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Cutting-edge R&D activities of CIRTEN in support of the Technology Park annexed to the Italian National Repository of radioactive waste

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Summary. — R&D activities taking place at the institutions belonging to Consorzio Interuniversitario per la Ricerca TEcnologica Nucleare are here presented and discussed. A special focus is on Technology Park annexed to the Italian National Repository of radioactive waste.

1. – Nuclear Engineering @ CIRTEN - Politecnico di Milano

Established in 1863, Politecnico di Milano (POLIMI) is the largest Italian university for Engineering, Architecture and Industrial Design with more than 47000 enrolled students (more than 15% foreign students) [1]. It is ranked as one of the most outstanding

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universities in the Engineering field: 1st technical university in Italy, 7th in Europe, 13th in the world according to QS World University Ranking (2023). POLIMI has a 2-years M.Sc. in Nuclear Engineering and a Ph.D. programme on Energy and Nuclear Science and Technology offered in English. The Nuclear Engineering Division belongs to the Department of Energy. Thanks to its facilities and expertise, POLIMI is one of the few universities in Europe that can boast modern and complete equipment for didactic and R&D purposes on several innovative applications of nuclear engineering and ionizing radiations. It is involved in didactic, scientific and technical research activities at international level in the fields of Radiochemistry and Nuclear Decommissioning, Radiation Chemistry, Radiation Measurements and Protection, Health Physics, Radiation Metrology, Electronics and Nuclear Instrumentations, Nuclear Power Plants, Safety and Risk Analysis.

1˙1. *Decommissioning and Radioactive Waste Management @ CIRTEN - Politecnico di Milano.* – Since the Nineties, the *Rad*io*chem*istry and *Rad*iation*Chem*istry (*RadChem*^{2}) research group of POLIMI has actively participated in dozens of International (IAEA CRPs), European (EURATOM JRPs) and National collaborative Projects devoted to the development of cutting-edge research activities. All this has been possible thanks to the well-established *RadChem*^{2} research group expertise and the recently built laboratories endowed with surveilled and controlled areas fully equipped with state-of-the-art nuclear, conventional chemical-electrochemical and radiochemical equipment for manipulation of activated/contaminated samples (including physico-chemical treatments, selective radiochemical separations, electrodepositions), use of radiotracers, determination of radionuclides (*e.g.*, by high resolution gamma and alpha spectrometers with semiconductor detectors, low and super-low level liquid scintillation counters, inductively coupled plasma - mass spectrometer).

The research topics of the *RadChem*^{2} lab that are closely related to the Technology Park at the National Italian Repository for radioactive waste are:

- hydrometallurgical separation of radionuclides from nuclear waste;
- in-situ and in-lab non-destructive and destructive analyses for the radiological characterization of environmental and nuclear/industrial/medical samples;
- decommissioning activities, such as dismantling and decontamination of components;
- treatment technologies for challenging radioactive waste;
- innovative matrices for radioactive waste conditioning;
- radiation damage on materials for nuclear and technological applications;
- education and training in nuclear and radiochemistry topics by innovative didactic methods.

Great efforts have been devoted worldwide and in Europe to make nuclear fuel cycles more sustainable. Despite the technological challenges, Spent Nuclear Fuel (SNF) recycling implies several advantages such as a better natural resources exploitation, the reduction of amount, long-term radiotoxicity and heat load of the ultimate nuclear waste and a smaller environmental footprint of nuclear energy [2,3]. Indeed, advanced fuel cycles offer the prospect of multi-recycling of uranium and plutonium, thus improving

benefits in the resources utilization, and the recycling of Minor Actinides (MA) can also address issues related to public acceptance, proliferation resistance and flexibility for reprocessing of non-oxide and high-burn up fuels. The multi-recycling of U, Pu and MA can be achieved by heterogeneous or homogeneous recycling routes [4,5]. In the first scenario, uranium, plutonium and neptunium recovered by modified PUREX processes can be recycled in present-day light water reactors as reprocessed uranium oxide fuels or mixed oxide fuels, while MA, such as americium and curium recovered from PUREX raffinate, are converted in MA fuels or targets to be used in fast reactors or accelerator driven systems. In the homogeneous recycling approach, instead, uranium and transuranic elements (TRU) are used to produce a single fuel type with a lower MA percentage (1-5%), homogeneously distributed in the reactor core. The homogeneous route is stronger from the point of view of proliferation resistance but technologically more complicated.

Several hydrometallurgical processes have been designed and developed to support the abovementioned recycling route. Downstream of PUREX process, the separation of An(III) could be achieved by the co-extraction of An(III) and trivalent lanthanides followed by their separation in a two-step concept. Later, the more challenging selective An(III) separation from the PUREX raffinate have been attempted in the SANEX like processes by means of tailored lipophilic extractants, taking into consideration also the process simplification. A further concept was based on the selective An(III) stripping from the PUREX raffinate by exploiting the selectivity of hydrophilic complexing agents. Currently, the separation of sole Am(III) from advanced PUREX raffinate is under study for the several benefits it could bring to the subsequent fuel fabrication step. Indeed, the separation of Am(III) from Cm(III) enables to benefit from the positive impact of the subsequent Am(III) transmutation on reducing the long-term radiotoxicity, but also to simplify new fuel fabrication and handling by removing the highly radioactive and heat-releasing Cm isotopes.

The *RadChem*^{2} group has built its expertise in the hydrometallurgical advanced recycling of SNF within this continuously evolving context. Thanks to participating in European projects since 2000 the *RadChem*^{2} group has established solid collaborations with several European universities and research institutes leading to outstanding scientific results. In collaboration with University of Parma, Karlsruhe Institute of Technology (KIT) and Forschungszentrum Jülich (FZJ), the group was able to propose a new reference system for the selective stripping of An(III) to be used in the so called innovative-SANEX process. The PyTri-Diol ligand combined with TODGA molecule provides a new extracting system fulfilling the CHON principle, burnable without producing solid secondary waste, able to efficiently separate trivalent actinides from lanthanides with a fast stripping kinetic and a good radiolitic resistance, that make it suitable to be used in industrial centrifugal contactors battery [6-10]. Furthermore, PyTri-Diol ligand resulted to be of interest also for application in the so-called GANEX (Group Actinide Extraction) process within the homogeneous recycling option to separate Actinides in all the oxidation states. Partitioning studies carried out at the *RadChem*^{2} lab enabled to highlight also the promising properties of the lipophilic derivatives of the PyTri ligand family for the selective extraction of trivalent Actinides in SANEX-like processes [11-13]. The *RadChem*^{2} group has developed also a long experience in assessing the radiolitic and hydrolytic resistance of such extractants, by studying the impact on the extracting performances and identifying the degradation mechanisms [14].

In the last decades, hundreds of nuclear power plants and research reactors have been shut down, and several will be during the next years [15]. Even though great experience and knowledge have been gained so far, continuous efforts for education, training, research

and development actions in the field of nuclear decommissioning and radioactive waste management are required, not only to successfully accomplish the technical challenges, but also to gain public credibility [16].

Decommissioning is a complex and multidisciplinary process which aims at removing regulatory constraints from a nuclear site by fostering safety and environmental protection. It entails dismantling and decontamination of structures and components, followed by treatment and conditioning of the resulting radioactive waste in view of their disposal [17]. The execution of radiological characterization is a common and pivotal task that supports and allows the safe implementation of all these activities. The *RadChem*^{2} lab has earned great experience on this topic within several collaborations and contracts with JRC-EC, ARPA, SOGIN, NUCLECO, ENI, ANSALDO NUCLEARE, FEDERBETON, etc. The environmental radiological characterization should be carried out before, during and after decommissioning to assess if and how the operations have contaminated the site surroundings. For example, topsoil analyses of L-54M nuclear research reactor surroundings were carried out to obtain the reference blank of the forthcoming decommissioning activities [18]. Samples collection, treatment, radiochemical separations, and radiometric analyses of Cs-137, Co-60, Am-241, Eu-152 and hard-to-measure (HTM) Sr-90 were carried out following standardised methods. Moreover, the determination of some challenging HTM radionuclides in environmental samples still deserves the development of always improved methods. A recent research activity has dealt with the optimization of selective radiochemical procedures to purify Cs from interfering elements, among all the isobaric interferant Ba, to allow the non-radiometric determination of the HTM Cs-135 radionuclide [19]. Some innovative radiochemical methods have been investigated and optimized by the *RadChem*^{2} lab to produce internal protocols for the determination of relevant HTM radionuclides (*e.g.*, H-3, C-14, Cl-36, Fe-55, Ni-63, Sr-89/90, actinides...) in real samples from decommissioning (such as irradiated graphite, metallic and cementitious materials, effluents, etc.), nuclear and industrial activities (NORM and TENORM), medical applications and environmental monitoring (including food samples). Most of these radioanalytical procedures have been validated by profitably participating to several editions of the proficiency tests organized by the IAEA. In order to reduce the costs associated to radiological characterization and obtain a larger database, a computational MonteCarlo-based approach has been developed and validated. The latter allowed to estimate the activation of impurities in nuclear graphite and biological concrete of L-54M nuclear research reactor [20,21]. The accuracy of the simulations was improved by developing suitable methods for measuring the impurities concentration in nuclear grade non-irradiated materials [22,23]. Besides radiological characterization, efforts were made to estimate the radiological risks associated to the management and disposal of TENORM wastes [24].

An important operation of decommissioning is the dismantling of structures and components. Thanks to a recent scientific collaboration between the *RadChem*^{2} lab and the Department of Mechanical Engineering of POLIMI, the feasibility of graphite cutting by the abrasive water jet (AWJ) technology has been verified. The process parameters have been optimised with a view to reducing radiation protection and secondary waste management concerns [25]. The consequent step for reducing the footprint of the repository and optimising the recycling of scrap metals in a circular economy perspective is decontamination. An integrated process for surface decontamination of steel, treatment and vitrification of the residues was investigated at the lab-scale [26]. The process validation in a pilot scale facility is now ongoing thanks to the collaboration between the *RadChem*^{2} lab and Ansaldo Nucleare.

To meet the continuous need for research and innovation in the management of the radioactive waste resulting from decommissioning operations, the *RadChem*^{2} lab is an active partner of the H2020 PREDIS (PRE-DISposal management of radioactive waste, grant agreement No. 945098) project, which is focused on challenging radioactive waste still lacking adequate or industrially mature solutions, such as reactive metals, liquid and solid organic wastes. In particular, the project targets the development and optimization of treatment and conditioning technologies. The main duties of the *RadChem*^{2} lab consist in the verification of radiation and water immersion stability of novel cementitious and geopolymeric matrices proposed for the direct conditioning of reactive metals and liquid organic waste. Their mechanical, microstructural, and thermal properties are studied, as well as the preservation of contaminants and waste retention capability. Moreover, dry and Fenton-like wet oxidation treatment of solid organic waste, and the conditioning of the obtained residues in a novel and sustainable geopolymer are studied [27-29]. Over the years, the *RadChem*^{2} lab has developed innovative materials for nuclear applications [30,31], as well validated cementitious matrices commissioned by private companies, such as SOGIN, NUCLECO, ENCO, ISMES-ISTEDIL, etc. When dealing with the disposal of radioactive waste, the assessment of material's radiolytic stability is of paramount importance. So far, the *RadChem*^{2} lab has gathered consolidated experience on the characterization of irradiated materials, in order to determine the radiation-induced changes of their physico-chemical properties and performance [32-35].

The growing national interest and the continuous expansion of nuclear decommissioning and radioactive waste management activities call for the adoption of a robust education and training programme to ensure the availability of well-trained and skilled workers. Besides contributing to the M.Sc. programme in Nuclear Engineering with the "Applied Radiochemistry" course (10 CFU), the *RadChem*^{2} research group has supervised the theses of dozens of M.Sc. and Ph.D. students, thus fostering the training and mobility of the future nuclear specialists. Indeed, the *RadChem*^{2} lab has provided lecturers for the "Nuclear Safeguards" first level Specialization Master and the training course within Italy-China bilateral cooperation project (Sino Italian Capacity Building for Environmental Protection), an Italian Environmental Ministry program dedicated to high formation of Chinese government officers in the fields of sustainable development and environmental management, especially on radioactive waste management and nuclear plants decommissioning [36, 37]. In addition, efforts should be focused on dissemination actions aiming at improving the nuclear awareness of general public as well as at renewing the interest of the youngest towards the nuclear disciplines, to pursue the acceptability of the nuclear sector. In support of such initiatives, the *RadChem*^{2} group is actively involved since 2017 in European E&T projects (H2020 MEET-CINCH and A-CINCH projects). In this context the *RadChem*^{2} group has developed webinars and Massive Open Online Courses for students [38] and general public and new didactical materials by applying innovative approaches in teaching, where the students are the centre of the learning process and their active involvement passes through also gaming and Virtual Reality environment. [39,40].

2. – Nuclear Engineering @ CIRTEN - University of Pisa

University of Pisa (UniPi) was officially established in 1343, it is one of the largest Italian university for Engineering, Architecture and Industrial Design with more than 43000 enrolled students. The University of Pisa ranks highly in the most prestigious rankings, both globally and by discipline. The various ranking institutes put it between

the 200th and 400th positions, thus in the top 1-2% worldwide [41].

Its main strength is academic performance, hence it ranks higher wherever the latter is given more emphasis (*e.g.*, in the ARWU and NTU global rankings, as well as in QS and THE "by discipline" rankings). In the rankings by discipline, the University of Pisa often ranks in the top 100 worldwide in Physics, Mathematics, Classics, Computer Science, and among the top Italian universities in the same disciplines.

UniPi has a 2-years M.Sc. in Nuclear Engineering and a Ph.D. programme on Nuclear Engineering offered in English. The Nuclear Engineering Division belongs to the Department of Civil and Industrial Engineering. Thanks to its facilities and expertise, UniPi is one of the few universities in Europe that can boast modern and complete equipment for didactic and R&D purposes on several innovative applications of nuclear engineering and ionizing radiations. As a matter of fact, the studies in Nuclear Engineering at the University of Pisa, at any level, were always mainly characterized by a sound education in Mechanical Engineering, with a specific attention to all the nuclear matters needed to build the safety culture of Nuclear Engineers.

It is involved in didactic, scientific, and technical research activities at international level in the fields of nuclear decommissioning, structural design and analysis of nuclear components, neutronics, thermal-hydraulics, I&C, radiation protection, safety analysis, medical applications of nuclear technology.

2˙1. *Decommissioning and Radioactive Waste Management-RWM @ CIRTEN - University of Pisa.* – The RWM research group has been a leading player since the 1970s in the field of radioactive waste management and related activities. The main aspects that characterize the research activities mainly concern the numerical-experimental qualification aspects of containers for the storage and transport of radioactive and dangerous materials, the safety design of temporary surface deposits for waste storage, pre-disposal of radioactive waste, etc.

The RWM group has participated and participates in numerous national and international technical tables, such as the IGD-TP platform, the NUGENIA/SNETP technical group, PETRUS consortium, IAEA group on RWM, etc.

Recent research activities are currently aimed at assessing the performance of packaging system, such as CC-440, IP3, Type B package etc., by performing numerical simulation and experimental characterization, and the behaviour of cementitious/concrete-based/polymer materials used for the immobilization of several type of RWs. Particularly the durability and the degradation and aging suffered and caused by compatibility/interaction between waste stream and package material are studied. In this framework the research activity is aimed to optimize and supporting the selection of immobilization waste technologies that must demonstrate the obtained matrices are reliable, durable, and stable thoroughly the institutional storage period.

A proper thermo-mechanical characterization of the cemented matrices of radioactive liquid organic wastes (RLOW) is at present ongoing. Fire is one of the most severe environmental conditions (important design requirements to fulfil) that packaging system stowing RLOW may face during both transportation and storage. The heterogeneous nature of concrete and high temperature exposure makes it difficult for the researchers to assess the exact extent and cause of the deterioration of the concrete structural elements. However, the knowledge of material properties of individual concrete constituents at the temperature exposed may help assess the extent of damage.

Predictive numerical simulations carried out using advanced finite element codes, such as MSC©MARC or ANSYS©, of storage facilities are also carried out by taking into

account environmental, operating and design/extended design basis condition.

The research topics of the LIN lab [42] of DICI are closely related to the Technology Park at the National Italian Repository for radioactive waste are:

- Numerical and experimental qualification of RW transport and storage packaging system
- non-destructive and destructive analyses of concrete/cement-based material for immobilization of nuclear waste streams
- characterization of innovative matrices for challenging radioactive waste
- decommissioning activities, such as dismantling and decontamination of components
- analysis of radiation damage on materials for nuclear and technological applications
- education and training by innovative didactic methods.

In the last decades, most of the operating nuclear power plants and research reactors will face decommissioning and waste management issues. The D&D activities will generate a lot of waste and materials to be safely packed, transported, and stored. To guarantee IAEA [42,43] and international safety requirements are met, packaging system is of meaningful importance. The waste package, made from metals, concrete, polymers or composite materials must be robust, safe, and reliable [43]. The packaging system must be able to guarantee the containment and the confinement (integrity assurance) of the radioactive material or waste (RAM or RW) avoiding any additional dose exposure (respect of ALARA principle). The packaging must be designed according to the activity, and the physical and chemical form of the waste material (*e.g.*, raw solid wastes, wastes immobilized in cement or bitumen and compacted pellets immobilized by grouting).

To verify the main design requirements testing (qualification process) is required [44-48]. In doing that normal and accidental transport conditions set forth by the National Safety Authority and, in general, by IAEA [42] in (Italy (UNI, 2011) and (ENEA, 1987)) are considered. Although great experience and knowledge have been gained so far, continuous efforts for education, training, research and development actions in the field of decommissioning and RWM are required, not only to successfully accomplish the technical challenges, but also to gain public credibility. The DICI Nuclear group has decades of experience in the field of (re)qualification of nuclear packaging system; Lin lab is the only IAEA facility on the national territory for such a type of test.

The LIN lab has long experience on this topic within the collaborations with Sogin, Ansaldo, AGN, Nucleco, Campoverde, CISAM, LemerPax, etc.

Another important aspect of the waste management is to the open issues of the dismantling of graphite piles of the 1st generation gas cooled reactor of Latina NPP (Italy) [49-51]. In this framework, the retrieval of the graphite elements by identifying the way to access the reactor core, developing, and qualifying a suitable remote handling technique, capable for dry extraction of graphite bricks from the top was investigated. A smart solution for removal of the graphite of Latina NPP layer by layer was proposed. The activity was carried out in collaboration with Sogin, and also the University of Bologna. The equipment, in line with similar tool developed for harsh working condition, will allow to minimize the radiological issue posed by the irradiated graphite. The performed numerical simulation by FEM inputting data on fresh nuclear grade and irradiated graphite,

provided the design constraints for the design of proper lifting and gripper tools and handling equipment, for single brick or multi-bricks.

Decommissioning is a complex and multidisciplinary process which aims at removing regulatory constraints from a nuclear site by fostering safety and environmental protection. It entails dismantling and decontamination of metallic systems and components contaminated by Co60, *e.g.*, by Phadec [52], followed by treatment and conditioning of the resulting radioactive waste in view of their disposal. The decontamination in view of decategorization is a key task for all the following waste management activities. The LIN lab acquired experience on this topic within the collaborations with Sogin, Nucleco.

To meet the continuous need for research and innovation in the management of the radioactive waste, material waste immobilization is investigated. The activity aims to provide a preliminary assessment of the thermo-mechanical behaviour of RLOW cemented material or simulant, with a particular focus on the durability of the waste form. And on all the conditions that may deteriorate/degrade the waste form. The degradation may cause, *e.g.*, variations in geometry, porosity, density, etc., and plays a key role in the development of performance models for long-term storage conditions. To investigate the influence of such parameters, also the variability of the waste loadings into the cement matrix was considered and numerically analysed. Experimental activity will be performed as well at LIN Lab of the University of Pisa in collaboration with partners involved in WP5 of the PREDIS H2020 project [53].

Another important topic is the radioactive waste monitoring that is crucial for protecting human health and environment from the harmful effects of radiation exposure. In recent years, there has been growing concern over the potential risks associated with radioactive waste, particularly considering several high-profile incidents such as the Fukushima accident in 2011. Various measures have been taken by governments, regulatory agencies, and industry stakeholders to address concerns related to the safe handling, transport, and storage of nuclear waste [54, 55]. Advanced technologies and monitoring techniques are being used to track dispersion and behavior of radioactive materials throughout their lifecycle. Continuous monitoring of dedicated Radioactive Waste Drums (RWDs) is crucial for a safe storage and disposal. Non-destructive testing (NDT) techniques like gamma counting and spectroscopy, passive neutron counting, and imaging techniques [56, 57] can provide essential information about the content of the drums without any further manipulation, as opening for inspection, destructive inspection etc. Additionally, visual inspections, temperature, and pressure measurement [58] are among the other parameters of radioactive wastes that may be monitored.

Within the activities performed in the frame of WP7 of PREDIS H2020 project [53], it is developed an innovative NDT approach for the continuous and smart monitoring of radioactive wastes. In fact, recently developed Internet of Things (IoT) technologies have made possible to monitor radioactive wastes and the environment by means of a combination of wireless, compact, low cost and low power distributed detectors and open-source software [59-61]. Consequently, a radio transceiver technology provided with radiation sensing detectors has been developed as an IoT solution for the monitoring of radioactive wastes through a network of radio frequency nodes to be installed on RWDs, and it is capable to periodically provide unique identification to waste-drums for chain of custody and radiation monitoring purposes. The approach developed at the University of Pisa was implemented as a distributed Wireless Sensor Radiation Monitoring Network (WSRMN) consisting in micropower end-nodes to be installed on waste drums and communicating through Long Range Radio technology (LoRa). Indeed, IoT technologies offer a cost-effective and efficient solution for monitoring and managing ra-

dioactive waste drums. They can provide real-time data, increase operational efficiency, and enhance safety and security in radioactive waste management facilities [62]. In this solution, LoRa nodes provides a unique identifier (ID) to each RWD, and they periodically measure the gamma-ray and thermal neutron radiation coming from within the packaging material by means of solid-state detectors mounted on a dedicated mechanical support. Data collected from the detectors can be used to assess the structural integrity of the package (particularly of the contained concrete matrix) and in turn ensure that the design criteria are still satisfied over long period of times. LoRa technology was chosen because the radio signals should be able to penetrate buildings and coexist with many other devices. Moreover, nodes —and the attached sensors— must be battery-powered and operate for several years with minimal maintenance. Based on these requirements, data transmission and communication were achieved via LoRa that provides long-range (around 2 km in dense urban areas and up to 15 km in rural areas) and low-power wireless communication. Alternatives, such as passive RFID tags, Wi-Fi and Low-Energy Bluetooth, were discarded due to either high power consumption or limited range. Indeed, the characteristics of LoRa in terms of low power and transmission range make it the best option for wireless data transmission where small amounts of data need to be sent regularly over a wide area [63]. The received data are automatically saved on a non-volatile media (SD card) and transmitted to a web router for cloud storage and further processing.

The prototype provided with off-the-shelf gamma and thermal neutron detectors was tested and characterized at the Laboratory of Nuclear Measurements (LNM) of the University of Pisa to determine its sensitivity and limit of detection. This information is important to evaluate the system's ability to detect an increase in fluence rate resulting from the reduction of the structural integrity of the concrete filling RWDs. Additionally, the system's reliability was assessed by evaluating its ability to perform the scheduled activities, including data collection, data transfer, and entering or exiting deep-sleep mode. The collected data have shown that the sensitivity and limit of detection are suitable for the task of radiation monitoring of RWDs, since they shall allow to detect even small increases in the fluence rate compared to the natural background. Moreover, in addition to its ability to detect ionizing radiation, the system underwent successful testing in terms of minimal power consumption of end-nodes, high communication range in non-line-of-sight (NLOS) conditions, and neglectable susceptibility to electromagnetic interference (EMI).

After the preliminary characterization conducted at the LMN, the LoRa node will be installed on a RWD at a 1:1 scale and placed in a storage configuration that simulates a genuine RWD deposit. This step will enable the evaluation of the system's ability to function correctly and investigate its sensitivity to environmental conditions. Additionally, the study aims to identify potential reductions in the structural integrity of the concrete through radiation monitoring. To optimize the detection process, the study will consider the impact of the material and its aging, the implementation of the entire measurement chain, the possibility of expanding the range of potential measurement types, and the implementation and maintenance costs.

3. – Nuclear Engineering @ CIRTEN - University of Rome

Sapienza University of Rome was founded in 1303 by Pope Boniface VIII, resulting one of the oldest universities in the world. Since its foundation, Sapienza has constantly played a significant role in Italian history and has been directly involved in key

changes and developments in society, economics and politics. With over 120,000 students, Sapienza is the biggest university in Europe. Ten Nobel Prize winners and internationally renowned scientists have taught and/or studied at Sapienza [64].

The first Engineering Study Programme born in Italy was established in our faculty, by Pope Pius VII in 1817. In 1960 the Engineering Study Programmes was reorganized including Nuclear Engineering. Actually, Sapienza has a 2-years M.Sc. in Energy Engineering with a Nuclear Science and Technology curriculum and a Ph.D. programme on Energy and Environment with a Nuclear Engineering curriculum.

Sapienza is classified as the 3rd university in Italy in Engineering & Technology according to QS World University Ranking (2022). Nowadays, the Nuclear Section is part of the Department of Astronautical, Electrical and Energy Engineering. The research activities carried out involve several fields, in particular: i) theoretical and experimental analyses associated with heat and mass transfer; ii) two-phase thermal-hydraulics (also coupled with neutron kinetics); iii) MagnetoHydroDynamics; iv) Severe accidents; v) Thermo-mechanical analyses; vi) study, design, construction and testing of innovative components (test sections, heat exchangers, etc.) and innovative fluid systems for heat removal. Such studies are related to both nuclear fission and fusion applications and applied also in the decommissioning field.

3˙1. *Decommissioning and Radioactive Waste Management @ CIRTEN - Sapienza University of Rome.* – Since the 80's, the Nuclear Engineering Research Group (NERG) of Sapienza has actively participated in several International (IAEA CRPs, NEA CNSI), European (EURATOM JRPs) and national project in the nuclear field. The first application in the decommissioning and radioactive waste management was during the MARS reactor design, with innovative solutions for the dismantling of the primary circuits [65] and considering a possible reduction of the waste production due to the CVCS resins [66]. Recently, in collaboration with SOGIN, an analysis of methods to complement risk assessment and management in decommissioning activities was carried out, with particular attention to the assessment of probability evaluation for the scenarios analyzed, of which the term of damage is known and quantified. This procedure is part of the Probabilistic Safety Assessment (PSA) methodologies. The innovative character of this activity lies mainly in extending PSA-type methods and procedures to decommissioning activities, integrating the deterministic "classical" safety analysis with a probabilistic approach, established practice for decades in the nuclear plants design and assessment. A test case was developed observing the dismantling activities of SAG 46 inside laboratory 42 of the ENEA Casaccia Plutonium plant, based on the THERP method that reviews the sequential analysis of the activities of the operators subdivided in subtask. This activity is characterized by a high level of procedural definition, where operations have a low degree of automation, resulting in a high incidence of the human factor on the determination of the probability of occurrence of an incidental or accidental event. To complement this analysis and to operate a more complete classification of plant conditions, according to a defense-in-dept approach, a preliminary hazard analysis was carried out according to the DOE-STD-1027 methodology. The frequency database was based on the DECO PSA software, making an adjustment of the probability of failure defined a priori according to two different approaches: the first based on the assessment of the frequency of events that occurred in the plant and that led to failures or errors; the second, Bayesian-type, which consists in statistically inferring the probabilities with distributions functions based on the occurrence of failures. A new decontamination technique using liquid decontaminants for concrete structures was analyzed and tested at the Livanova

plant, located in Saluggia (Italy) [67] in collaboration with INAIL, Livanova and WOW. Different decontaminant solutions were tested into the concrete structures contaminated mainly by Cs-137, and, after a period of soaking, treating these liquids with an evaporative concentration process able to concentrate the radioactive liquid waste to a small volume and producing decontaminated water. As a result, this activity has shown a certain efficiency in removing radioactivity from the walls of the structures, ensuring the safety of the workers involved during the operations and reducing the potential risk of exposure in comparison to mechanical removal. In view of the Italian national deposit, it is essential to understand the timing of durability of manufactured products, containers and cement barriers against radioactive waste up to the category Intermediate Level Waste (ILW) and these structures should cover (in total) a period of approximately 300 years. Sapienza in collaboration with INAIL and RINA CSM proposed a project for the evaluation of the state of degradation of all engineering barriers that will constitute the future National Depot, that will be realized in the coming years in Italy. In particular, the activities will be focused on deepening the physical-chemical and mechanical characteristics of the materials that make up these structures, considering all the main causes of long-term damage. Laboratory tests will therefore be carried out to simulate such damage and, on the basis of the results obtained, models will be created to numerically assess the mechanical strength of the barriers over long time periods, in order to verify the overall tightness of the engineering barriers that form the deposit, to demonstrate the adequacy of the resistance values used in the calculations, and assessing the suitability of the barriers for the long-term containment function of the radionuclides. Another study performed (in the framework of the ENEA MOLY project) was the procedure for inserting and extracting molybdenum samples inside the TRIGA RC-1 Casaccia research reactor as well as performing a preliminary engineering design of the automatic handling system of irradiated samples, able to ensure the safety of personnel, with a fully automated operation. This procedure is intended to address the dose problems related to Mo-99 production inside the TRIGA reactor, physically separating the sample from the containment capsule directly inside the reactor building.

4. – Radiation Protection, Radioactive Contamination Modeling and Ionizing Radiation Sources in Medical Applications @ CIRTEN - University of Bologna

The research activities on radiation protection and radioactive contamination modelling at University of Bologna are actually focused on the ongoing development of the GENII-LIN (classified as CCC-0601 in the RSICC repository) as an open-source multipurpose health physics code, aimed at providing a reliable tool to be used for purposes such as siting facilities, environmental impact statements, and safety analysis. The code can handle a wide range of exposure pathways, like external exposure from finite or infinite atmospheric plumes, inhalation, external exposure from contaminated soil, sediments, and water, external exposure from special geometries and internal exposures from consumption of terrestrial foods, aquatic foods, drinking water, animal products, and inadvertent soil intake. The radionuclide environmental concentrations are calculated over time up to the end of the exposure period by numerical models of appropriate transport phenomena through air, deep and surface water, deep and surface soil and biotic transport. Actually, the code has been developed to manage land use and occupation, simultaneously managing up to three soil distinct main areas: residential soils, non-agricultural soils, and agricultural soils. The non-agricultural soils are used only

in near-field scenarios in order to define parameters for arid and humid climate biotic transport. Immediately after the beginning of human use of the soils, the soil reverts to either residential, when the person lives there, or agricultural, when crops are grown there. Each food pathway has its own associated zone of soil, with specific transfer properties, reason why a large number of soil zones can be active in a single simulation. A single soil zone may be composed of up to 4 compartments. The always present surface soil is modeled as a 15 cm thick layer and is the soil portion that can exchange pollutant with the atmosphere by air deposition, irrigation, and particulate resuspension. For most far-field and many near field scenarios, this is the only portion of soil that is used. In those scenarios, where subsurface contamination is present, radionuclides may be contained in waste forms or simply distributed in the deeper layers. Radionuclides, that are simply distributed in the available subsurface soil, may be transferred to the surface soils by root uptake by plants, by physical transport by native animals, or by human activities which lead to redistribution of contaminants from deeper to surface layers. When the contaminants are packaged in a form, they may be released to the deep soil and made available to biotic transfer. The release process is described by the waste package decomposition model. If the deep soil overburden is greater then 0.15 m, one optional intermediate layer is added, located between the surface and deep soils. Any soil layer may also loose radionuclides through harvest removal, radiological decay, and leaching to deeper soil strata. The soil zones corresponding to each food type, animal type, and residential exposure are treated separately.

The GENII-LIN code has been fruitfully used to analyse the consequences of potential releases along research activities commissioned by SOGIN and as routinely adjourned radioactive risk management in accident conditions in nuclear medicine units [68-70].

Another, more recent research topic actually still under development at University of Bologna, deals with the application of Monte Carlo codes to develop digital twins of complex systems in the field of radiation sources modeling in medical applications [71,72] and radioisotope production [73]. With respect to this point, it is worth to recall that with the growing demand of radionuclides for medical applications both for diagnosis and therapy and the increasingly required high-quality standards, it has become necessary to look for new and efficient production systems. Several radionuclides of interest were historically produced in research reactors or were the by-product of nuclear fuel reprocessing activities, but with the increasing shortage of these facilities and the shutdown of several of them, the current production technology relies on a more standard and safely manageable accelerator-target approach, which can also be more freely developed at a commercial level. This new industrial and market related approach makes the tuning of production facilities even more strategic: reliability, safety, timing, product quality, and isotope related extraction issues are becoming mandatory aspects to be analyzed looking at the overall efficiency of the production chain, from the setup of the beamline to the target post-processing. So, this implies that the process must exit from a classical "trial-and-error" approach in favor of a more rigorous production standard definition. One of the methods under development for finding reliable and cost-effective solutions in several industrial contexts is represented by the "digital twin" philosophy of design —the virtual representation of a physical entity of an arbitrarily complex system. For the actual problem, the innovation stands on the analysis of the beam-solid target system model. More specifically, looking at a cyclotron as a beam source (a quite standard one) coupled with a solid target the design involves a quite complex configuration space, such as the source particle beam spectrum characterization, the material composition and characteristics of the target hosting device and details like target tilting, shape, and thickness, all playing a

crucial role regarding the production efficiency of the whole chain. This approach, which is becoming more effective due to the availability of efficient computational tools like the MC code MCNP6 and HPC resources, is quite promising because it opens the possibility of the setup of a holistic optimization process in terms of both geometry and materials and creates a robust approach for experimental production data analysis. Finally, an interesting output is the possibility of a more critical interpretation of the available data on the particle beam cross-sections with the various elements and isotopes that often rely on poorly populated experimental data-sets. This digital twin approach, developed also in a scientific collaboration with private companies (COMECER S.P.A.) perfectly works as a transfer function between the external source characteristics and the post irradiation processing. It makes possible to establish a direct relationship between kind of cyclotron beam characteristics and profiles, materials and, last but not least, the post-processing constraints. In this way, it become possible to establish some formal and rigorous correlation between the physical and technological parameters that define the possible yield of the whole process.

5. – Nuclear Engineering @ CIRTEN - Politecnico di Torino

The Politecnico di Torino - POLITO (`www.POLITO.it`), founded in 1906 from the roots of the Technical School for Engineers created in 1859. It is one of the most important universities in Europe for engineering and architecture studies, strongly committed to collaboration with industry.

POLITO offers a BSc program in Energy Engineering, with an introductory course on nuclear engineering, and a M.Sc. program in Energy and Nuclear Engineering, with a dedicated track on "Sustainable Nuclear Energy". The latter attracts every year a significant number of students, including ERASMUS students from all over Europe. Furthermore, POLITO offers a Ph.D. programme in Energetics, which includes a track on nuclear engineering, focusing on both fission and fusion research. 15 faculty from the assistant professor level upwards work in the Energy Department at POLITO in the field of nuclear power plant design and modelling, nuclear decommissioning studies, reactor physics and core design, fusion reactor modelling and analysis, energy scenario planning, radiation protection, safety and risk analysis for both nuclear and non-nuclear applications.

5˙1. *Modelling activities of residual activation of NNP components and development of dismantling strategies.* – The research activities of the NEMO group involved mainly the development of a four-step hybrid Monte Carlo deterministic calculation scheme for the evaluation of the residual activation in the supporting structures surrounding the core of a PWR, such as the Reactor Pressure Vessel (RPV) and the Reactor Vessel Internals (RVIs) [74]. The scheme was developed for the reactor of the Enrico Fermi NPP, and validated using activation data provided by SOGIN. With suitable modifications, it could be adapted to investigate other PWRs.

The first step of the scheme consists of a Monte Carlo (MC) calculation, whose purpose is to generate the neutron source term according to inputs such as fuel composition and enrichments, core geometry and nuclear data [75]. The second step consists of a set of fixed source MC simulations, in which neutrons are generated according to the previously mentioned neutron source and propagated towards the external structures with the help of variance reduction techniques. In the third step the residual activation of the structures

is evaluated using data provided by the previous steps, such as the integral neutron fluxes and spectra. In the fourth step, a comparison between the calculated values and the measured ones is carried out using the C/M ratio, obtained dividing the calculated specific activities by the measured ones for each point and each isotope considered [76]. The software used for the development of the scheme are Serpent 2 for the MC part and FISPACT-II for the activation part. The overall performance of the scheme is satisfactory, as it provides conservative results without excessive overestimations [74]. The scheme was developed to analyse the thermal shield of the reactor because specific activity measurements were available for that component, but future work envisions the analysis of other parts such as the RPV, the RVIs or the bioshield.

The other topic addressed is the development of a methodology to select the best cutting technology to dismantle a reactor, considering not only advantages and drawbacks of the single cutting techniques, but also site-specific requirements [77]. This activity was carried out in collaboration with the Department of Mechanical and Aerospace Engineering (DIMEAS) at Politecnico di Torino. Initially, the available cutting technologies were analysed and compared considering a set of parameters that are typically important when developing a decommissioning plan, such as the safety, the cutting speed and the amount of secondary waste generated [78]. A value ranging from 0 to 10 was attached to each parameter, taking into account the experience available from the literature. Afterwards, the values are multiplied by the respective weigh, ranging from 0 to 1, that expresses the relative importance of each parameter, as their sum is equal to 1. In this kind of evaluations, the values of the weights are chosen by the stakeholders based on the judgement of a pool of experts, and may change for different decommissioning projects with different priorities. The weighted values of the parameters are then summed to obtain the score of that cutting technique. This score by itself can be misleading, as it does not consider the specific requirements of each decommissioning site, such as the material and thickness of the components that have to be cut, the applicability of a cutting technology to those components, the commercialization readiness and the size/volume required by cutting tool and associated machinery. The issue of the available working space is especially challenging, as some cutting machines can be quite big; therefore, it might be necessary to exclude certain solutions for a specific case, even if they score higher (*e.g.*, avoid a large stationary saw and using a small and flexible plasma torch instead), which is an aspect that the simple weighted score of the technology does not consider. The applicability factors determine whether the selected technology can be used for the specific decommissioning project under analysis or not. This methodology provides a supporting tool for decision making to stakeholders, in the framework of complex, multidisciplinary decommissioning projects [79].

The current work is mainly focused on the application of the previously mentioned calculation scheme to other large components of the reactor, in particular the reactor pressure vessel (RPV). As the RPV has been irradiated for the entire lifespan of the reactor, and various modifications involving the core geometry, the fuel enrichments and the refuelling pattern occurred during this time, the irradiation of the RPV has not been uniform in space or constant in time. Therefore, the final residual activation of the metal is strongly dependent on this rather complicated irradiation history. An optimized approach, based on the definition of a representative operation cycle, is currently being adopted to describe more accurately the local conditions of the RPV at different heights and angular coordinates and provide a more detailed fluence map for the evaluation of the residual activation. This information will be helpful to work in the direction of a more efficient and cost-effective dismantling plan of large components of the reactor.

5˙2. *Treatment and conditioning of spent radioactive ion exchange resins.* – PoliTo is supporting the private company *green-land* (`https://green-land.it/index.php/it/`) in the development of the innovative process HYPEX® for the treatment and conditioning of spent radioactive ion exchange resins (IEXs). The process is currently under qualification by qualified laboratories, to meet the requested specifications by the Italian Regulatory (Guida Tecnica 33, ISIN [80]).

The process consists of three fundamental steps: first, the IEXs grinding to reduce the swelling effect and to increase the homogeneity. Second, the incorporation in a geopolymeric matrix based on metakaolin [81,82], chosen in view of its lack of freeze-thaw problems, its minimal production of radiolitic hydrogen, fire resistance and good capability to immobilize some radionuclides [81]. On top of that, geopolymers have the capacity to incorporate the Boron into their structure [84], whereas cements are negatively affected by the presence of Boron, which can reduce their compressive strength [83]. The final step of HYPEX® is constituted by a hyper-compaction, from a minimum of 100 to a maximum of 300 MPa, of the fresh mixture, to reduce the porosity and final volume. The assets of HYPEX® are simplicity and safety, since both the reaction and solidification of geopolymers occur at ambient temperature, guaranteeing high safety in the operating conditions. HYPEX®, based on existing press such as that of the Westinghouse - HANSA Project [85], is designed to be implemented on a transportable plant, that would allow the transfer from one NPP to other Italian or European power stations. Being the plant reusable, HYPEX® should achieve a low-cost treatment of the IEXs.

5˙3. *Chemical decontamination of stainless-steel materials.* – PoliTo is supporting the *green-land* (`https://green-land.it/index.php/it/`) also in the development of a fine-tuned process (CHEDOX) for the chemical decontamination of stainless-steel materials (AISI 304). CHEDOX draws its principles from the HP/CORD process, developed by Siemens in 90s [86]. The HP CORD process consists of the metallic surfaces treatment (INOX) of the primary circuit of LWRs whose inner surface has been contaminated during the reactor operation lifetime by fission products derived from micro-losses of the nuclear fuel and corrosion products materials activated by the neutron flux. The CHEDOX process aims to efficiently remove stainless steel external micrometer layer thanks repetitive phases of oxidation and solubilization of the oxide layer produced, optimizing the old HP CORD process by increasing its efficiency (high selectivity and low chemical/radiological volume waste) and effectiveness also for wide steel surface components. The effectiveness of the process is based on the use of chemicals having high and low oxidation capacity, with the purpose to first oxidize the outer steel layer and then remove the coherent oxide layer produced thanks to the solubilization. The experimental validation phase, with the adjustment of the chemical conditions of the initial solution and time duration of the cycles, is currently carried out by *green-land* in collaboration with both Energy Department and Applied Science and Technology Department at PoliTo.

5˙4. *Modelling of laser-particle interaction.* – One of the issues in the management of radioactive waste is the presence of long-lived radionuclides, which must be stored in deep geological disposal facilities. In addition to the development and realization of geological repositories, research and development activities can focus on the reduction of the half-life of long-lived isotopes, with artificially induced transmutation. These activities require research on radionuclide separation and transmutation with advanced techniques such as

lasers. The technology for laser treatment of radioactive waste is currently challenging, but thanks to additional developments fostered by research activities it could become an efficient and economic means of transmutation [87].

Another field where laser-induced transmutation could be applied is non-power nuclear applications, *e.g.*, the production of radioisotopes useful for nuclear medicine, since several reactors currently used for their production are being shutdown [88].

From a broader perspective, energy applications of laser-matter interactions are also being investigated in different laboratories all around the world (*e.g.*, the recent progresses in inertial confinement fusion at NIF [89], or the FUSION project at INFN [90]), as well as by private companies (*e.g.*, Marvel Fusion [91], HB11 energy [92]). In the last 15 years, p11B fusion has been effectively induced by means of high-power lasers. In this case, an impressive and not yet explained progression in the reaction yield has been observed to the extent that the reaction has become of interest to the energy sector, where it is being considered as an alternative approach to conventional inertial confinement fusion schemes.

The Energy Department at Politecnico di Torino is involved in the INFN project "FUSION" (FUsion StudIes of prOton boron Neutronless reaction in laser-generated plasma). The aim of this project, started at the beginning of 2023, is to design a new generation of solid targets enhancing the p(^{11}B,α)2α reaction rates, as well as new diagnostic approaches for the reaction product measurement. The activities at Politecnico di Torino will focus on the development of a simplified analytical model of the entire process, including the laser/target interaction and the generation of the particles [93]. This approximate model will allow a first quantification of the particles (energy) / radioisotopes generated, that needs to be better assessed through more detailed models, in turn requiring validation. Therefore, more detailed modeling strategies, based on particle-in-cell (PIC) simulation tools like EPOCH [94], will also be investigated. The chance to optimize the p11B reaction producing intense α-particles streams in a compact and potentially economic way could also open the path for the realization of future sources to be used in medical and radioactive waste transmutation. Moreover, thanks to the several applications reported, a strong effort in the development of laser technology is expected in the next future, potentially allowing their application for transmutation purposes.

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