PROGRESS REPORT

Nuclear Safety

11

Introduction

The Program on Nuclear Safety comprehends Radioprotection and Radioactive Waste Management. The Radioprotection activities are developed at all radioactive and nuclear facilities of IPEN-CNEN/SP and by the Radioactive Waste Management Laboratory. Both activities belong to the Nuclear Safety Directory.

The main task of the Radioprotection Service is to provide IPEN workers and general population with an adequate protection against ionizing radiation. To achieve this aim, RPS implements adequate procedures and monitoring techniques in full compliance with the national and international regulations and standards. Moreover, other activities include: to save exposure records for each worker as long as it is required; to provide recording licenses and other important parameters regarding radiation protection; to ensure the control of radioactive contamination and level of exposure at workplaces. Researches related to the main activities are also performed.

In addition, the Radioprotection Service supports other public organizations and private companies in topics related to radiation protection, in particular work with the National Nuclear Energy Commission (CNEN), in case of nuclear and radioactive emergencies. Our commitment is to specialize human resources through training courses, to provide and disseminate scientific information in radiological and nuclear areas. The radioprotection Service organizes training courses in radiation protection, for several levels, such as IPEN workers, CTM/SP, INPA (Manaus), LAPOC/CNEN (Poços de Caldas), firemen and the Brazilian Army.

The Radioactive Waste Management Department (GRR) at IPEN is one of the centralized waste storage facilities, responsible for receiving, treating and storing the radioactive waste generated in the country. The GRR acts as an executive organization for the National Nuclear Energy Commission (CNEN) to discharge one of the responsibilities established by Federal Law 7781 of 1989, that is 'to receive and dispose' radioactive waste. In this context, GRR receives about 80% of the institutional waste generated in the country. The GRR also provides an essential service for the operation of IPEN's research laboratories and radioisotope production facilities and plays an important role in the development of technologies for the management of radioactive waste and the training of qualified personnel in Brazil.

RADIOPROTECTION

Description of the main highlights of the Radioprotection Service (Fig. 1).

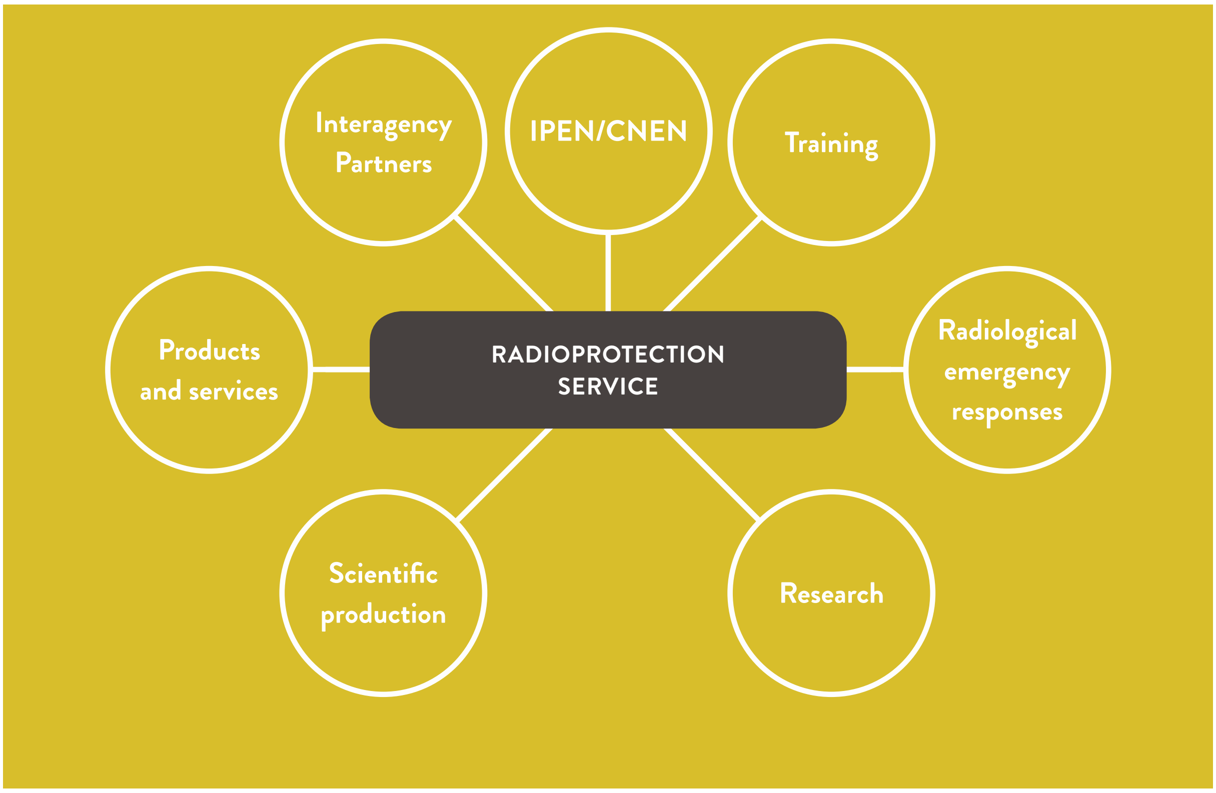

Fig. 1 Highlights of the Radioprotection Service.

RESEARCH AND DEVELOPMENT

Occupational epidemiology

The main evidence for the presence or absence of various health outcomes is provided by epidemiological investigations and the main objectives of the research group are:

To get a solid introduction and a detailed study of the basic epidemiologic methods including the special features of occupational epidemiology;

To assess the different types of epidemiological study, the applications, advantages and limitations of the major types of observational and experimental studies, emphasizing the many possibilities for errors in epidemiological for a clear understanding.

Study of the occupational risk agents and their possible harmful effects on human health

The occupational risk assessment is a structured and systematic process, which depends on the correct identification of probable risk factors and agents potentially found at workplace. The objective of this project was to carry out the basic characterization of a Brazilian radioisotope production facility through ample knowledge of the workplace, workforce, task performed and identification and evaluation of occupational risk agents in the workplace. Moreover, the risk agents identified at the workplace were correlated with the possible harmful effects on human health.

Follow up of the natural radiation exposure from gamma rays in the city of São Paulo, Brazil

The effective doses received by the general population from the natural radioactivity in São Paulo City, Brazil, were assessed from 2008 to 2013 to evaluate the variation from place to place due to the background gamma levels in air, which do not remain constant as time goes by. The outdoor gamma radiation levels were carried out with thermoluminescent dosimeters, TL, quarterly exposed using twelve monitoring stations, covering both places frequented daily by people with emphasis in the most populated districts and safely recessed places, with no influences from man-made ionizing radiation sources (Figure 2). The average annual effective dose in the city of São Paulo, found as 1.3 ± 0.1 mSv, is below the annual global per caput effective dose due to natural radiation sources of 2.4 mSv and within the annual effective doses range of 1 to 3 mSv, expected to be received by 65% of major population. The effective dose (natural background exposure) showed, over the years, small variations among the twelve monitoring stations representing São Paulo city. From 2013 until the present, this project focused only in two monitoring points, considering mainly the occupancy level of each region. One of the selected points is located on the outskirts of the city, with low population density. The other selected point is located in an urban area. In both cases, it was considered the absence of influences from man-made ionizing radiation sources. The average dose results obtained of the environmental outdoor gamma radiation in terms of external exposure were 1.22±0.12 mSv (county area) to 1.58±0.13 mSv (urban area). These results have shown that the average radiation dose from natural sources (external exposure) in both selected points is slightly greater than the annual average reported by the UNCEAR 2000 (0.3-1.0 mSv).

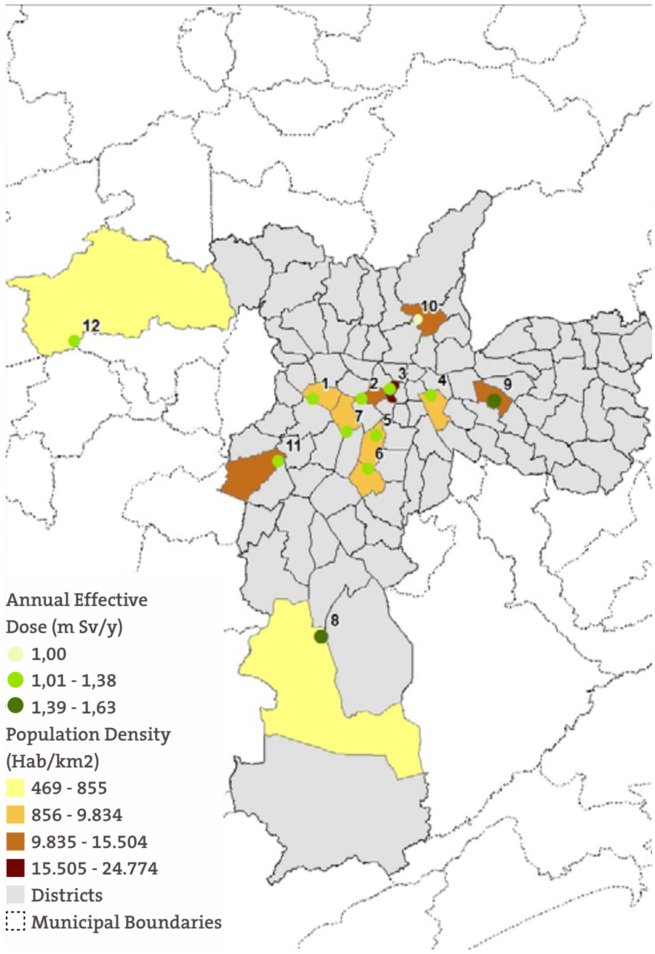

Figure 2. Map of São Paulo city, with the annual effective doses and the population density for the twelve assessed regions.

Potential Exposure to Occupational Risk Agents – Overview of the perception of risk

The risk that a worker has found on the job is a function of the local hazards and the level of exposure to these hazards. Exposure and risk assessment is therefore the heart of all occupational health and industrial hygiene programs involving a continuous process of information gathering. The use of a systematic method to characterize workplace exposures to chemical, physical and biological risks is a fundamental part of this process. The study aimed to carry out an evaluation in a radioactive facility, identifying potential exposures and consequently the existing occupational hazards (risk/ agent) in the workplace to which the worker may be exposed. The study provided an overview of the perception of the risk founded at the facility studied and has contributed with the occupational health program resources for welfare of the worker.

MicroPET Scanner- Evaluation of Ambient Radiation levels in Positron Emission Tomography/Computed Tomography in MicroPET-CT Laboratory

The present project aimed to evaluate the radiations levels in a micro PET/CT research laboratory of the IPEN-CNEN/ SP in full compliance with national and international standards. The study, started in April 2014, continued for about two years. The results of this project demonstrated that the ambient radiation levels (ambient and effective estimated radiation dose), as well as the effective shielding equipment were both adequate. Moreover, this study emphasized that it is essential to strictly follow the principles of radioprotection in workplace, whenever researches involve radioactive unsealed sources.

Social responsibility in the area of nuclear energy for power generation in Brazil

The project focused on nuclear energy for power generation regarding its contribution to sustainable development. The NBR ISO 26000: guidelines on social responsibility was used as a source of the demands and expectations of the society, the mechanisms of participation of stakeholders and the manifestations of collective will. The project recommended a more effective policy of mass dissemination, promoting clarifications to the society as a whole and not only to the population of the surrounding area as a more effectively characterization of the social responsibility.

Study for the development and characterization of concepts of high specific mass for protection to the gamma and X radiation

This project aimed at the natural raw materials produced in Brazil and the production of high density concrete. A methodology was developed for characterization, preparation, molding, testing to determine the linear attenuation coefficient of experimental and theoretical calculation of the linear attenuation coefficient, and determination of the effective Z, culminating with the production of an embryo stock data for the specific high density prepared with local raw materials.

Web-based system to unify the radiological protection programs: ionizing radiation monitoring and optimization

This research work focuses on the potential value of Information and Communication Technologies (ICTs) to enhance communication and education on Radiological Protection throughout Brazil. The work includes the informatization of the monitoring policy and techniques, interrelating information currently scattered in several documents, as well as new approaches from some recommendations, presenting several initiatives towards safety, such as the need for an auditor monitoring and discussions on potential exposures according to international requirements established by the IAEA and ICRP.

The evolution of doses in the IEA-R1 reactor environment and tendencies based on the current results

The purpose of this project was to analyze the individual doses of occupationally exposed individual resulting from changes in the reactor operation regime. Optimizations studies were carried out at the reactor facility as well as radioprotection procedures were adopted aiming at the safety and the goal of reaching acceptable dose of workers.

Policy evolution of the dose limitation system and the issue of replacements in the "superseded" publications

The study aimed to present a careful analysis about the policy evolution of the dose limitation system based on two entities, the International Commission on Radiological Protection publications and International Atomic Energy Agency recommendations. Through this research, from the 50´s to present day, it was possible to clear and detail valuable information that was lost during the process of updating publications and editing recommendations of both entities.

The flexibility of competence and regulatory process regarding safety and radiation protection

The use and increasingly application of consistent nuclear technology in areas related to health, energy, industrial, war, agriculture, among others, means that there is a need for regulation in accordance with the safety standards and international radiological protection. Using concepts from the Constitutional, Environmental and Labor Laws, the focus of this research was to investigate the difficult issue of nuclear competence and environmental responsibility, the impossibility of legislating states, as well as, the lack of regulation on radioactive waste in our country.

Virtual environment for information and communication: online system about the CNEN´s radiological protection plan

This research is premised on responding to the emergence of the need for dissemination of information to radioactive facilities in the field of radiological protection. The work involves the development of an integrated system for the computerization of the CNEN´s Radiological Protection Plan, contemplating the several items required in the RPP (Radiological Protection Plan) and REP (Radiological Emergency Plan), regarding potential exposures, seeking CNEN national standards and the international recommendations of the ICRP and the IAEA. This subject is currently the main field of radiological protection research. Information and Communication Technologies (ICT´s) will enable a quantitative and qualitative increase of available information, contributing to the sustainability of the decision-making process and strengthening of radiological protection throughout the National Territory.

Products and services

The main objective of the Radioprotection Service is to provide IPEN workers and the general public adequate protection against ionizing radiation. Adequate procedures and monitoring techniques are, therefore, implemented according to national and international standards. Also, Radioprotection Service supports general obligations for any practices involving or likely to involve exposure to radiation or radioactive substances, including:

- Preparation of local rules and procedures;
- Designation of radiological areas;
- Control and accounting of radioactive material;
- Restriction of exposure;
- Optimization of radioprotection for practices;
- Final assessment of the individual monitoring internal and external;
- Occupational and environmental control and contamination monitoring;
- Contingency planning and radiological risk assessment;
- Training in radiological protection.

In additional, when required, the Radioprotection Service can provide the following services: preparation and review of radiological protection aspects of safety documents; advice and assistance on radiological aspects of categorization of plant and modifications; participation in safety audits; support to engineering projects; analysis of transport packages and waste contents, including assistance with waste characterization; investigation of abnormal dosimetry results; routine reports on personal dose statistics; provision of appropriate radiological information for reports; personal protective equipment; planning and preparedness for emergency response to accidents involving radioactive material.

Concerning the program for the improvement of infrastructures for protection and safety at IPEN, the Radioprotection is the authority responsible for managing the radiological activities survey.

Table 1. The main activities carried out in the period from 2014 to 2016

	number		
Products and services	**2014**	**2015**	**2016**
Shielding assessment	1	1	3
Control of radioprotection equipment	321	246	180
Radioactive decontamination	533	321	47
Procedures elaboration	83	23	46
Radiological emergency responses	09	06	05
Transport packages labelling	56,270	56,591	61,000

Packages shipping	57,331	57,505	61,000
Inspection on gamma camera	827	623	330
Technical reports	325	624	541
Radiological monitoring	546,781	406,933	411,631
Radioprotection training	632 people	506 people	455 people

Preparedness and response for nuclear and radiological emergencies

IPEN is part of the Protection System for the Brazilian Nuclear Program (SIPRON), a group of organizations whose objectives are: integrated planning combined action and continuous execution of measures to assure the nuclear safety throughout the country and to respond to radiological and nuclear accidents in Brazil. IPEN also takes part in the implementation of the Emergency Situation plan developed by CNEN to respond to emergencies, such as the loss of radioactive sources and accidents during the transport of radioactive material. The Nuclear and

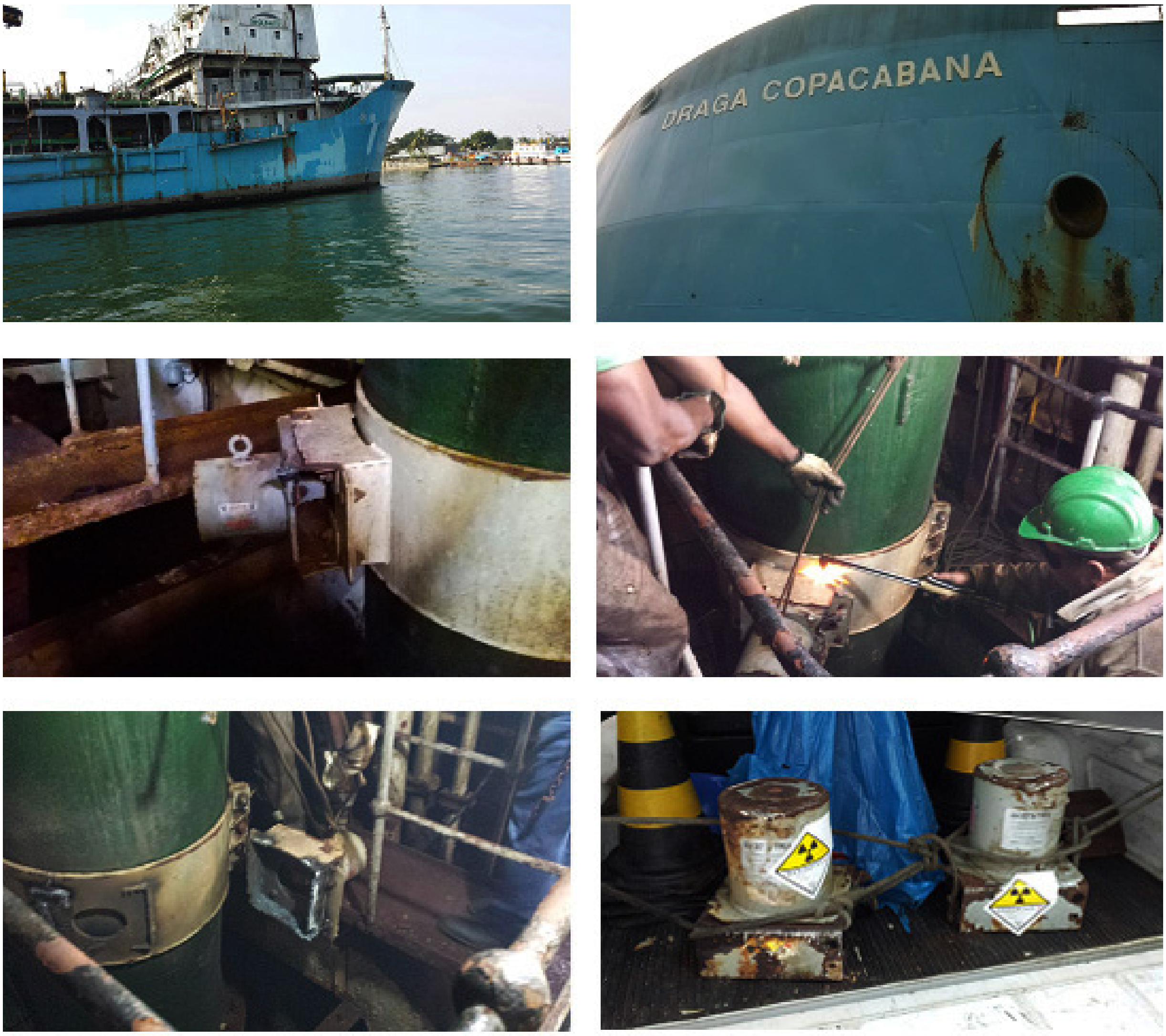

Figure 3. Response to radiological emergency

Radiological Emergency Response Team (NRERT) of the Radioprotection Service is responsible for the evaluation and first response to emergencies situations in São Paulo state. NRERT works with federal and local agencies to monitor, contain and clean up the release of radioactive material, protecting people and the environment from harmful exposures to radiation. Figure 3 shows the response actions to radiological emergencies.

Moreover, we can highlight a National Strategy for planning, preparedness and execution of a Nuclear and Radiological Security Plan to support Major Public Events.

The Radioprotection Service supported International major public events held in Brazil, among them: Pope´s visit to Brazil (2013), World Cup – Brazil (2014), Olympics games (2016).

The Preparing for Major Public Event Involving Radioactive Materials requires the establishment of a system, at the National Level, to ensure that:

> A nuclear or radiological Security Plan is developed to prevent, detect, interdict and respond to nuclear and radiological incidents and accidents
> First Responders are trained and have proper instruments
> To identify the presence of radiation and adjudicate alarms
> Radiation Specialists are readily available to promptly respond and advise First Responders
> Emergency Management Systems are in place to allow unified actions.

To achieve these objectives, the operations involve prevention, detection and response, as seen in Figure 4 and illustrated in Figure 5.

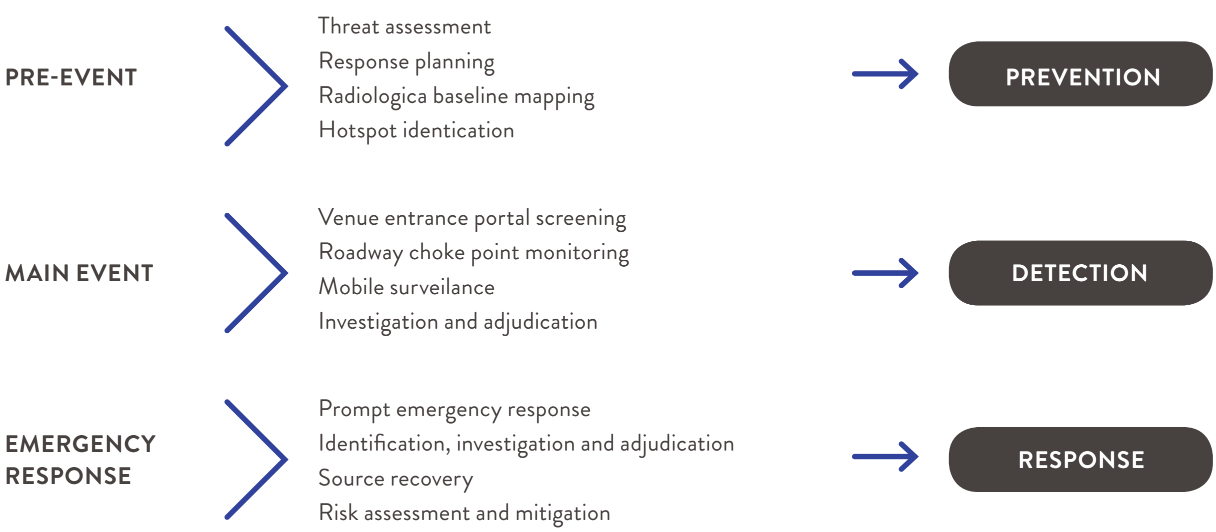

Figura 4. Operations involving prevention, detection and response

Figure 5. Support Major Public Events

Training in radiological protection at IPEN

The Radioprotection Service is responsible for the development and implementation of training in radiation protection for a range of users and applications of ionizing radiation. This activity has been established to attend: the training requirements for IPEN workers for any levels; to emergency response personnel, such us fire fighters, civil defense personnel; and to provide and disseminate information in radiation protection education for students and community.

Workers who are occupationally exposed to ionizing radiation need more extensive and deeper training to ensure that radiation is used safely. The training of the principles of radiation protection is based on the Standards of the CNEN and IAEA recommendations (International Atomic Energy Agency).

The competences are acquired, developed and maintained through a programme of regular training. The courses are offered, such as basic training, refresher training and on the job training. The content and level of the courses offered are established for each category of persons to be trained.

During the years 2014-2016, the courses were offered periodically. Upon completion of the course, an examination is given to authenticate the program requirements. A Certificate of Achievement is provided to those who have successfully completed the course, and a permanent record of training is kept in the Radioprotection Service. The basic course covers the general principles of occupational radiation protection in the following subject areas: basic radiation physics, definitions and units of radioactivity, principles of radiation protection against external and internal exposures, biological effects of radiation, the risk and assessment of such exposures, instrumentation, inventory and contamination control, emergency response, requirements of the National and International Standards and IPEN procedures. After this basic course, all workers must be trained in this specific practice in each work area.

Radioactive Waste Management

Research and development

Radioactive waste characterization, treatment and disposal

Radiochemical and radiometric methods for characterization of filter materials from the water polishing system of the IEA-R1 reactor.

The operation of the IEA-R1 nuclear research reactor generates several kinds of radioactive waste, which require treatment for adequate disposal. Among them, three special waste materials must be highlighted: filter cartridges, activated charcoal and mixed-bed ion exchange resins from the cooling water purification system. These filter materials remove dissolved, or suspended radionuclides in the reactor cooling water when the reactor is in operation, to keep the quality of the water within the operational limits. The filters are replaced when saturated and then become the radioactive waste with the highest activity generated in the operation of the facility. This waste contains activation and fission products and actinide elements, the so-called transuranium elements.

The management of this waste requires as a first step the determination of activities of the radionuclides present. Three determination methods can be used to obtain the radioisotope content of the waste: radiochemical and radiometric analysis, and mathematical modeling. Radiochemical methods include taking samples of the waste material, dissolution of the samples, and separation of all radiologically significant radioisotopes from the waste matrix and the measurement of their activities. Radiometric methods consist of measuring the radiations emitted by whole waste packages, for instance gamma spectrometry or gamma scanning, and correlating the results with the concentrations of the gamma emitters inside. The mathematical modeling uses the knowledge of the physical and chemical processes that occur in the waste generating facility to estimate the radionuclide content of the waste. These methods are used complementarily aiming at expediting the determinations, keeping the costs as low as possible and producing the more accurate and precise results achievable.

Some of the radiologically significant radionuclides emit low energy or less penetrating radiations or are present in very low concentrations, which make the determination of the activities a lengthy and complex task. These radionuclides are called Difficult-To-Measure (DTM) and are the object of development of analytical methods worldwide. They are usually determined by the method of Scaling Factors and Correlation Functions that allows estimating their concentrations as a proportion of the activity of radionuclides that are easily measured by radiometric methods, which are strong gamma emitters, called Key Nuclides (KN).

The research and development work performed by the GRR staff on the radioisotopic characterization of the waste from the IEA-R1 reactor aims at establishing the analysis protocols, creating the instrumental infrastructure and training skilled analysts to perform the job (Fig. 6).

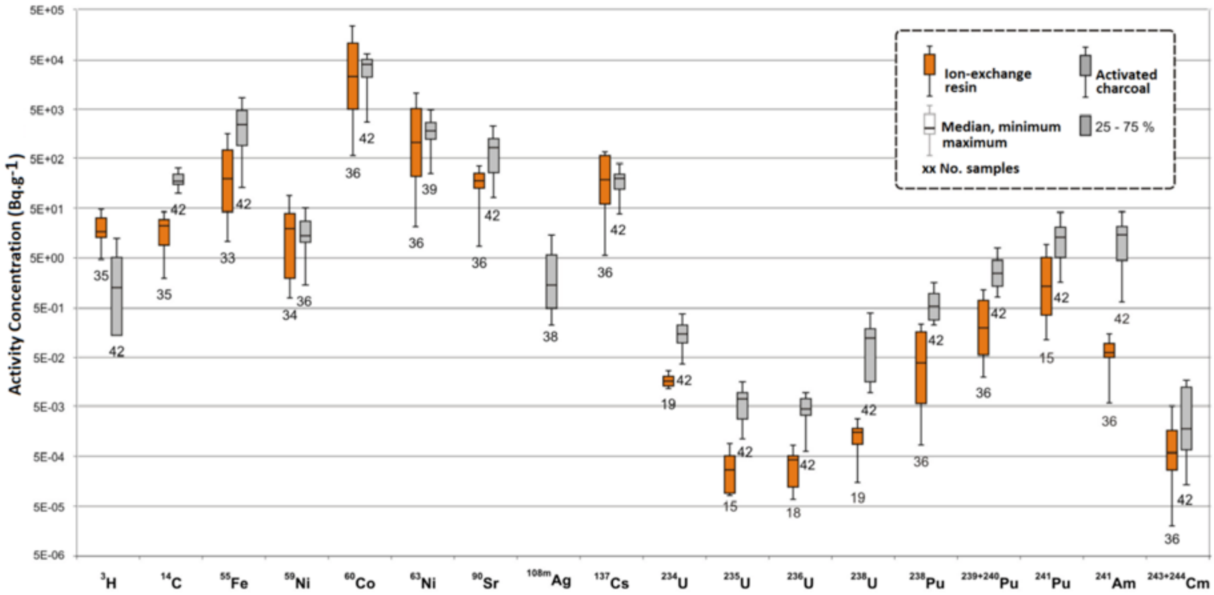

Figure 6 - Activity concentration in waste samples from the IEA-R1 Nuclear Research Reactor filter media.

Development of Microwave Technology for TENORM Waste Treatment

Some sludge and piping scales generated in the operation of oil and gas production rigs may contain radionuclides of the thorium and uranium decay chains in significant concentrations, constituting one instance of the so-called technologically enhanced naturally occurring radioactive materials (TENORM) waste. The management of this waste requires caution both because the radionuclides present a radiation risks and because some chemicals that result from the decomposition of oil residues, for example hydrogen sulfide, are toxic and corrosive. The hazardous compounds can be destroyed by appropriate chemical, thermal or other treatment, but the radioactivity remains in the bulk waste. In Brazil, Public Law 10.308 limits the options for disposal of this waste, because disposal of any radioactive waste in seawaters, seabed or oceanic islands is prohibited. Therefore, the only possibility is the waste being drummed and transported to a waste management facility on shore.

As no licensed disposal facility is presently available in the country, the waste is being kept under long term storage without any treatment. The costs of this management are rising as more and more waste is being produced and the risks increase as the radioactivity and the quantity of toxic substances build up in the storage.

The work undertaken by GRR under an agreement with oil companies aims to develop a treatment process using a specially designed microwave oven, which removes simultaneously water and hydrocarbons from the sludge, thus reducing the volume, the chemical toxicity and the corrosiveness of the waste (Fig. 7).

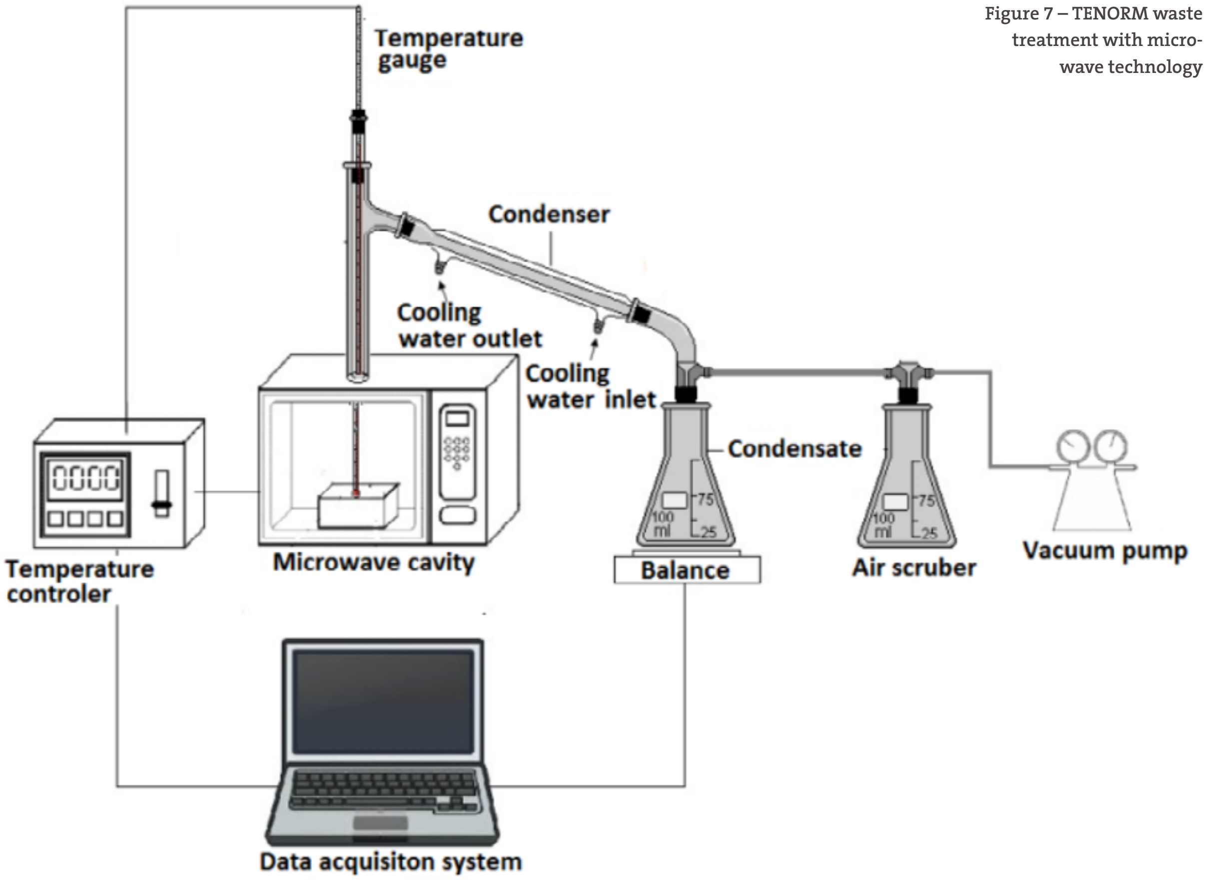

Figure 7 – TENORM waste treatment with micro-wave technology

Assessment of cement durability in repository environment

Cementitious materials made with Portland cement are widely used in the management of radioactive waste, particularly as immobilization matrix of low- and intermediate-level waste and as structures in the engineered barriers of repositories. As any other engineering barrier, the cementitious materials must perform as required for the period of service life in the disposal facility. However, Portland cement is a relatively new engineering material and its behavior in the period of hundreds or thousands of years is still mostly unknown.

The GRR is performing a research work in order to contribute to the assessment of the durability of cementitious materials in a deep borehole for disposal of disused sealed radioactive sources. In the environment of a deep borehole for this waste, the aging hydrated cement material is exposed to the radiolytic effects of the radiation field of the sources, the high temperature determined by the geothermal degree of the disposal site and the disposal depth, and is possibly exposed to aggressive chemical species dissolved in the ground water. Presently, the assessment of the long-term behavior of cement materials can only be done by accelerated tests in laboratory and modeling. The GRR's work in this field is combining both methods, taking advantage of the availability of the Multipurpose Irradiator to irradiate cement specimens cast in laboratory with the expected integrated radiation dose delivered to the material until the sources are decayed. The effects of the radiation, temperature and chemical species in the cement specimens are evaluated by X-Ray Diffraction

	Primary products of radiolysis:	
	$H\cdot + OH^- \rightleftarrows e_{aq}^-$	$pK_a = 9,6$
	$OH\cdot + OH^- \rightleftarrows O\cdot^- + H_2O$	$pK_a = 11,9$
	$HO_2\cdot + OH^- \rightleftarrows O_2\cdot^- + H_2O$	$pK_a = 4,8$
	$H_2O_2 + OH^- \rightleftarrows HO_2^- + H_2O$	$pK_a = 11,68$
	$HO_2^- + OH^- \rightleftarrows O_2^{2-} + H_2O$	$pK_a = 16,5$
	Secondary reactions of radiolysis (chain reactions – initial):	
Initiating	$O\cdot^- + H_2 \rightarrow e_{aq}^-$	
Developing	$e_{aq}^- + HO_2^- \rightarrow O\cdot^- + OH^- + H_2O$	
Balance	$H_2 + HO_2^- \rightarrow OH^- + H_2O$	
	Secondary reactions of radiolysis (chain reactions – after accumulation of H_2):	
Initiating	$e_{aq}^- + O_2 \rightarrow H_2O + O_2\cdot^-$	
Developing	$O\cdot^- + O_2\cdot^- \rightarrow O^{2-} + O_2$	
Balance	$e_{aq}^- + O\cdot^- \rightarrow H_2O + O^{2-} \rightarrow 2\ OH^-$	
	Secondary reactions in alkali medium:	
	$H_2O_2 + HO_2^- \rightarrow O_2 + OH^- + H_2O$	
	$H_2O_2 + O_2\cdot^- \rightarrow O_2 + OH\cdot + OH\cdot$	
	$HO_2^- + O_2\cdot^- \rightarrow O_2 + O\cdot^- + OH^-$	
	Formation and dissolution reactions of octahydrate calcium peroxide	
	$Ca(OH)_2\downarrow + H_2O_2 + 6H_2O \rightarrow CaO_2.8H_2O$	
	$CaO_2.8H_2O \rightleftarrows Ca^{2+} + O_2^{2-} + 8\ H_2O$	
	Balance of the formation and dissolution reactions of octahydrate calcium peroxide	
	$Ca(OH)_2\downarrow + H_2O_2 + 6H_2O \rightarrow CaO_2.8H_2O$	
	$CaO_2.8H_2O \rightarrow Ca^{2+} + O_2^{2-} + 8\ H_2O$	
	$O_2^{2-} + H_2O \rightarrow HO_2^- + OH^-$	
	$H_2O_2 + HO_2^- \rightarrow H_2O + OH^- + O_2$	
	$H_2O_2 + HO_2^- \rightarrow H_2O + OH^- + O_2$	
	$Ca^{2+} + 2\ OH^- \rightarrow Ca(OH)_2\downarrow$	
	Balance: $2H_2O_2 \rightarrow 2\ H_2O + O_2$	
	Portlandite and hydrogen peroxide equilibrium in cement:	
	$Ca(OH)_2 \rightleftarrows Ca^{2+} + 2\ OH^-$	
	$H_2O_2 + HO_2^- \rightleftarrows H_2O + OH^- + O_2$	
	Allen chain reactions that regulate H_2 quantity in the system:	
	$O^{\cdot-} + H_2 \rightarrow e^-_{aq}$	
	$e^-_{aq} + HO_2^- \rightarrow O^{\cdot-} + OH^- + H_2O$	
	Alterations in Allen chain reactions in the presence of contaminants (Fe, TI, Cr)	
	$O^{\cdot-} + Fe\ (II) \rightarrow O^{2-} + + Fe\ (III)$	
	$e^-_{aq} + Fe(III) \rightarrow H_2O + Fe\ (II)$	
	$e^-_{aq} + O_2 \rightarrow H_2O + O_2^{\cdot-}$	
	$O^{\cdot-} + O_2^{\cdot-} \rightarrow O^{2-} + O_2$	
	$e^-_{aq} + Ti(IV) \rightarrow H_2O + Ti\ (III)$	
	$O^{\cdot} + Ti\ (III) \rightarrow OH^- + Ti(IV)$	
	$e^-_{aq} + Cr\ (III) \rightarrow H_2O + Cr\ (II)$	
	$O^{\cdot} + Cr\ (II) \rightarrow OH^- + Cr\ (III)$	

Figure 8. Modeling the behavior of cementitious materials in the environment of a radioactive waste repository

and microtomography, among other methods, to observe changes in the mineralogy and microstructure of the material. The results of the accelerated tests in laboratory are important as input data to model the behavior of cementitious materials under the conditions expected in a borehole repository and to validate data used in the safety assessment of the disposal facilty (Figure 8).

Use of laser for cleaning of radioactively contaminated surfaces

Laser ablation is a process of removing material from a surface by irradiating it with a laser beam. This technique was previously tested and showed to be effective in decontaminating the surface of radioactively contaminated metal scrap produced in the dismantling of radioactive lightning rods. The energy of the laser beam deposited in the surface produces the ejection of a thin layer of the material in the form of plasma that cools down after flying a short distance from the ejection point, eventually resulting in an aerosol cloud. The ablated material is captured by vacuuming the surface during the ablation and collecting the particles in an air filter.

The main advantage of laser ablation over other techniques is the low volume of secondary waste generated in the decontamination process. Indeed, laser ablation generates the lowest volume of secondary waste that is the volume of the filter used to collect the ablated material. Other advantages are the independence of the process on different surfaces, the portability of the decontamination equipment and the low cost.

As the dismantling and decommissioning of nuclear facilities generate high volume of radioactive waste composed of pieces of equipment and structures contaminated in the surface, the laser ablation is a technique that may be of interest as a decontamination tool. The GRR is participating in a development project together with the IPEN's Center of Laser Applications whose goal is to build an experimental laser-ablation decontamination tool.

Isotopic characterization of radioactive waste drums

GRR has built an automated system for isotopic characterization of radioactive waste drums using segmented gamma scanning (SGS). The figure 2 shows the equipment that resulted from the project. The detection system is composed of an HPGe detector and associated electronics. A PLC (Programmable Logic Controller) automates and controls the drum driving system. This system allows controlling the elevation and rotation of the base where the radioactive waste drum is positioned. The result is a three-D visualization of the content of the drums in terms of radionuclides present and their respective concentrations.

The system operates in continuous and programmable mode, and allows the number of measurements, operation time and the axial positioning of the detector relative to the drum to be preset.

The calibration of efficiency of the system used four standard drums with different densities that mock up actual waste drums: compressed paper, water, sand and concrete. Five water-equivalent solid standards containing Eu-152 were prepared in rod geometry with density of 1.15 $g.cm^{-3}$.

Figure 9 – Gamma Scanning System developed by GRR

The acquisition of data and the interpretation of results of the operation of the system use computational algorithms based on the Monte Carlo Method and Artificial Neural Networks to characterize radioactive waste drums reliably and efficiently (Fig. 9).

Biosorption of heavy-metal ions and radionuclides from aqueous solutions.

In the recent years, there is an increasing interest in the application of biological materials for the removal of heavy metal ions from aqueous solutions. The biosorption is a technique that uses biological material on removal of metals. A variety of biological materials, such as agriculture residues, bacteria, algae, among others, proved to be efficient biosorbents. The use of these materials is attractive and advantageous because they are inexpensive in comparison with commercial adsorbents. Biosorption shows great potential among many possible techniques for treating radioactive liquid waste since it is capable of decontaminating large volumes of waste containing low concentrations of metals at low costs with relatively high efficiency.

Biosorption of thorium from aqueous solutions by hydroxyapatite.

Bone meal is a biological material that reunites low cost and efficiency. It is a natural material that contains large amount of calcium phosphate, in the form of hydroxyapatite. Studies with hydroxyapatite showed that this material is efficient in removing heavy metals from polluted soils due to their ability to adsorb molecules and can be used to remove radionuclides from liquid aqueous solutions, as liquid radioactive waste generated in many activities. In the work done by GRR, bone meal purchased in local market was chopped and sieved to obtain particle sizes between 0.125 and 0.297 mm. Batch biosorption experiments were performed to determine the metal uptake capacity and equilibrium time. Fixed concentrations of thorium solutions were prepared by dissolving thorium nitrate in distillate water. The bone meal suspended in 5 mL of thorium solutions in a ratio of 0.2% w/v was left in contact during different times: 0.5, 1, 2 and 4 hours. After the contact time, the bone meal was removed by filtration and the supernatant, analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES). The results were evaluated using isotherms and kinetics models. The maximum sorption capacity for the bone meal was 11.5 mg/g in 2 h. These results suggest that biosorption with bone meal can be applied in the treatment of aqueous solutions and liquid radioactive waste containing thorium and deserves further studies with other radionuclides.

Treatment of radioactive liquid waste using different macrophytes

Among potential biosorbents, aquatic macrophytes are attractive because they may remove metals present in the liquid radioactive waste at low cost. The aim of this study was to evaluate the use of macrophytes Pistia Stratiotes, Limnobium laevigatum, Lemna sp and Azolla sp in the treatment of liquid radioactive waste. This study was divided into two stages, one for characterization and preparation of biosorption materials and the other to carried out tests with simulated liquid radioactive waste and with real waste samples. The biomass was tested in raw form and biosorption assays were performed in polypropylene vials containing 10 mL of uranium nitrate solution and 0.20 g of biomass. Solutions with 150 mg/L uranium nitrate were used for the determination of contact time, and solutions ranging from 75 to 20,000 mg/L were used for the assessment of the concentration in the biosorbents, for the various macrophytes tested. After contact, the biomass was separated from the solution by filtration and the concentration of uranium in the remaining solution was analyzed by ICP-OES. Contact times were set in 0.25, 0.5, 1, 2 and 4 hours. The behavior of the biomasses was evaluated by sorption kinetics and isotherm models. The highest sorption capacities found were 162 mg/g for the macrophytes Lemna sp and 162 mg/g for the Azolla sp. The equilibrium times obtained ranged from 30 minutes for Azolla sp and 1 hour for Lemna and Azolla sp. The macrophyte Azolla sp presented a sorption capacity of 2.6 mg/g in tests with actual waste samples. These results suggest that biosorption using the macrophyte Azolla sp can be applied in treatment of liquid radioactive waste (fig. 10).

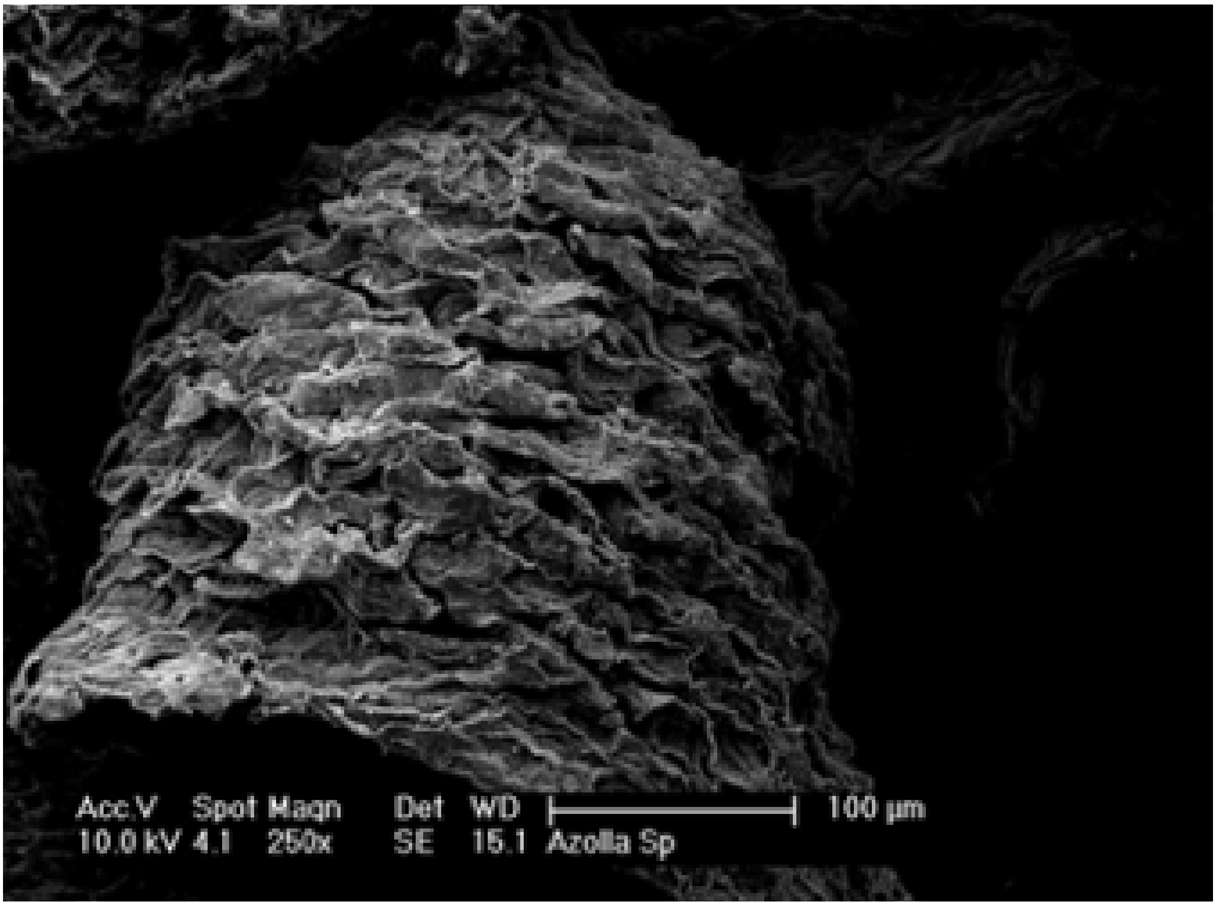

Figure 10 – Scanning Electron Micrograph of Azolla sp. biomass

Application of agricultural residues in the treatment of the radioactive liquid waste

The biosorption of radionuclides from aqueous using vegetable biomass from agricultural waste is a very attractive technique because it involves the removal of heavy metals ions by low cost biosorbents. The aim of this study was to evaluate the potential of different biomass (coconut fiber, coffee husk and rice husk) in the treatment of organic, liquid radioactive waste. For testing biosorption capacities, experiments were conducted in 20 mL polyethylene bottles in which 10 mL of radioactive waste and 2% (w/v) biomass were added. At the end of the contact, the biomasses were separated by filtration and the concentrations of radioisotopes remaining in the filtrate were determined by ICP-OES and gamma spectrometry. The following parameters were evaluated: the contact time between the biomass and waste and the concentration of radioisotopes. The adopted contact times were 0.5, 1, 2 and 4 hours. The results were evaluated by means of the maximum sorption, kinetic models and ternary isotherms. The best sorption capacities were observed with coffee husk and coconut fiber. To complete the study, the filtered biomasses were tentatively immobilized in cement and observed in respect to waste form properties. The best immobilization products for these biomasses were obtained with a water cement ratio of 0.30 %, for waste forms containing 5, 10 and 15%w of biomass, with peeled coffee husk and raw coffee husk respectively.

PRODUCTS AND SERVICES

GRR is responsible for the reception, treatment and interim storage of the radioactive waste generated at IPEN, as well as those generated at many other radioactive facilities all over the country. GRR operational units are: waste reception and segregation room; laboratory for decontamination of small pieces; laboratory for liquid waste immobilization and conditioning; facility for in-drum compaction; facility for disassembling of radioactive lightning rods; facility for disassembling of disused sealed source shielding; laboratory for characterization of primary waste and waste forms; and storage of untreated and treated waste. The storage facility is divided into two adjacent areas, one for conditioned waste and the other for untreated waste, including the disused sealed radioactive sources.

Table 2 shows the summary of waste reception and operational costs during the period.

Table 2. The main activities carried out in the period from 2014 to 2016

	2014	2015	2016	
Waste collection costs	716.34	704.6	712.6	k R$
Market size	102	104	84	customers
Stored waste total activity	631	819	827	TBq
Collected waste total volume	17.37	11.5	15.0	m^3
Compactable waste volume	7.3	1.1	0.54	m^3
Non-compactable waste volume	0.96	0.76	0.02	m^3
Collected disused sealed sources	510	162	637	pieces
Collected lightning rods	290	87	31	pieces
Collected smoke detectors	851	653	1150	pieces

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Honor Mention and Awards

Demerval L. Rodrigues, awarded by ASSOCIAÇÃO BRASILEIRA DE LIDERANÇA and nominated “Comendador” with “Prêmio Excelência e Qualidade Brasil 2014”, cathegory Professional of the year.