protocol on Biological Dosimetry (González-Bermúdez et al., 2022).

2.2. Projects with European Union funding

Spain also participates in the radiological protection R&D strategy followed in Europe is mainly proposed and coordinated through six interrelated platforms devoted to radiological protection:

- Multidisciplinary European Low Dose Initiative (MELODI)
- European Radiation Dosimetry Group (EURADOS)
- European Platform for Nuclear and Radiological Emergency Response and Recovery (NERIS)
- European Radioecology Alliance (ALLIANCE)
- European Alliance for Medical Radiation Protection Research (EURAMED)
- Social Science and Humanities in Ionizing Radiation Research (SHARE)

A key activity for each platform is the identification of priorities for European research within their respective areas. In order to do so, the above entities worked together in the context of the CONCERT European Joint Program for the Integration of Radiation Protection Research (https://www.concert-h2020.eu). CONCERT program began in 2015 and ended in 2020, as a partnership devoted to research strategy in radiation protection in Europe. It was conducted under Horizon 2020 framework program (2014–2020), aiming at attracting and pooling national research efforts with European Member States in order to make better use of public R&D resources and to tackle common European challenges in radiation protection more effectively by joint research efforts in key areas.

Nowadays, the aforementioned European platforms are involved in the European Partnership for Radiation Protection Research (PIANOFORTE) (https://www.pianoforte-partnership.eu). PIANOFORTE initiative began in 2022 under Horizon Europe framework program (2021–2027). This partnership grounds on previous work, and in particular on the results of CONCERT, but it is still too young to allow an assessment of its results.

Other European platform not devoted, but indirectly involved in radiological protection R&D projects carried out with Spanish participation is the European Association of Metrology Institutes (EURAMET) (https://www.euramet.org). EURAMET is responsible for the elaboration and execution of the European Metrology Program for Innovation and Research (EMPIR), conducted under Horizon 2020 framework program (2014–2020). Nowadays, EURAMET focuses on the European Partnership on Metrology Research program (Metrology Partnership), which began in 2021 under Horizon Europe framework program (2021–2027). The Metrology Partnership program builds on the progress achieved under EMPIR, and aims to contribute to the development of self-sustaining, coordinated metrology infrastructures, with the capacity to continue joint research and innovation after 2030.

2.2.1. CONCERT program projects

The Federal Office of Radiation Protection (BfS) in Germany coordinated the CONCERT program. It had a budget of 32 M€, and launched two calls for projects, in 2016 and 2017. It funded nine projects under Horizon 2020 grant agreement n° 662287, five of them with Spanish partners. The projects with Spanish participation were the following:

- **CONFIDENCE project. Coping with uncertainties for improved modelling and decision making in nuclear emergencies (2017–2019):** CIEMAT and the University of Extremadura were the Spanish participants in this project. CONFIDENCE main objective was to identify and reduce uncertainties in the release and post-release phases of an emergency. The project aimed to close existing gaps in several areas of emergency management and long-term rehabilitation (Raskob et al., 2020).
- **TERRITORIES project. To enhance uncertainties and stakeholders involvement towards integrated and graded risk**

management of humans and wildlife in long-lasting radiological exposure situations (2017–2020): CIEMAT was the Spanish participant in this project. The main objectives of the project were both the reduction of uncertainties associated with dose evaluations and the improvement of the participation of interested parties in risk management, in situations of long-term radiological exposure.
- **ENGAGE project. Enhancing stakeholder participation in the governance of radiological risks for improved radiation protection and informed decision-making (2017–2019):** The Barcelona Institute for Global Health (ISGlobal) was the Spanish participant in ENGAGE, which has been the first major European project entirely dedicated to the participation of stakeholders in the field of radiation protection. The ENGAGE project analyzed and compared stakeholder engagement prescriptions and practices in three contexts: medical exposure to ionizing radiation, emergency and recovery preparedness and exposure to indoor radon (Perko et al., 2020; Schieber et al., 2020).
- **PODIUM project. Personal online dosimetry using computational methods (2018–2019):** UPC was the Spanish participant in PODIUM. The objective of this project was to improve occupational dosimetry by an innovative approach: the development of an online dosimetry application based on computer simulations without the use of physical dosimeters. This PODIUM approach was performed using a combination of (i) monitoring of the position of workers in real time and (ii) the spatial radiation field, including its energy and angular distribution, based on analytical or Monte Carlo calculations.
- **SHAMISEN-SINGS project. Stakeholder Involvement in Generating Science After Nuclear Emergencies (2017–2020):** The ISGlobal and the Autonomous University of Barcelona were the Spanish participants in this European project. SHAMISEN-SINGS aimed at improving countermeasures for nuclear emergency preparedness and providing important knowledge on stakeholder engagement in radiation protection (Vanhavere et al., 2020).

2.2.2. EMPIR and Metrology Partnership projects

Some Spanish entities have participated with different degrees of involvement in several EURAMET programs. The last of them, EMPIR, had a budget of 600 M€ and finished in 2020. Metrology Partnership is the on-going program, with a budget of 690 M€. The following summarizes some of the most relevant projects related to radiation protection, with Spanish participation:

- **MetroERM. Metrology for early warning networks in Europe. ENV57-REG2 (2014–2017):** CIEMAT and UPC participated in this project which aimed to improve Europe's ability to detect and respond to radiological incidents. New scintillation-based spectrometric detectors were characterized using radioactive sources that simulated released nuclear contamination, sophisticated data analysis protocols and databases were developed leading to increased radiological data quality for aiding authority decision making, and developed and tested instrumentation for airborne-radioactivity monitoring using simulated contamination filter sources to confirm their likely performance in an emergency.
- **EUNADICS. European natural airborne disaster information and coordination system for aviation. H2020-723986-EUNADICS-AV (2016–2019):** UPC took part in this project which addressed airborne hazards (environmental emergency scenarios), including volcano eruptions, nuclear accidents and emergencies and other scenarios where aerosols and certain trace gases are injected into the atmosphere. In particular participated in the dose estimation due to both, external exposure (i.e. cloud immersion, deposition inside and outside an aircraft), and due to internal exposure (i.e. inhalation of radionuclides inside the aircraft) to passengers and crew in case of a nuclear accident.
- **MetroDecom II project. In-situ metrology for decommissioning nuclear facilities. 16ENV09 (2017–2020):** CIEMAT carried out this European project in Spain, in the frame of EMPIR program. MetroDecom II aimed to provide nuclear site operators with measurement techniques that can be used to measure radioactivity for planning decommissioning, for segregating and checking waste materials during demolition, and for monitoring the condition of waste packages in radioactive waste repositories. CIEMAT workgroup developed and implemented a novel automatic measurement system named SuperMUM, able to characterize waste packages and large amount of waste materials in a fast and very accurate way by means of gamma spectrometry.
- **FreeRelease project. Transfer of developed pre-selection and free release technology to decommissioning Industries. 20SIP02 (2021–2024):** CIEMAT takes part in the development of this European project, in the frame of EMPIR program. The aim of this project is to transfer the pre-selection and free release measurement technology, developed in the EMPIR 16ENV09 MetroDecom II project, to end-users (e.g. managers of shut-down nuclear power plants and waste decommissioning companies) with different requirements such as throughput (i.e. the amount of measured waste per year) and to maximize the uptake of the technology. To achieve this, the developed measurement technology (including software and hardware) must be adapted according to different end users' needs in terms of modularity, waste categorization and nuclear regulatory requirements, for commercial business.
- **GuideRadPROS project. Harmonization, update and implementation of standards related to radiation protection dosimeters for photon radiation. 22NRM07 (2023–2026):** CIEMAT takes part in the development of this European project, in the frame of the Metrology Partnership program. This project aims to develop standards and dosimetry guidelines that are easily implementable by end users.
- **PREPAREDNESS project. Metrology for mobile detection of ionizing radiation following a nuclear or radiological incident. 16ENV04 (2016–2021):** laboratories in the *Universidad del País Vasco* and the UPC participated. The central goal in this research project was the measurement of ionizing radiation and radioactivity in the environment by means of spectro-dosimetry systems that can be remotely controlled by unmanned aerial vehicles (drones). In addition, fully automated airborne dust samplers were developed, with some of them being created as industrial prototypes. Moreover, passive dosimetry systems were investigated for their suitability for the long-term monitoring of contaminated areas.
- **REMOTE ALPHA project. Remote and real-time optical detection of alpha-emitting radionuclides in the environment. 19ENV02 (2020–2023):** with the participation of the UPC, in this project a novel instrumentation and methods and a sustainable metrological infrastructure for outdoor detection systems is being developed, which can detect remotely alpha-emitting radionuclides in the environment. It is based on the optical detection of alpha particle emitters in the environment by air radioluminescence over a detection range of more than two meters, including the development of the first prototype of a mobile-outdoor optical detection system. Moreover, an unmanned airborne monitoring system (UAMS) will be integrated in the unmanned aerial vehicle (UAV) and the novel alpha radioluminescence detection system developed to scan and obtain an image of the contaminated area. This will lead to real-time collection of traceable radiological data and faster, more reliable information for the decision-making authorities.

3. Specific Spanish activities in radiation protection

In this section some specific radiological protection activities developed by different Spanish organizations are explained with more detail. The examples refer to radiological protection activities undertaken for research, monitoring and routine production.

3.1. Developments in connection with environmental radioactivity measurements

Environmental radioactivity laboratories in Spain support the CSN and regional governments for the environmental radiological surveillance of the country and the radiological protection of the Spanish population and the environment. Since the early years of NPPs operation, these laboratories have mainly focused on environmental monitoring of NPPs and other nuclear facilities under routine operating conditions. However, in recent years new challenges have arisen for these laboratories. For example, the assessment of radioactive contamination in the event of a nuclear or radioactive emergency, where the type of samples could be different and the time of analysis must be as low as possible (Croudace et al., 2016; EPA, 2012, 2009a, 2009b, 2008; IAEA, 1999); or the declassification of radioactive materials in the decommissioning and dismantling of NPPs, that involves the analysis of large numbers of samples and isotopes not covered by routine environmental monitoring programs (IAEA, 2008, 1998).

The decommissioning and dismantling (D&D) of NPPs is one of the present technological challenges due to the management of the waste generated during its development and the potential environmental impact that can produce a waste dispersion into the environment. This is of great relevance not only in the nuclear power generation sector, but also in reprocessing and research plants. Apart from the nuclear fuel, the large part of remaining radioactivity comes from the construction materials and moderators. During the process of D&D, radioactive wastes are generated and they have to be classified for their correct management or declassification according to the activity concentration of the different radionuclides and their chemical and physical properties. The characterization is mainly performed by in-situ measurements, but some samples are analyzed in laboratories. In addition, an environmental radiological surveillance of the surrounding environment must be performed to assure the decontamination of the area and the radiological protection of the public and the environment. For these reasons, the laboratories have to develop and validate fast and reliable procedures for the determination of radionuclides, with detection limits below the ones required by the regulatory body. In addition, it is a bigger challenge because many of the radionuclides present in the D&D process are long-lived radionuclides with low energy radiation (beta, electron capture, etc.) and they require complex chemical separations for their quantification, such as ^{3}H, ^{14}C, ^{36}Cl, ^{41}Ca, ^{55}Fe, ^{63}Ni, ^{99}Tc and ^{129}I (Abelairas Arce, 2021).

Regarding emergencies, different research activities have been developed during these years to improve the existing response capacities. For example, in its Emergency Room (SALEM) the CSN has two advanced Decision Support Systems (DSS): RASCAL (Radiological Assessment System for Consequence Analysis for radiological emergencies; Ramsdell et al., 2015) and JRodos (Real-time Online DecisiOn Support; Raskob et al., 2016). Both DSS are connected to numerical weather provider organizations in real time and they feature advanced atmospheric dispersion models for predicting the dispersion of radioactive contamination, which make it possible to simulate the extent and level of contamination in the event of an accident at a NPP or a radiological event. JRodos also includes modules for integrating monitoring data from environmental surveillance networks and to simulate the effectiveness of different countermeasures to protect the population during the emergency and in the long-term recovery phases. Additionally, several mobile detection equipment based on land and airborne vehicles, have been developed or improved, such as NaI and $CeBr_3$ detectors and CZT (CdZnTe) semiconductor airborne spectrometric detector mounted on unmanned aerial vehicles (UAV) (Vargas et al., 2021).

The automatic surveillance networks perform real-time monitoring of radioactivity in the atmosphere; they consist of several automatic stations with instrumentation for continuous measurement of radiological variables (gamma dose rate, radon concentration, radioiodines, alpha and beta emitters in air) and meteorological variables (temperature, relative humidity, wind direction and speed, precipitation and atmospheric pressure). These networks are generally located in the vicinity of the NPPs. In case of Spain, that is in Catalonia, Valencia, Extremadura and Basque Country regions. For example, the Environmental Radioactivity Laboratory of the University of Extremadura (LARUEX) monitor the radioactive and dosimetric levels in the environment (RAREX network) in quasi-real time and generate warnings to the CSN and the regional government when significant changes occur. These stations are located in the surroundings of the Almaraz NPP, in different points of the Extremadura Community and in several locations in Portugal, close to the Spanish-Portuguese border. Moreover, in 2014 the ALERTA2 building was inaugurated, known as the Spanish-Portuguese Center for Early Warning Networks. The main objective of this project was to strengthen and expand civil protection capabilities, providing a specialized center for early detection and response to possible emergency situations close to Almaraz NPP.

Finally, some analytical methods for the assessment of radioactivity contamination need to be performed in a laboratory, as they require a pre-treatment of the sample, or a measurement with a particular technique. Thus, new methodologies based on the fast analysis and measurement of environmental samples in case of nuclear or radiological emergency have been developed. For example, the ones developed by the *Laboratorio de Radiactividad Ambiental* of the *Universitat Politècnica de València* (LRA-UPV), with some examples shown below.

The LRA-UPV form part of the CSN Sampling Stations Network (REM) and participates in the quality control of the radiological surveillance program around the Cofrentes NPP (PVRA-IN). In these programs, the LRA-UPV analyses the radioactive content of different environmental matrices such as air, water, food, vegetation and soil. Specifically, it determines gross alpha and gross beta indices, the gamma isotopic composition and the content of ^{3}H, ^{131}I, ^{90}Sr, ^{89}Sr, among others. Since 1985, it has been carrying out activities in the field of environmental radioactivity measurement and some of these analyses are accredited according to ISO/IEC 17025 standard (ISO, 2017) by the Spanish National Accreditation Body (ENAC).

In recent years, the LRA-UPV has been participating as a support laboratory in the event of a radiological emergency in coordination with the Valencian Agency for Safety and Emergency Response (AVSRE) of the Valencian Regional Government within the Special Radiological Risk Plan of the Valencian Community (DECREE 114/2013). With this objective, the LRA-UPV is developing rapid radiochemistry methods to identify and quantify radionuclides dispersed in the environment in the shortest possible time thanks to collaboration agreements with the AVSRE. A normal procedure for a pure alpha or pure beta emitter in an environmental sample could take more than a week for activity quantification. For this reason, the laboratory is modifying its routine methods and developing new ones to reduce the time of analysis and assess the contamination in few hours or days with accurate results.

As a result of these projects, the LRA-UPV established a methodology for a fast response in case of a radiological emergency according to the recommendations of international organizations and safety guides (Fig. 1). In particular, screening techniques to identify the origin of the radioactive emission were implemented, taking into account the main environmental matrices (air, water, soil, vegetation, food, building materials, etc.) and isotopes present in NPPs.

In case of an emergency, a real-time monitoring could detect the contamination. In Spain, there are two main networks, REA ("*Red de Estaciones Automáticas*") and RAR ("*Red de Alerta a la Radiactividad*") with instrumentation to measure ambient gamma radiation (ambient gamma equivalent dose rate) and ambient aerosol concentrations: alpha and beta particles, radon and radioiodines. In particular, Geiger-Müller detectors are used for ambient gamma radiation and a pump for aerosol sampling with filters faced to a scintillation detector of ZnS(Ag) for

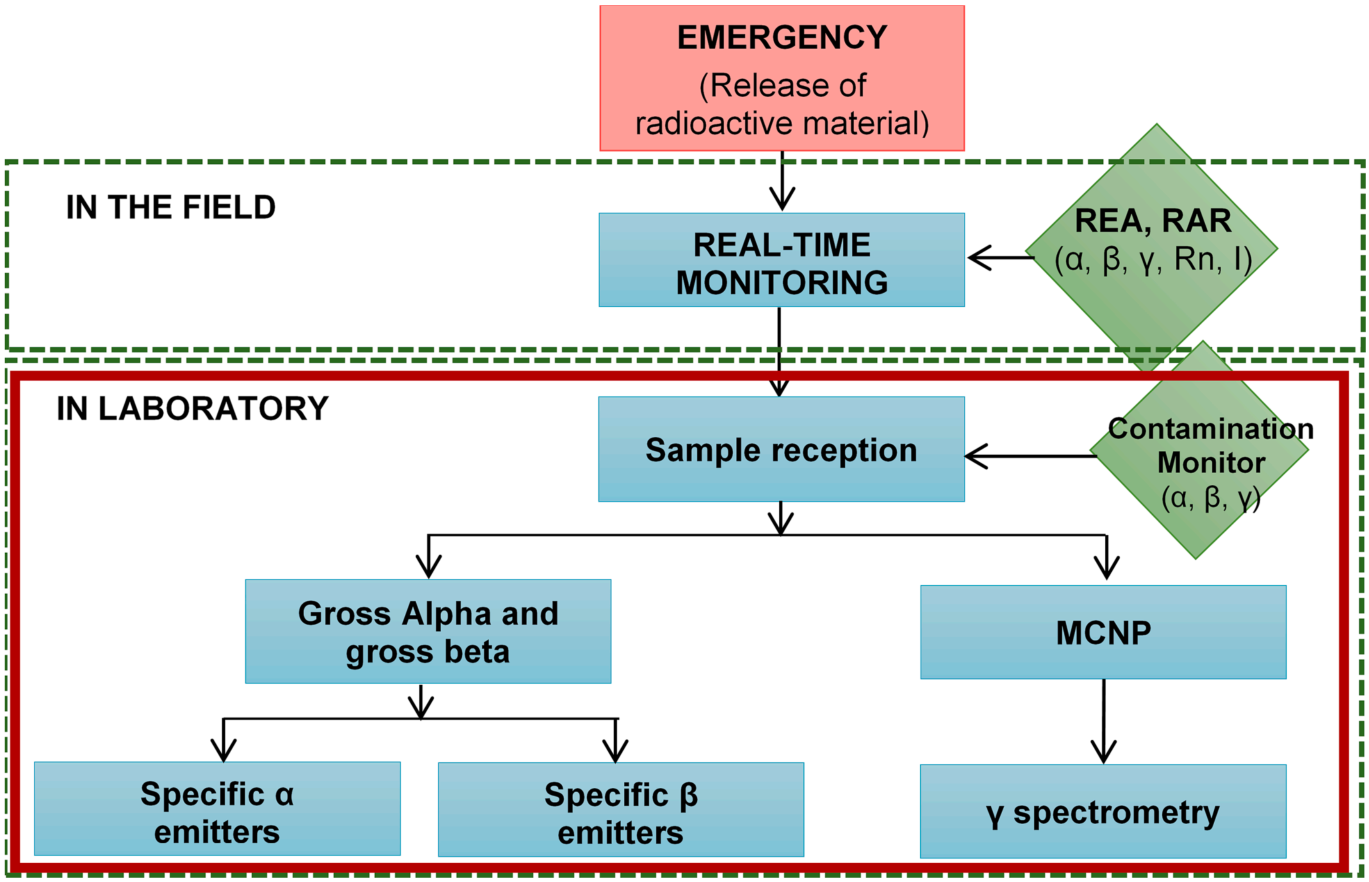

Fig. 1. LRA-UPV methodology for a fast response in case of a nuclear or radioactive emergency.

alpha and beta particles, and NaI(Tl) for radioiodines, among others.

The first step to be developed at the laboratory is a screening measurement with a contamination monitor to know the level of contamination of the sample. Then, taking into account the cps of the sample, a MonteCarlo simulation is performed for the optimization of the measurement by gamma spectrometry and the radiological protection of the laboratory staff (reduction of sample handling and exposure, reduction of dead time, etc.) (Ordóñez et al., 2020; Ordóñez Ródenas, 2020). MonteCarlo code was used for efficiency calibration of the detector with different geometries, type and amount of sample, and distance between the sample and the detector in order to avoid a high dead time in the measurement. Gross alpha and gross beta analysis are also performed to quantify the total contamination by alpha and beta emitters (Sáez-Muñoz et al., 2020, Sáez-Muñoz et al., 2018b).

Once the type of emitter is identified, analysis of specific radionuclides are made using alpha spectrometry and liquid scintillation techniques, which are essential for the measurement of alpha and beta emitters, respectively. In both cases, the measurement requires prior separation of the radionuclide to be determined from the rest of the emitters in the sample. Different techniques for a fast pre-treatment of the sample were selected, such as microwave digestion with acids or fusion method for more complex matrices. Then, a fast radiochemical separation of the radionuclides of interest is performed, mainly using extraction chromatography resins. For example, the LRA-UPV developed different methods for the fast determination of ^{89}Sr and ^{90}Sr in milk, vegetation and aerosol filters by liquid scintillation and plastic scintillation (Sáez-Muñoz et al., 2018a, 2019; Sáez Muñoz, 2019) using deconvolution techniques for ^{89}Sr/^{90}Sr spectra separation. The equipment was calibrated for these particular isotopes and matrices, and these methods were validated with the analysis of reference materials and intercomparison samples organized by the CSN, the IAEA and the European Commission to ensure that they were fast enough and reliable in emergency situations.

The efficiency of these protocols is being evaluated by the laboratory's participation in radioactive emergency drills organized by the AVSRE in recent years. In this way, the LRA-UPV could detect shortcomings and correct any errors detected during the exercises. In addition, the lessons learned during the drills permit the laboratory to be better prepared in the event of a real emergency. For example, the drill carried out in 2021 consisted of evaluating the contamination present in a water sample prepared by an external company to which different beta and gamma emitting isotopes were added. And the scenario in 2022 was part of a large simulation exercise carried out in an industrial zone in Valencia (Spain), where an accident during the transport of nuclear fuel from the nuclear fuel manufacturing company in Juzbado to Cofrentes NPP was simulated. The CSN took also part of the exercise and the laboratory received samples of swipe filters, soil and associated vegetation from the vicinity of the accident. In this case, the samples did not show activity higher than the natural background of the area. In both cases the laboratory issued periodic reports to the AVSRE, at 6 h, 24 h or 48 h, to report the contamination of the samples.

These methods were also applied with good results in the rapid response intercomparison exercises (72 h) carried out annually by the CSN. The LRA-UPV has recently participated in the determination of gross alpha, gross beta, gamma emitters and radiostrontium in milk (2018), water (2019), filters (2021) and food ash (2023).

This shows the growing interest of national and regional organizations in the preparation of the different basic intervention units for nuclear or radiological emergencies. Particularly noteworthy is the interest of the organizations responsible for radiological safety and protection in ensuring that the laboratories involved in their surveillance programs are prepared and capable of providing a rapid and reliable response in emergency situations. This highlights the need to develop rapid test procedures to assess the radioactive content of environmental samples, thus enabling the competent authorities to take measures to protect people and the environment.

3.2. Gamma spectrometry environmental surveillance by real-time monitoring

Since 2006, the Medical Physics Unit of *Universitat Rovira i Virgili* (URV) oversees the analysis of the data registered in the Radiological Surveillance Network of Catalonia (Spain). At the beginning, the Network had 9 Berthold BAI-9850 (Berthold Technologies GmbH & Co. KG, Germany) monitors spread along the Catalan territory to measure alpha, beta, gamma and radon, and 8 Geiger Müller counter tubes (Berthold LB-6500) located at the surroundings of the two NPPs that operate in the area: Vandellós and Ascó. Two river water monitors, both implemented with a Berthold LB/BAI 9110 (Berthold Technologies GmbH & Co.KG, Germany), also monitor the water of Ebro river before and after its flow through Ascó NPP.

In 2007, a nuclear incident marked as a 2 in the INES scale in Ascó NPP (Casanovas et al., 2011) was the starting point of the improvement of the Network. During the incident, the Catalan government and the URV realized that the information obtained with the monitors of the Network was insufficient, and thus, the government committed to enhance the capabilities of the Network updating it with gamma spectrometry monitors. From that moment, and with the collaboration of the UPC, the URV contributed to improve the Network developing equipment and analyzing gamma spectra in real time for the establishment of early-warning alarms.

The Gamma Spectrometry Network was built with the main objective of obtaining data in real time with isotopic information of the possible radiological increments detected. Furthermore, the network is a research field to study the performance of different scintillator detector crystals, different crystal sizes and different equipment configurations to constantly improve the capabilities of the Network. Currently, the Network (XVRAC, 2023) is set with 37 detectors of $LaBr_3$(Ce), SrI_2(Eu) and NaI(Tl) scintillator crystals of 3″x3″, 2″x2″ and 1″x1″ volumes. There are also different configurations: the particulate filter monitors and the monitors that discriminate the radiation between the superior and the inferior half-planes (two detectors, one pointing up and other pointing down. Both are strategically shielded with Pb to allow the separate measurement of the airborne isotopes with respect to the deposited isotopes (Casanovas et al., 2014b)).

Some of the developed monitors were patented: the RARM-F for aerosol surveillance using a particulate filter (Casanovas et al., 2014a) either with $LaBr_3$(Ce) and SrI_2(Eu) detectors, and the RARM-D2 for the surveillance of the upper and lower half-planes (Casanovas et al., 2014b). The RARM-F, which is equipped with a particulate filter, a shielding and an air suction bomb offers a high capacity of detection of the isotopes bound to airborne particles. On the other hand, the RARM-D2 has two shielded detectors directed upwards and downwards, either with NaI(Tl) or $LaBr_3$(Ce). The detectors distinguish the origin of the isotopes, whether they are present in the air or deposited in the soil. In addition, the river water monitors were improved with NaI(Tl) detectors (Casanovas et al., 2013) and were also tested with $LaBr_3$(Ce) and SrI_2(Eu) detectors (Prieto et al., 2018a).

The research group of the URV elaborated various methodologies to ensure the correct performance of the equipment and of the analysis of spectra. The group developed and obtained optimal calibration equations in energy, resolution and efficiency for every monitor type (Casanovas et al., 2014a, 2014b, 2012a; Prieto et al., 2018b; Cerezo et al., 2023) and a stabilization method to avoid peak-shifting in spectra due to temperature changes (Casanovas et al., 2012b). More recently, the group focused on the analysis of gamma spectra, and different methods were developed, based on the regions of interest to subtract the contributions from natural occurring radioisotopes (mainly ^{212}Pb, ^{214}Pb and ^{214}Bi) to follow the activity concentration of artificial radioisotopes (^{131}I, ^{137}Cs and ^{60}Co) in real time (Cerezo et al., 2023; Prieto et al., 2018b). With these methods, it is possible to avoid false positive detections of artificial radioisotopes and to obtain a Minimum Detectable Activity Concentration (MDAC), following the ISO 11929, that varies with the fluctuation of the natural isotopes. The URV also calculated the ambient dose equivalent $H^*(10)$ from gamma spectra obtained with scintillation detectors (Casanovas et al., 2016).

Moreover, the group developed a mobile unit that consists in a 4-wheel traction car equipped with two $LaBr_3$(Ce) detectors (Fig. 2) (Prieto et al., 2020). The objective of the mobile unit is to map the radioactivity in Catalonia, track plumes in nuclear emergencies and search for possible lost sources. The mobile unit calculates in real time the rate of the ambient dose equivalent $H^*(10)$ in μSv/h and activity concentrations in Bq, Bq/m^2 or Bq/m^3, of ^{212}Pb, ^{131}I, ^{214}Pb, ^{214}Bi, ^{137}Cs and ^{60}Co depending on the source term geometry.

Lately, thanks to all the knowledge and experience gained over the years, the group won various competitive international tenders of IAEA projects to supply equipment and assistance to build radiological surveillance networks in the countries of Uruguay, Paraguay, Argentina and Mexico. Each of these countries were supplied with various particulate filter monitors (RARM-F) and the group supervised the set-up of the monitors on field. The URV is in charge of the remote maintenance of the equipment and the remote scientific supervision which includes the continuous analysis of measured gamma spectra and the evaluation of the radiological significance of the data studied for each network (external auditor functions) applying the techniques developed for the gamma spectrometry network of Catalonia. Daily reports are generated on the environmental radiological quality and on the equipment conditions to notify any possible detection of artificial isotopes or equipment malfunctioning. The local staff that supervises the maintenance of the Networks is also trained by the URV with specialized courses about the detection and analysis of data in real time obtained with gamma spectrometry scintillation detectors.

3.3. Environmental dosimetry with passive detectors

In Spain, the environmental radiological monitoring program around NPPs is composed of the network implemented by the NPP operators at the sites and in their zones of influence, as well as by site-specific control program implemented by the CSN and nationwide monitoring networks managed by CSN. In particular, environmental dosimetry is in most cases based on active monitors that provide ambient dose equivalent rate values. Complementary to the use of active dosimetry or spectrometry systems, passive area dosimetry systems are also used. Passive dosimetry is of special interest when monitoring of a very large number of measuring places is needed or the use of active instruments is complex (missing infrastructure or harsh environmental conditions). Thermoluminescent dosimetry (TLD) is one of the most used passive dosimetry systems in Europe (Duch et al., 2021).

In the case of Ascó and Vandellós NPPs, located in Catalonia, the Government of Catalonia (under contract with CSN) runs a specific program, parallel to the NPP owner's programs. Contracted by the Government of Catalonia, during the last decades, the Laboratory of Thermoluminescent Dosimetry of the UPC has been in charge of the measurement of the environmental dosimetry around the NPPs of its territory with passive detectors.

The dosimeters are sent quarterly to the two Catalan NPPs in use: Ascó NPP (with 2 pressurized water nuclear reactors) at about 170 km road distance from the city of Barcelona, and Vandellós II NPP (1 pressurized water nuclear reactor) at about 140 km road distance from Barcelona. The Vandellós I site, now currently in the latency phase after its partial dismantling, is also periodically monitored. Since the UPC's Laboratory of Thermoluminescent Dosimetry is located in Barcelona, transport of dosimeters to the measurement sites takes few hours. The transport dose is measured in combination with the background dose by

Fig. 2. Mobile unit with two $LaBr_3$(Ce) in a retractable platform coupled on the car roof developed by URV.

using passive dosimeters of the same type. During the measuring period, the transport (and background) dosemeters are kept in the Government of Catalonia's premises where only the natural background radiation level is expected. The exposure time is approximately three months.

Although initially the dosimetry system was based in ^{7}LiF:Mg,Ti, since 2014 the gamma ambient dose equivalent, $H^*(10)$ is measured by using ultra-sensitive LiF:Mg,Cu,P thermoluminescent detectors (TL). Each dosimeter has six TL detectors placed an in-house holder for environmental dosimetry. To control thermal fading of the TL detectors, three of the TL detectors were irradiated to a known reference dose. Before each irradiation, the detectors were annealed at 240 °C for 10 min in a Könn LAB-01/400 oven. The detectors were read using a Harshaw-Bicron M5500 hot gas reader. The heating cycle consisted of two stages, i.e. a preheating phase at a temperature of 160 °C for 10 s and a reading phase of 26 s from a temperature of 160 °C up to 250 °C at a linear heating rate of 4 °C/s followed by a constant temperature plateau of 250 °C. Individual calibration factors were established for each detector and stability checks are performed periodically with a ^{137}Cs beam. The estimated uncertainty of the system is around 16 %, with a coverage factor corresponding to a 95 % confidence level. The Laboratory is accredited by ENAC since 2002 according to ISO/IEC 17025 (ISO, 2017) in the range of 1 μSv to 1 Sv. The characterization of the dosimetry system was carried out at the UPC secondary calibration laboratory, which is also accredited by ENAC.

The system has been validated in different national and international intercomparison exercises (Duch et al., 2008; Dombrowski et al., 2017; Hranitzky et al., 2023), with satisfactory results in all cases. In particular can be highlighted the participation in the last IC2021area intercomparison organized by EURADOS (Hranitzky et al., 2023). The EURADOS intercomparison IC2021area was carried out between May 2021 and April 2022 for 66 participating passive $H^*(10)$ area dosimetry systems from 47 different institutes and monitoring services. Three measurement conditions were provided at locations of the Karlsruhe Institute of Technology: 3-months indoor, 3-months outdoor and 6-months outdoor. The challenge of this intercomparison was measuring irradiations with low dose radiation on top of the natural background dose. The UPC Laboratory participated for an exposure of 3-months outdoor conditions.

Six dosimeters were irradiated with ^{137}Cs gamma reference radiation: three dosimeters with 150 μSv and three dosimeters with 300 μSv, and another six were used for background subtraction. Despite the challenge of the low reference dose values, the results of the Laboratory met with ISO 14146 response limits (ISO, 2018).

The gamma ambient dose equivalent (including background) in the monitoring sites around NPPs has been in all cases below 1 mSv/year.

3.4. Operational radwaste management. Clearance of metal scrap

In normal operation of NPPs, metal scraps are produced as a result of decontamination activities, cleaning, maintenance, design modifications, etc. In case of the Spanish NPP of Vandellós II, these metal scraps are present since the beginning of commercial operation in 1988.

Until 2011 there were only two waste management streams: (1) conventional path for scraps with radiologically measurable geometry and activity values below natural background; and (2) radioactive waste path for the rest, involving the packaging of containers and their transfer to the final storage facility at the national disposal center. In 2011 the regulatory authority published the Instruction IS-31 (CSN, 2011) defining the technical documentation for a generic clearance authorization process, but it was not until the end of 2012 that Vandellós II NPP decided to undertake a specific project related to metal scrap, concurring with the publication of the Law 15/2012 (Spanish Law, 2012) which set economic taxes on the production and storage of radioactive waste. Prior to the entry into force of this law, several waste conditioning campaigns were carried out on site, generating a significant amount of metal scrap containers including a batch of 23 units containing activity levels that could potentially be cleared according to the applicable legislation at that time, IS-31 (process) and RP-122 part 1 (reference levels) (European Commission, 2000).

In 2013 the Spanish Association of Nuclear Operators (UNESA) issued the guide CEN-36 (UNESA, 2013) describing the clearance methodology, basis for starting the project at Vandellós II NPP. Between 2015 and 2016, 25 clearance units were conformed using 1.32 m^3 capacity metallic containers, with masses between 400 and 950 kg, densities of 0.3 to 1.18 g/cm^3 and filling levels of 60 to 100 %.

However, in 2017, Order ETU/1185/2017 (Spanish Order, 2017), transposing the EURATOM Directive 2013/59 (European Union, 2013), replaced the values of RP-122 part 1, which led to the recalibration of the measurement system (In Situ Object Counting System, ISOCS) in order to adapt it to the new regulations (Fig. 3). Once recalibrated, the clearance units were characterized by gamma spectrometry, measuring each one in 8 fractionated segments to obtain an isotope concentration above the decision threshold with a confidence level limited by the measuring equipment of 95 % (2 sigma) (Fig. 4). For alpha and beta emitting isotopes, scale factors or average activity concentrations related to gamma emitting isotopes such as ^{60}Co or ^{137}Cs were used. To verify that each container could be cleared, the container must meet that the activity index is less than or equal to 1, i.e., the sum of each isotope concentration (*Ci*) divided by its clearance level (*CLi*):

$$\sum_{i=1}^{n}\frac{Ci}{CLi}\leq 1 \quad (1)$$

After the clearance units' measurements and the compliance verification process was completed, the test plan, which describes the entire process and ensures that all the regulatory requirements were met, was sent to the regulator as required by Instruction IS-31.

In 2018, several requests for additional information were received from the regulator, resulting in a rejected container for having a density greater than 1 g/cm^3, subsequently reconfigured. Additionally, the regulator carried out an on-site inspection of the container forming process, resulting in additional requests about justifications on the ability to detect potential hot spots and mass efficiencies of the measurements. Finally, as part of the quality control, a sample of each fractionated segment was taken of 1 container for analysis in an independent external laboratory in order to verify the proper activity estimation process (Fig. 5).

In 2019, the final test plan was favorably approved by the regulator with the following limits and conditions: exclusively for metallic materials, in 1.32 m^3 volume metal containers, and maximum density of 0.8 g/cm^3. With these technical limitations, Vandellós II NPP could only have cleared 8 of the 25 clearance units, so an extension of density up to 1 g/cm^3 was asked to the regulator by extrapolating the mass efficiency ratio against the apparent density. This extension was granted in 2022, adding new conditions to the authorization: clearance unit filling level greater than 50 % and metal alloys with an average maximum atomic number of 26, corresponding to iron. Related to this last condition, the engineering of Vandellós II NPP carried out a study of metal alloys that comply with this restriction; 2 clearance units were rejected for this reason because they were made of galvanized alloys with the presence of zinc.

With these new conditions and prior to the release of the clearance units from the site, an additional quality control check was carried out on 5 % of the batch (2 containers randomly selected), which involved repeating the entire clearance process including package conformation requirements, regulations compliance and measurements verifications.

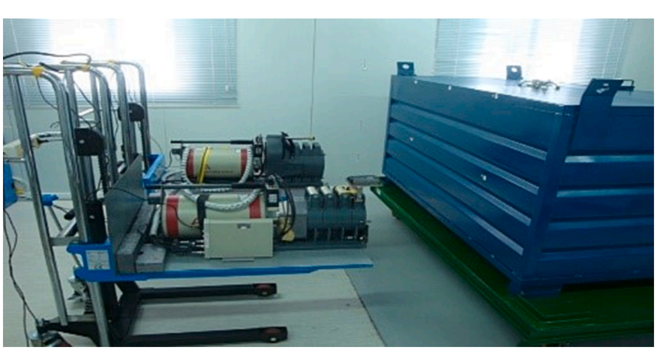

Fig. 3. Measurement system ISOCS.

Fig. 4. Recalibration of the measurement system ISOCS.

Fig. 5. Sampling for analysis in an external laboratory.

Finally, in December 2022, Vandellós II NPP cleared 23 metal scrap containers by transferring the material to a nearby external scrapyard (a total of 26 m^3 and 6500 kg) (Fig. 6).

In this way, Vandellós II NPP could clear 23 stored metallic waste containers with very low levels of activity and manage them as conventional waste in a standard scrapyard, instead of treating them as radioactive waste, shipped and stored in the national disposal center (as it was previously done). This new approach includes segregation, cutting and physical conditioning of metal scrap in containers, as well as its individual radiological characterization by gamma spectrometry and quality control process, in order to demonstrate compliance with the activity limits laid down in the national regulations prior to their transfer from the site to a scrapyard. This whole process must be previously authorized by the Spanish Government with delegation to the regulator.

Therefore, although the clearance projects are very complex and require legal compliance, regulations and administrative authorizations, they have great benefits at administrative and economic levels, through tax savings, transport of dangerous goods by road and the release of space at both the site and the national disposal center.

4. Conclusions and future work

Radiation protection is essential to ensure the protection of the public, workers and the environment against the harmful effects of ionizing radiation, such as those produced throughout the life cycle of nuclear facilities. For this reason, Spain and Portugal have regulations and organizations that ensure compliance with them, such as the *Consejo de Seguridad Nuclear* (CSN) and the *Agencia Portuguesa do Ambiente*, although the activities related to radiological protection in Spain are much more diverse due to the presence of commercial nuclear power

Fig. 6. Loading of containers for departure from Vandellós II NPP site.

plants, unlike in Portugal.

In Spain, the CSN has sponsored, together with other international organizations, the improvement of radiological protection in all its different areas, with the participation of the nuclear power plants themselves, companies in the sector and research groups from national universities. Therefore, the future of R&D in radiation protection in Spain involves various actors, both national and international, responsible for strategic planning and decision-making on research funding. On the one hand, PEPRI and the CSN are the main proponents of the strategy on radiation protection research in Spain, but also regional governments and plant owners undertake different projects to improve radiological protection. On the other hand, regarding the European platforms on radiological protection research, a key activity for each platform is the identification of research priorities for European research within their respective areas, as aforementioned.

European platforms have worked together in the context of CONCERT program. Within CONCERT a Joint-Platforms roadmap for research over the long term, 2030 and beyond, was prepared (Impens and Salomaa, 2019). This roadmap identifies eight different challenges for radiation protection, namely:

1. Understanding and quantifying the health effects of radiation exposure.
2. Improving the concepts of dose quantities.
3. Understanding radiation-related effects on non-human biota and ecosystems.
4. Optimizing medical use of radiation.
5. Improving radiation protection of workers.
6. An integrated approach to environmental exposure and risk assessment from ionizing radiation.
7. Optimize emergency and recovery preparedness and response.
8. Radiation protection in society.

On the future of R&D in radiation protection in the field of fission technology, the strategy that Spain will follow in the coming years depends, fundamentally but not exclusively, on the objectives identified in challenges 5, 6 and 7 listed above.

Some specific examples of activities related to RP in different areas have also been presented, such as, for example, environmental radiological surveillance in the Spanish territory and in the environment of nuclear power plants.

On the one hand, routine measurements of environmental samples (air, water, soil, food, etc.) are carried out in environmental radioactivity laboratories, but also rapid procedures are being developed for emergency response. The future of these laboratories is adapting their procedures to analyze more complex matrices (building materials, wastes, etc.) and developing new methods to determine isotopes present in decommissioning samples, reducing the cost and time of analysis but ensuring their reliability. To achieve this objective, laboratories must continuously invest in research and development of new techniques and acquire more modern equipment.

At the same time, real-time measurements are carried out mainly of gamma emitters, but also of alpha, beta and radon, in the Spanish territory and in the environment of nuclear power plants. Specifically, the Radiological Surveillance Network of Catalonia has been presented, whose detectors are constantly being improved to detect activities above the environmental background in case of emergency. In the future, the network can be upgraded with new measuring equipment and algorithms to create state of the art methodologies to guarantee the detection of artificial radioisotopes in difficult measuring situations. Moreover, new procedures to remotely calibrate in energy and resolution the gamma spectrometry detectors of the surveillance network and developing a new algorithm to analyze gamma spectra based on machine-learning techniques will be applied.

Regarding the environmental dosimetry, passive area dosimetry systems are used together with active dosimetry or spectrometry systems when monitoring of a very large number of measuring places is needed or the use of active instruments is complex. The passive dosimetry is usually performed with TLDs. At present, as it is not expected a high neutron dose contribution outside the borders of the facilities, only the gamma ambient dose equivalent is measured. However, in some cases could be of interest the measurement of neutron doses. Nowadays very few dosimetry services offer the measurement of neutron ambient equivalent dose in Europe (Duch et al., 2021) since special materials should be used together with an appropriate holder. Therefore, future research lines will address this topic.

Concerning the declassification of low-level radioactive wastes, methodologies are being improved in order to manage them as conventional waste in a standard scrapyard, once authorized by the regulatory authority. In addition, these declassification procedures can continue to be applied throughout the life of the facility, for example, during decommissioning, where large quantities of waste will be produced and will need to be managed.

CRediT authorship contribution statement

Marina Sáez-Muñoz: . **Agustín Cerezo:** Methodology, Writing – original draft, Writing – review & editing. **Elena Prieto:** Methodology, Writing – review & editing. **Marçal Salvadó:** Methodology, Writing – review & editing. **Iñigo Vildosola Hernandez:** Methodology, Writing – original draft. **Maria Amor Duch:** Methodology, Writing – original draft, Writing – review & editing. **Anna Camp:** Methodology, Writing – original draft, Writing – review & editing. **Eduardo Gallego:** Writing – original draft. **Juan Gonzalez-Cadelo:** Writing – original draft. **Gumersindo Verdú:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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