Application of Ionizing Radiations
The dynamism to be always developing new technologies, associated with the advancements of other fields, is the main characteristic of the nuclear technology application. The environmental preservation, radio-sterilization, grafting, curing, nanotechnology and polymer production are strongly associated with radiation processing and have being consolidated with the development of new irradiators. The progress of the instrumentation and information technology has stimulated the development of innovative gamma industrial tomography system for the optimization of multiphase industrial process. Basic research and nuclear technology application in the fields of food science, biomaterial, and nanotechnology have been improved continuously. Others fields, such as dosimetry, nuclear instrumentation and industrial electron beam, X-ray and gamma ray irradiators have been accomplished, showing their importance in the innovation of nuclear technology applications. As long as the processes, considered innovative in the present days, prove to be environmentally safe and economically more interesting, new nuclear applications tend to be standard in many areas. To follow this trend and to keep update, the Radiation Technology Center (CTR) Brazil has been working to spread the nuclear application techniques with new developments in standard applications and brand new nuclear technologies, with high impact on the future of the agriculture, medicine, industry and the environmental preservation. The CTR mission is “to apply the radiation and radioisotope technologies in Industry, Health, Agriculture, and Environmental Protection, expanding the scientific knowledge, improving human power resources, transferring technology, generating products and offering services for the Brazilian society”.

**MAIN ACTIVITIES**
The CTR main R&D activities are in consonance with the IPEN Director Plan (2011-2013) and the Applications of Ionizing Radiation Program, with four subprograms:

1. Radioactive Facilities and Equipment for the Applications of Nuclear Techniques
2. Irradiation of Food and Agricultural Products
3. Radiation and Radioisotopes Applications in Industry and Environment
4. Radioactive Sources and Radiation Applications in Human Health.
Facilities and Devices for application of Nuclear Techniques

Facilities installed in the Radiation Technology Center

Radiation processing is one of the most important activities developed by the Radiation Technology Center –CTR. Currently, the CTR has two small-scale gamma ray irradiators, a Gammacell and a Panoramic irradiation system and the Multipurpose Gamma Irradiation Facility, semi-industrial irradiator based on cobalt-60. These facilities have been providing services on radiation processing, especially for sterilization of health care and disposable medical products as well as support to research studies on modification of physical, chemical and biological properties of several materials to the local scientific and industrial communities.

Remarkable applications are related to food processing, cultural heritage preservation, human tissues sterilization, environmental applications, gemstone color enhancement, hydrogels polymerization, etc. Additionally, the CTR has two industrial electron beam accelerators (EBA) of 1.5MeV. Applications such as the treatment of wire, electric cable, heat-shrinkable tubing and film and tires are routinely carried out using the EBA facilities.

The EBA facilities supplied by IBA Industrial Inc. have a capacity of 97.5 kW (1.5 MeV - 65 mA) and 37.5 kW (1.5 MeV - 25 mA) respectively (FIG 1). The installed activity of the Gammacell is around 3.5x10^10 kBq (965.53 Ci) - Dec – 2016 - (FIG 2) and for the Panoramic irradiator around 6.5x10^9 kBq (177.34 Ci) - Dec-2016) (FIG 3). On the other hand, the Multipurpose Gamma Irradiator Facility (FIG 4) was totally developed with Brazilian technology, category IV (IAEA - SSG8). This irradiator can be operated on stationary and continuous modes (product overlap sources) and the source design capacity of cobalt-60 is 37 PBq (1 MCi). The installed activity of this facility is 12 PBq (321.89 kCi - Jul 2014). In the near future, a new cobalt-60 irradiation source will be installed with 7.4 PBq (200 kCi). Almost all disposable supplies used by the Radiopharmacy Center (CR) of IPEN to produce technetium-99m generators and other medical radioisotopes are continuously sterilized by the Multipurpose Gamma Irradiation Facility. Many biomedical research laboratories and centers, especially those working with...
equipment for cell cultures and vaccine production, also make use of the gamma sterilization. Animal feed and shavings used by certified bioteries are routinely disinfected. Alternative underwater irradiation methods were developed to meet the demand of gemstone color enhancement using gamma radiation. Human tissues including bone, skin, amniotic membranes, tendons, and cartilage belonging to National Banks tissues are routinely irradiated. In particular, disinfections and disinfection processes applied on cultural heritage objects (books, wood, paintings, furniture, etc.) using gamma radiation were intensified over the last years. Almost 20,000 cultural heritage objects have been disinfected by the Multipurpose Gamma Irradiation Facility.

Additional applications developed by these facilities are related to treatment of industrial and domestic effluents, sludge and hospital waste; paints, varnishes, adhesives and coating curing; polymer grafting and modification; radiation processing of composite materials and natural polymers. Only in 2016, more than 1000 m³ of medical, pharmaceutical, and biological products were sterilized by the Multipurpose Gamma Irradiation Facility. Between 2014 and 2016, around 8063 km of wire and electric cables for chemical; automobile, aircraft and electro-electronic companies were processed by the EBA facilities. Radiation processing promotes crosslinking among the polymeric chains, increasing electrical, thermal, mechanical, and chemical properties. The upgrading of the EBA facilities increased the wire and electric cables processing speed to 300 m/min and the polyethylene foams to 15 m/min, becoming the product prices more competitive in the Brazilian market.

Development of an automated system for the operation of an electron beam accelerator

Electron beam accelerators are sophisticated equipment used in many applications, such as basic physical research, chemistry, medicine, molecular biology, microelectronics, agriculture and industry, among others. All the electron beam accelerators have an electron source, a vacuum acceleration chamber and a device to extract and distribute the electrons over the product surface. The majority of the accelerators have electrons from a hot tungsten filament and their energy is increased as it passes through an electric field in the vacuum chamber. For industrial purposes, the most common model is Dynamitrons®. At IPEN-CNEN/SP, there is an electron beam accelerator Dynamitron® Type (Manufactured by RDI- Radiation Dynamics Inc., 1978) model DC1500/25/4. The technology applied was available in the 60’s and 70’s, but, nowadays is obsolete. Moreover, there are not original spare parts for this equipment any longer. The aim of this work was to develop a nationalized automated operation system for the accelerator to replace the old equipment. The project started with an economic and technical feasibility study and industrial dosimetry study. The safety standards from the IAEA and CNEN were used to guide the project. Several studies and major
development have been conducted, including printed circuit boards construction, mechanical solutions, CLP automation, software for the automation and process parameters. In this work, the services of the industrial dosimetry laboratory, at IPEN-CNEN-SP Radiation Technology Center (CTR), were used. The main results are the development of an automated control system, signal converting boards, electron beam intensity and sweep system, safety system, overall control system and a device to simulate the electrical signals of the accelerator, allowing the whole system to be tested. This work will permit a considerable amount of money to be saved, since the market price of this system can reach as much as US$ 400,000.00.

**Development of a mobile unit with an electron beam accelerator**

Nowadays, the Radiation Technology Centre is involved in establishing a mobile unit with an electron beam accelerator to treat industrial effluents for reuse purposes ([FIG. 5](#)). The mobile unit will be equipped with an electron beam accelerator (0.7MeV and 20kW) with safety requirements (BSS, IAEA and CNEN Safety Standards), and can be used for treatment of effluent from petroleum production, for petroleum desulfurization, and, in addition, for degradation of toxic organic compounds in wastewater for reuse. This project is supported by the IAEA (TC Project BRA1035 - 2016-2018) and by the Brazilian Financial of Studies and Projects (FINEP). To enlarge the national capacity to treat industrial effluents using electron beam accelerators, the mobile unit treating effluents on site from 1m³/h up to 1,000m³/day, will provide an effective facility between a laboratory-scale plant to a large-scale plant, with the objective to demonstrate the efficacy and to transfer the technology. Studies have taken place in various productive sectors in the country and in other foreign laboratories to prove that the radiation treatment offers technological and economic benefits over the conventional techniques for treating recalcitrant pollutants.

![Figure 5. Mobile unit using electron beam accelerator for wastewater treatment at IPEN.](image)
Dosimetry Systems

Industrial Dosimetry in Radiation Processing

Reliable absorbed-dose measurements traceable to recognized national and international dosimetry standards play an important role in radiation processing. In all electron and gamma radiation processes dosimetry, it is required as a necessary quality control, to establish the process and for research and development studies. The Industrial Dosimetry Laboratory (IDL) is in charge of a wide range of dosimetry activities covering the conventional scope of radiation processing applications and the development of new products and services. The dosimetry procedures are carried out in agreement with the International Organization for Standardization (ISO) and American Society Testing and Materials (ASTM) standard guides and practices. To establish reliable dosimetry systems, the IDL has participated of the intercomparisons of gamma dose measurements, organized by International Dose Assurance Service (IDAS) offered by the International Agency Energy Atomic (IAEA). Fricke solution has been used as reference standard and alanine as transfer standard dosimeters. Absorbed-dose measurements in the products are carried out using polymethylmetacrylate (PMMA) as a routine dosimetry system provided by Harwell Dosimeters Ltd. - UK, certified by the International Dose Assurance Service (IDAS) of the International Atomic Energy Agency (IAEA) and the alanine dosimetry system to increase the functional dose range. Additionally, the radiochromic thin film FWT-60 and the Cellulose Triacetate Film – CTA dosimeters are available for specific applications.
Development of Semiconductor Dosimeters

Medical applications: Silicon diodes have been used for photon beam dosimetry in the field of medical imaging and clinical diagnostic owing to their higher sensitivity per unit of volume in comparison with ionization chamber. However, in medical dosimetry, where a precise measurement of the absorbed dose is required, the routinely use of Si devices demands periodic recalibration of the dosimeter due to the sensitivity decay with the accumulated dose. This drop in sensitivity is the most important radiation damage effect that imposes constraint on the widespread use of ordinary silicon diodes as dosimeters. This scenario has been changed with the development of silicon devices with enhanced tolerance of radiation in the framework of High Energy Physics research projects. Samples of these radiation-hard diodes, free supplied by Helsinki Institute of Physics (HIP) and University of Hamburg, have been used as detectors in real-time dosimetry systems developed for diagnostic radiology, mammography and computed tomography. The best results were obtained with Epitaxial (EPI) silicon diodes processed on n-type thin epitaxial silicon layer grown on a highly doped Czochralski (Cz) silicon substrate. As dosimeter, each unbiased diode was housed in a PMMA probe (Fig 6) and directly coupled to a digital electrometer to measure the current produced across its p-n junction during the irradiation. In all measurements, the current was linearly dependent on the dose rate and negligible sensitivity decay was observed for accumulated doses up to 10 Gy. Other application that deserves be reported was the dosimetry response evaluation and beam data acquisition performance of a miniature Float Zone (FZ) silicon diode for clinical photon beams of 6 MV and 15 MV. Results obtained with this diode evidenced linear and stable dose response even for field size of 1 x 1 cm². Furthermore, the output factor values gathered in several field sizes point out the promising application of this specific FZ diode for the commissioning of small megavoltage fields (Fig 7).

Radiation Processing: The rising demand for applications in the field of radiation processing with very high doses has pushed researches to develop dosimetry systems to withstand harsh radiation environment. In this context, to improve quality assurance in electron beam processing of many products, active semiconductor dosimeters were designed based on radiation-hard diodes processed on n-type Magnetic Czochralski (MCz) silicon substrate. The main application envisaged was to monitor 1.5 MeV electron beam processing covering the dose range from 10 kGy to 2 MGy and dose rates up to 8 kGy/s. During the electron irradiation, the diodes were unbiased and directly coupled with a digital electrometer in a short circuit mode to record real-time currents and, consequently, dose rates. The dose delivered to the product can

![Figure 7. Miniature FZ diode in a waterproof protection and its connection to a coaxial cable.](image)
be obtained offline via integration of the current signals as a function of the exposure time. As expected, it was observed a negligible current sensitivity decay for accumulated doses less than 1.5 MGy. For higher doses, damage effects on electrical properties of the diodes rose up the dark currents with the accumulated doses and the sensitivity decay reached almost 10%. As a consequence, the correspondent dose-response curves were not linear being fitted by a second order polynomial function. So far, the results evidenced that MCz diodes are substantially tolerant to radiation damage assuring their potential use for high-dose processing dosimetry. It still remains to be dwindled the damage produced on both the entrance window and the walls of the dosimetric probe. Researches on this matter are under way.
Radiation Detectors

Purification and Growth of Semiconductor Crystals for Applications as Room Temperature Radiation Detectors

A great interest has been focusing on the development of a room temperature radiation detector, using semiconductor materials that have high atomic number and wide band gap, due to its applicability as X ray and gamma ray spectrometer, operating at room temperature. Layered semiconductor materials have a number of properties that make them attractive for such application. However, the role of crystal impurities on the detector performance is crucial, and, consequently, improvements on the chemical purification and the impurity reduction analysis should be achieved. To accomplish this goal, the Repeated Vertical Bridgman technique was established for previous purification of the raw materials before their growth, in order to obtain the single crystals of high-purity and highest crystal quality, whose characteristics are required for X and gamma rays detection. In this work, the BiI3 and TlBr powders with nominal purity of 99.99% were used as used as raw material and the efficiency of the Repeated Vertical Bridgman technique for removing impurities was evaluated by the measurements of the impurity concentrations in the crystals after different purification number. For the BiI3 crystals, previously purified, a blackish gray coloration and glossy surface were observed, while crystal grown without prior purification presented a non-uniformity opaque gray color, being more accentuated in the upper region (Fig. 8). The formerly purified TlBr crystals presented a fully translucent yellow color, while crystals grown without purification showed non-uniformity darker yellow color with dark residue in the upper region.

The impurities identified for both crystals as well as the tendency of the impurity concentrations to decrease in function of the purification number are presented in Fig. 9. The segregation of most of the total impurities to the beginning or end of the crystal indicates that the purification method established in this work was effective. After three purifications, most of the impurities for both crystals were, practically, removed in the middle region. Thus, Repeated Vertical Bridgman showed to be an efficient technique for purification of BiI3 and TlBr powders, with potential to be used in the radiation semiconductor detector development.

Figure 8. Pictures of the BiI3 and TlBr crystals without and after three purifications.

Figure 9. Reduction trend of the impurities concentration in function of the number of purifications (once, twice and three times purifications). The colored lines are a guide to the vision, evidencing this tendency.
**Development of the inorganic scintillator crystals used as radiation detector**

The Laboratory of scintillator crystal growth develops pure and doped crystals for the construction of radiation detectors. Inorganic scintillators play an important role in the detection and spectroscopy of gamma and X-rays, as well as in neutrons and charged particles. For a variety of applications, new inorganic scintillation materials are being studied. New scintillation detector applications arise continuously and the interest in the introduction of new fast scintillators becomes relevant. Scintillation crystals based on cesium iodide (CsI) have relatively low hygroscopicity, easy handling and low cost, features that favor their use as radiation detectors. Pure and doped CsI crystals are grown using the Bridgman technique. In this technique, the charge is maintained at high temperature for 10 h for the material melting and complete reaction, using a quartz crucible in vacuum atmosphere. The temperature gradient 21°C/cm and 1 mm/h descending velocity were chosen as technique parameters. After finishing the growth, the furnace is cooled at a rate of 20°C/h to room temperature. The best doping element concentration is studied. The main used dopants are thallium (Tl), bromine (Br), lead (Pb) and lithium (Li). The grown crystals are subjected to heat treatment. In this procedure, it is used vacuum of 10^-6 mbar and continuous temperature of 350°C, for 24 hours. **Figures 10** and **11** shows pure CsI crystal and the bromine doped cesium iodine crystals (CsI:Br), respectively.

For the detection system, crystals are coupled optically with the photocathode. The bright photons move the electrons of photocathodes and these are accelerated by a series of electrodes (dynodes) inside the photomultiplier tube. In the scintillation detection process, the proportionality is maintained in each step, that is, the number of photons released by the crystal is proportional to the energy released in crystal, from the incident radiation. The number of displaced electrons in

**Figure 10. pure CsI crystals**

**Figure 11.** shows the bromine doped cesium iodine crystals CsI:Br.

**Figure 12.** Pulse height obtained for gamma radiation from 54Mn (835 keV) source with crystals of CsI: Br and pure CsI

**Figure 13.** Pulse height obtained for gamma radiation from 137Cs (662 keV) source with crystals CsI:Br and pure CsI.
the photocathode is proportional to the number of light photons from the crystal and the electric current generated by the photomultiplier tube. This way, the height of the electrical pulse from the photomultiplier tube is proportional to the radiation energy absorbed by the crystal. This allows that the energy from different radionuclides can be distinguished from each other by pulse height. Measurements of pulse height using gamma radiation sources of 54Mn (835 keV) and 137Cs (662 keV) are shown in Figures 12 and 13.

**Gaseous Detectors**

The reference detector in experimental microdosimetry has been the tissue-equivalent proportional counter (TEPC) whose walls and filling gases have elemental composition and mass stopping powers similar to that of human tissues. Tissue-equivalent gas (TEG) mixtures, that also allow stable operation of proportional counters with high gas gain, have been employed in TEPCs operated at low pressure scaled to simulate the real size of microscopic tissue sites, as well as to ensure the validity of the cavity-chamber principle. Meeting these dosimetric requirements is also needed for correctly comparing with microdosimetric distributions obtained from Monte Carlo simulations of charged particles tracks. Since the interactions of electrons with matter are at the core of any charged particle transport code, the knowledge of electron-collision cross sections with their energy dependence in real tissues or in TEG mixtures is important. Likewise, experimental values of the first Townsend ionization coefficient, a key parameter for modelling the avalanche growth at high electric field strengths, are essential in the design of proportional counters. Measurements of the first Townsend ionization coefficient have been carried out in a small planar chamber, with a resistive glass anode and a metallic cathode, using the Pulsed Townsend technique. With this setup (Fig.14), reliable sets of data were obtained in pure gases, such as nitrogen, methane, carbon dioxide, isobutane, butane, all of them under continuous flow at low and atmospheric pressure.

In order to extend these researches towards gaseous microdosimeters, measurements of the first Townsend ionization coefficient in several TEG mixtures were performed for the first time (Fig.15). The main focus of interest was on those composed by hydrocar-
bon (methane, isobutane, butane) with carbon dioxide and nitrogen in distinct percentages. Since no experimental data on the first Townsend ionization coefficient in all mixtures investigated are available in the literature, our results were compared with Magboltz simulation with very good accordance within the experimental error.

Industrial Tomography Systems

Development of an Industrial Instant Non-Scanning Tomography System

A portable tomography known as instant-non-scanning type, a similar version of the fourth generation CT, was developed at IPEN, supported by FAPESP. The difference of this device compared to the fourth generation CT type is that this scanner has five fixed gamma source, rather than a single source in a circular motion, moving continuously around the detector ring. The proposed device is configured with a ring of seventy NaI(Tl) detectors distributed circularly around the object and five tungsten-shielding-case, distanced among them with 14 NaI(Tl) detectors. All five shielding cases contain, inside them, approximately the same level of radioactivity source. In summary, the seventy detectors were subdivided in five subsets, containing fourteen detectors positioned diametrically opposite to each radioactive source, in a fan beam configuration, inside an angle of 36 degrees. This scanner was designed to make it easily installable in complex refining towers, pipes and in general, adaptable to other components of industrial production. The seventy de-
detectors, the five tungsten-shielding-cases and collimators systems are mounted on two MDF plates of 20 mm thick and, thus, they are easily adaptable to different industrial objects. The source shielding-cases were built with tungsten, instead of lead, in order to make them as small as possible. They were designed to contain up to two radioactive sources with different energies and to have a system with stepper motor controlled by computer, maintaining the operators at a distance from the radioactive sources. In this CT, each of the seventy detectors is connected to a set of multichannel type electronic acquisition board, developed at our Laboratory. The developed tomography system is capable of generating real-time images of the interior of industrial process towers or tubes, with fast transients, without paralyzing the production. This non-destructive analysis system contributes to achieve high productive and optimized yields in industrial processes, as well as contributing to the reduction of environmental impact, inherent to industry activity. The beneficiaries of the results of this project are the oil refining industries and their derivatives and basic chemical industries.

Gas-Liquid Distribution in the Random Packed Column using a third-generation gamma tomography

Random packed distillation columns are used, extensively, in chemical and petrochemical industries to perform highly efficient process separation. Liquid flow distribution has been a major concern when scaling up random packed columns. The liquid distribution in random packed columns is not often uniform, even when the liquid is uniformly introduced into the column. The knowledge on porosity variation (gas holdup) of random packed columns is useful for understanding the fluid dynamics. The porosity variation in the random packed columns has long been recognized as a potential source of maldistribution and it has been studied extensively. A third-generation gamma transmission tomography system, developed at IPEN, was used to evaluate the liquid distribution of a Rasjig ring random packed column, at two different water flows: 2 and 6 liters/min. For each water flow, the measurements were carried out at nine column heights. The liquid-gas holdup was determined by the reconstructed images. The distribution of the Rasjig rings, as well as the position and the average accumulated amount of the water concentration, among the Rasjig rings, could be determined, even at a low temporal resolution of the system of 8.8 hours. The regions of accumulated water concentration were similar for the water flow velocities, at 2 and 6 liters/min. However, the average accumulated water concentration for 6 liters/min was higher, compared to 2 liters/min. The spatial resolution of the tomography system determined by the modulation transfer function (MTF) analysis was of 1.45 mm.

Ionizing Radiation Application in Food and Agricultural Products

News aspects on food irradiation and analyses of natural biocompounds in edible flowers

We highlight our objectives in the studies of ionizing radiation in eatable flowers and start with new studies to establish minimum and maximum amount of 2-Alkylcyclobutanones (2ACB) to endorse the safe consumption of irradiated fat food. There is extensive research on the most suitable technology for food preservation, which does not compromise the quality of its bioactive compounds and toxicity of irradiated foods. In this way, radiation processing has been shown to be an effective alterna-
tive in post-harvest, shelf-life extension, loss reduction and food safety assurance, as well as quarantine treatment since fresh food intended for human consumption needs to be free from insects and diseases. The growing application of food, especially fruits and edible flowers in gastronomic preparations, requires new technological approaches with the objective of improving conservation and commercialization in order to promote food security.

In this sense, one of our lines of research to which we have dedicated over the last three years was the research to provide consumers with safe and healthy eating options for edible flowers. The tendency to use flowers and petals in gastronomy has been growing in recent years and the taste of flowers pleases not only for the taste and refinement but also for the beauty it provides to culinary preparations, as well as the growth of scientific research on its nutritional potential. The edible flower market in Brazil and abroad is in full expansion and is a niche of high standard in the market of floriculture and vegetables. Brazil has a great diversity of fruits, increas-
ingly appreciated in culinary preparations or even “in natura” both in the domestic market and abroad. Indeed, the food irradiation must be carried out in packaged products, leading to minimal changes in fresh and perishable products, allowing them to be preserved for longer without losing their quality. However, due to the great diversity and complexity of food composition, further scientific research on the interaction of ionizing radiation with food products and components of food matrices is necessary. Additionally, it has some limits to irradiate food, as in any other process in the food industry. Irradiation is effective in public health by inactivating harmful microorganisms and food borne parasites.

Oxidation results in hydroperoxides decomposing into hydrocarbons, aldehydes, ketones, alcohol and acids, which interfere with sensory characteristics, as they form unpleasant flavors and a special flavor that are commonly known as rancidity, and reduce nutritional value by degrading fat and fat soluble vitamins. Oxidative deterioration of lipids leads to the development of rancidification, undesirable flavors, polymerization and other reactions resulting in reduced shelf life, nutritional quality and food safety. The oxidation of fatty acids gives rise to numerous compounds among them the formation of 2-ACBs among other compounds contained in the lipids of irradiated foods. Many studies report that 2-ACBs are compounds formed solely by the irradiation process and increase linearly according to the radiation dose. Studies of genotoxicity and cytotoxicity are being done by the group to provide basic information on cell culture and laboratory animals on this topic which should be deepened knowledge and provide data to government bodies for safe control of this process and establish minimal and maximum safe limits quantities in the food.
Industrial and Environmental Applications of Ionizing Radiation

Modification and preparation of polymeric materials and composites

Behavior of linear low density polyethylene films under UV ageing for agricultural application

Polyethylene is the most important polymer used in agricultural applications. Polymers are susceptible to changes in their chemical structures that affect their mechanical properties under weather condition. In Polyethylene, photo-oxidation can occur because of impurities or chromophore groups (catalytic residue, mineral fillers, some commercial additives as stabilizers, lubricants, plasticizers, etc.). The critical ageing factors for greenhouse built with LDPE film are: total solar radiation, air temperature, relative humidity, mechanical stress, agrochemicals, air pollution, and combinations of these factors. Exposure of plastics to UV radiation causes a loss in their mechanical properties and/or change in appearance, including reduced ductility, color changes, yellowing and cracking. Additives are added to plastics to enhance the durability of the final product. Today, there are several additive systems (light stabilizers) developed to work according to resin, final application, type of cultivation, and other characteristics. The main types of light stabilizers are: UV absorbers, quenchers and free radicals scavengers. In addition to the conventional organic additives, some inorganic additives were obtained recently with the development of nanotechnology. This study evaluates the different additive systems (HALS, NPCC, nZnO and nTiO2), applied 0.25 % (in weight) in LLDPE. The samples were mixed by high rotation homogenizer and extrusion. Later, the samples were molded by injection and aged in QUV-B simulating 6 months of exposure to weather. Tests of FTIR and tensile strength comparing to the non-aged samples were carried out in order to evaluate the performance of several additive systems concerning the degradation behavior of linear low density polyethylene.

Radiation effects in the crystal polystyrene composite with clays

The changes in the mechanical and thermal properties of the materials have been investigated by several authors after being irradiated. In this sense, the polymer nanocomposites consist of a class of materials formed with inorganic nanometer dimensions, such as clay and other minerals, dispersed in a polymeric
matrix. Indeed, there is a great technological interest in the study of polymeric nanocomposites due to their excellent properties and ability to control the characteristics of those systems to reach application requirements. In this work, polystyrene (PS) crystal composite with 3% of organically modified clay – Chocolate – were irradiated with radiation doses of 300, 450 and 600 kGy in an electron accelerator. The results demonstrated that irradiation PS with clay presented a reduction in tensile strength compared with pure PS. Furthermore, the Izod impact strength also had a reduction in samples of PS with clay compared to pure PS and TGA analysis indicate a tendency to decrease the thermal stability of the material after irradiation. In conclusion, the radiation is acting in the clay incorporated in the polymer and changing their properties.

**Effect of ionizing radiation in polyurethane catheters coatings with silver nanoparticles**

The present work aimed to study the use of ionizing radiation for coating of silver nanoparticles on central polyurethane catheters (FIG. 1), providing reduction of infections associated with contamination of catheters introduced into the bloodstream (FIG. 2). Fourier transform infrared spectroscopy (FTIR) enabled the identification of functional groups in the structure of macromolecules, such as polyether urethane. A study of the thermal behavior of central venous catheters before and after irradiation was performed in order to characterize the polymeric material of these catheters. The DSC and TG were employed to observe the changes material properties before and after degradation. The DSC curve at the constant heating and cooling rate allowed the characterization of thermal properties, such as Tm and Tg of copolymers, as well as highlighting the main thermal events. Silver nanoparticles have physical, chemical and biological properties only when compared to metal on a macroscopic scale, and they have been used in the medical field because of its remarkable antimicrobial activity. Titanium dioxide nanoparticles obtained by the sol gel method were used as the coating catheters for subsequent impregnation of silver nanoparticles with ionizing radiation at 25 kGy. A Raman spectrometry was used to identify the polymorph of titanium oxide, rutile. In trials with (ICP OES), amounts of titanium and silver coated catheters in titanium oxide and silver were evaluated. The comparative assessment conducted between the catheters before and after irradiation by FTIR, Raman and DSC enabled the use of ionizing radiation as an agent of sterilization and impregnating of silver nanoparticles.

**Mechanical and thermal comparison analyses in polyamide 6 compounds with talc mineral filler and colloidal silicon dioxide (Aerosil)**

In order to have sustainable development, it is very desirable that the possibilities of obtaining ecologically acceptable raw materials that increase dimensional properties and reduce cost in the industrial sector are explored. In this sense, the possibility of replacing mineral talc powder with the colloidal silicon dioxide (AEROSIL®) as a mineral filler in polyamide 6 (PA 6) compounds was tested. Colloidal silicon dioxide is an amorphous substance with low density that satisfies consumer demands. In this study, both fillers – talc and colloidal silicon dioxide – used with PA 6 were explored. Moreover, their density and properties in terms of thermogravimetric analysis (TGA) were evaluated. Additional mechanical tests such as tensile strength, elongation at break and impact resistance were also carried out. The tests concluded both compounds (PA 6 with colloidal silicon dioxide and PA 6 with talc) demonstrated the same behavior. The results have demonstrated that colloidal
silicon dioxide may be viable alternative filler for replacing talc as mineral filler in polyamide 6 compounds. Thus, this work contributes to minimizing environmental problems by enabling the use of colloidal silicon dioxide in the productive process.

**Investigation of the effect of ionizing radiation on composites based on biodegradable polymers and coconut fiber**

Product development and improvement has a crucial role to play in the further development of the biodegradable polymers market. Biodegradable polymers can be found in a wide range of end use markets. Continued progress in terms of product development and cost reduction is required before they can effectively compete with conventional plastics for mainstream applications. And, the addition of natural fibers to polymer blends can lead to physical properties improvement and also can diminish cost. Additionally, it will reduce the amount of agribusiness waste disposal in the environment. In Brazil, coconut production is around 1.5 billion fruits by year in a cultivated area of 2.7 million hectares, but the coconut husk fiber has not been used much for industrial applications. Moreover, when considering an application in the medical field, it is necessary that the products are sterilized and, ionizing radiation is widely used to sterilize medical and surgical devices. In this research, blends and composites based on two commercial polymers: poly (D-caprolactone), PCL, and poly (lactic acid), PLLA, and coconut fiber have been studied. Samples were irradiated with gamma rays from 60Co source and, electron beam from Dynamitron Accelerator, with radiation doses ranging from 10 kGy up to 1 MGy. The non-irradiated and irradiated samples were studied using several analytical techniques and characterization assays that allowed understanding their properties in order to enable their application as precursors for medical and surgical devices. Thermal processing used to obtain composites and previous acetylation by chemical treatment of coconut fibers contributed to the bioburden reduction. Furthermore, reducing initial bioburden it was possible to diminish radiation doses needed to perform sterilization. Enzymatic and soil degradation were not negatively affected by radiation processing. Even though fiber incorporation to the polymer blend slightly reduced degradation process, composites continued degrading through time. Artifacts produced by means of the materials studied here can be radiation processed with doses up to 100 kGy without prejudice of their biodegradability. Cytotoxicity In vitro results of lixiviate indicated that...
composites did not present IC50, so the quantity of substances released that would cause cell death was not significant.

**Modification and preparation of polymeric nanogels by ionizing radiation**

Hydrophilic polymers are widely used in medicine both in soluble and insoluble (hydrogel) forms. Water-soluble polymers have been used in the clinics and/or clinical trials for the modification of proteins, modification of liposomes, surface modification of biomaterials, and as carriers of drugs, genes, and oligonucleotides. The radiation-induced synthesis of PVP nanogels based on intramolecular cross-linking has been recently established. Such materials acquire specific properties that led to a great deal of potential applications, including drug delivery systems, nanosensors, nanoreactors, and bio-mimetic mechanical devices. In this work, we developed poly(vinyl-1-pyrrolidone) nanogels, synthesized by ionizing radiation. Additionally, we aimed to produce PVP albumin conjugate system for biomedical applications. On this account, PVP was irradiated in gamma and electron beam sources using cosolvent system (water/acetone) at room temperature. Bovine serum albumin was incorporated after nanogel formation, by resuspension of the lyophilized nanogel using saturated protein solution. The produced systems were characterized by means of particle size, using dynamic light scattering. Nanostructure images were obtained by scanning electron microscopy. Under the evaluated conditions, it was possible to synthesize nanostructured PVP hydrogels around 30-80nm hydrodynamic radius. The addition of protein to the system conferred distinct thermal profiles and led to changes in the overall structure of the system. Applications of the developed polymer albumin conjugate involve drug delivery systems with enhanced biological compatibility.
and specific site delivery. This study was performed with Dr. Gustavo Varca collaboration.

**Controlled radical polymerization and grafting onto polymeric substrates using ionizing radiation**

This research was developed during training (IAEA fellowship) at Department of Chemistry, Hacettepe University, Turkey, conducted by Dr. Murat Barsbay and coordinated by Dr. Olgun Güven. Modifying the surface properties of polymers, like cellulose, is not only desirable but also very important to control the surface interactions and responses which are required especially in adsorption, separation, and biotechnology applications. Cellulose linear chains have a large number of hydroxyl groups capable of forming hydrogen bonds between and within the chains, making it possible to functionalize cellulose through the well-established methods such as esterification. So, by means of a single reactive polymer it would be possible to obtain a variety of different materials with characteristics achieved by the modifying reagent. The grafting technique can be improved and yield superior results when it is performed in conjunction with controlled radical polymerization (CRP) techniques instead of conventional free-radical polymerization methods. Among the CRP methods, the reversible addition–fragmentation chain transfer (RAFT) polymerization is considered as advantageous considering its applicability to most monomers that reacts through radical polymerization, compatibility with various reaction conditions and simplicity of execution compared to competitive techniques. Glycidyl methacrylate (GMA), has both vinyl and epoxy functions, is a reactive monomer which can be used for post-polymerization modification. Moreover, after the modification of PGMA, the obtained polymer can be further used for other reactions via the hydroxyl groups formed in the epoxide ring-opening reaction. Further studies were performed by Dr. Barsbay adding ethylenediamine (EDA), onto cellulose by opening the epoxy rings. Amine groups have been known as one of the most efficient functional species for removal of toxic heavy metal. The irradiation was performed at room temperature in N2 atmosphere by using a Gammacell 220 60Co source at absorbed doses from 2 up to 15 kGy, dose rate of 0.26 kGy h⁻¹. RAFT-mediated grafting. The effects of adsorbed dose, monomer concentration and solvent choice on grafting yield were investigated at three different monomer/RAFT agent ratios. The syn-

![Figure 29. PC phenoxyl radical decay as relative EPR signal intensity at 0.35 T (peak-to-peak) after time of irradiation. Figure inset shows EPR spectrum of PC gamma irradiated in saline solution, first measurement (considered time=0).](image-url)
thesized copolymers with various graft ratios were characterized by ATR-FTIR spectroscopy, X-ray photoelectron spectroscopy (XPS), thermal analysis and scanning electron microscopy (SEM). Cumyl dithiobenzoate (CDB) mediated RAFT polymerization of GMA revealed the difficulty of controlling the polymerization of GMA due to high crosslinking tendency of this monomer under β-irradiation.

Polycarbonate chromatography column to be used in a 99Mo/99mTc generator irradiated in saline solution with electron beam and gamma rays 99Mo/99mTc generator is a device used to extract the 99mTc of decaying 99Mo. Currently, chromatographic column of acid alumina (Al2O3), principal component of generator, is made of borosilicate type 1 glass. The goal of this study was to characterize irradiated polycarbonate (PC) column in saline solution to mimic a 99Mo/99mTc generator in real condition of use. PC column and samples were electron beam and gamma irradiated in saline solution with radiation absorbed doses up to 200 kGy. Samples were analyzed by electron paramagnetic resonance (EPR), infrared (FTIR), ultraviolet (UV) spectroscopies, differential scanning calorimetry (DSC) and wide-angle X-ray diffraction (WAXD). Additionally, saline solution gamma irradiated in presence of PC column was analyzed using high performance liquid chromatography (HPLC) in order to investigate chemical phase diffusion of bisphenol A (BPA). EPR results showed strong singlet attributed to phenoxy radical, which decays within 40 days. UV spectra presented increase in relative absorbance at 400-450 nm with increasing radiation absorbed dose. Ionizing radiation caused greenness of original clear PC samples. On the other hand, glass transition temperature decreased 1% (5K) for maximum applied radiation dose. Similarly, small decrease on carboxyl group peak at 1770 cm⁻¹ was observed by FTIR. No detectable change on crystallinity was observed by WAXD. HPLC with fluorescence detector can be employed to analyze chemical phase diffusion of BPA in saline solution at ppb concentration. For sterilization absorbed dose, no significant changes on studied properties was observed, that way it can be recommended to use PC instead of borosilicate glass column in 99Mo/99mTc generator.

**Recycling Polymers by Irradiation Process**

High density polyethylene (HDPE) and ethylene-propylene-diene monomer rubber (EPDMR) were recycled to obtain blends and composites for several applications. Some char-
Characteristics as high impact and high tensile stress were increased by irradiation process with absorbed doses between 50 kGy and 100 kGy from gamma and electron beam sources.

**Ionizing Irradiation Applied to Modification of Polymer Substrate from Biological Molecules**

Olefinic polymers were modified by irradiation process. Biological molecules as chitosan were incorporated to the original polymeric matrix and gave specific characteristics such as antibacterial activity, capture of metal ions and bio-material suitability for medical applications. The new polymeric material was also developed with irradiation processes where natural chitosan (from Brazilian coast alien species Charybdis helleeri crabs) was used to modify the base polymer.

**Creating Selective Membranes with Ionizing Irradiation**

Polymeric membranes were styrene grafted by several irradiation methods and the obtained material is chemically modified to become aluminum selective. For this purpose, polymeric substrates like PVC (polyvinyl chloride) and PP (polypropylene) were styrene grafted mutually by gamma and electron beam irradiation. The modification process included three basic reaction paths: Friedel-Crafts acylation, 2-methylanisole coupling and a final oxidation to achieve aluminum selectivity. The obtained product was an aluminum selective material where original membrane characteristics (physical shape and mechanical resistance) were conserved even after this aggressive treatment.

**Cure of inks, paints and varnishes by UV/EB technology and evaluation of its degradability**

Figure 32. Chitosan from Charybdis helleeri crabs.


Figure 34. Preparation of coating film and UV curing.
The search for environmentally friendly materials is becoming the major focus of research at the twenty-first century, considering the high level of pollution generated by the inadequate disposal of materials, especially polymers, in the environment. In addition, environmental legislation already in course in many countries limits the emission of volatile organic compounds (VOC) in the atmosphere, affecting mainly the paint manufacturers who are seeking for alternatives by replacing the paint solvent for those with high solids. Thus, the technology of curing polymer coatings by radiation is based on the interaction of the chemical system to the ultraviolet (UV) or electron beam (EB) incident radiation, forming reactive species capable of inducing the polymerization reactions and cross-linking, resulting in formation of the cured product. In this technology, the solvents used to reduce the viscosity of the formulations are replaced with reactive monomers that remain in the cured product, providing no VOC, and the film formation occurs at room temperature. However, the cured products are insoluble and infusible, increasing the degree of complexity for reprocessing, recycling and/or (bio)degradation. Thus, this project evaluated coating films cured by UV/EB and its mixtures with pro-degrading agents, on a polymer substrate by means of its thermal, mechanical, rheological and morphological characteristics.

**Reduction of environmental impact generated by UV/EB radiation-cured print inks coatings on post-consuming biodegradable plastic packaging**

The high level of pollution generated by the inadequate disposal of polymeric materials has motivated the search for environmentally friendly systems and techniques such as the application of biodegradable polymers and the replacement of the solvent-based paint systems by those with high solids content, based water or cured by UV or EB radiation practically free of volatile organic compounds, VOC. However, the cured polymer coatings are neither soluble nor molten, increasing the complexity of the reprocessing, recycling and degradation. Thus, this work aimed to develop print inks modified with pro-degrading agents, cured by ultraviolet radiation or electron beam, for printing or decoration in plastic packaging products of short lifetime, which are biodegradable or not. Six coatings (varnish and inks in five colors: yellow, blue, white, black and red), three pro-degrading agents (cobalt stearate, cerium stearate and manganese stearate), five polymeric substrates (Ecobras®, low density polyethylene and its respective modifications with pro-degrading agents). The coatings were applied to the substrates and cured by ultraviolet radiation or electron beam, resulting in 180 samples. These materials were
then exposed to accelerate aging chamber, type “QUV”, and composting in natural environment. In order to assess the effects of the polymer coatings on the degradation process of the specimens, only the yellow and black samples were exposed to a controlled composting environment via respirometry, reducing to 16 the number of samples. The organic compound generated by the biodegradation process was analyzed by the ecotoxicity tests. It was observed that the coating layer acted as a barrier that inhibits degradation of the plastic when exposed to weathering. The addition of pro-degrading agents accelerated the degradation process, promoting the migration of the metal ion to the medium without affecting the final quality of the organic compost/soil.

**Synthesis of metal/graphene based composites using electron beam for electrochemical applications**

Graphene is an allotrope of carbon obtained in a monolayer form from graphite. This nanomaterial has exceptional chemical, electrical and mechanical properties: a precise surface area of 2,630 m²/g per monolayer, excellent electrical and thermal conductivities and high mechanical resistance and chemical stability. The existence of metallic nano-particles augments the surface through which the electric current passes, thus increasing the electrical...
conductivity of the nanocomposites. Ionizing radiation (electron beam and gamma radiation) was utilized to synthesized and combine nickel, copper, palladium and silver nanoparticle on graphene-based material. This methodology requires neither toxic reagents nor generates toxic wastes. These new nano-composites have several applications in the electrochemical field, such as components for supercapacitors, solar cells, sensors, electro catalysis and lithium batteries.

**Graphene oxide as adsorbent for Cesium ions removal from aqueous solution and radioactive liquid waste.**

Graphene Oxide (GO) is a graphene-based nanomaterial that has enticed attention on account of its functionalized surface which comprises hydroxyl, epoxy, carbonyl and carboxyl groups, and has a robust complexation ability with ion metal. GO has shown high sorption competence to eliminate cesium ion from aqueous solution. The trials were performed in batch and the following parameters were considered: contact time, pH and cesium ion concentration in aqueous solution. An equilibrium was reached after 60 minutes contact in neutral solution. The percentage of removal was around 80%.

Coconut fibers in raw and treated forms for Sr+2 removal from radioactive liquid wastes

90Sr, a radioactive isotope of strontium, is one of the fission products and generally present in the radioactive waste
generated by nuclear power plants. The biosorption is one of the most effective techniques to eliminate cations from aqueous solution. This procedure has the advantage to remove the metals in low concentration by means of renewable sources. The removal efficiency of strontium ions by raw and treated coconut fibers was assessed and reached up to 45 and 95% respectively in an aqueous solution.

Figure 40. The image by electron microscopy scan coupled to an energy dispersive spectrometer shows strontium ions on the treated coconut fibers surface after the biosorption experiments.
Preservation of cultural heritage objects and archived materials

Use of gamma radiation for recovery of papers infected with fungi: case study about São Luiz do Paraitinga

The objective of this study is determining the optimal conditions for the use of gamma radiation to recover paper documents that constitute cultural heritage affected by flood in the city of São Luiz do Paraitinga in Brazil in 2010. The importance of this study comes from the unique opportunity to perform destructive tests to documents partially destroyed or biologically contaminated until recovered from the flooded city archives. Hundreds of blank pages from seven different books were provided by the Public Archive of the State of São Paulo for this research. Most of these books were logbooks or other type of registry notebooks containing blank pages. Prior to being sent to the researchers, these books were stored in plastic bags for three months after being recovered from the flood, without any proper measure to prevent the development of microorganisms from the contaminated moist.

Three stages of this work have been conducted:

1. Identification of the genera of the fungi present in the selected samples to establish the appropriated radiation dose based on the genus most radioresistant

2. Comparison of the mechanical properties of non-irradiated paper with irradiated, aged and re-irradiated paper, including tensile elongation and zero-span tensile strength, and

3. Verification of the occurrence of color variation in mud spots and purple and black fungi when subjected to different doses of gamma radiation.
Preservation of cultural heritage objects and archived materials

The climate of Brazil comprises a wide range of weather conditions across a large area and varied topography, but most of the country is tropical. High temperature and humidity levels have been favored the growth of mold and other fungi in artworks, books and archived materials. Another relevant problem found in the conservation of cultural heritage is related to xylophagous insects specially termites and wood-boring beetles. In this sense, disinfection of cultural heritage (CH) artefacts and archived materials by gamma radiation has been successfully researched and applied in recent years by the Multipurpose Gamma Irradiation Facility at CTR/IPEN becoming a leader to preserve tangible objects in South America. Basic research of the ionizing radiation effects in contaminated paper in Brazil started in 1996 at IPEN, but only in 2010s decade, related activities were relevant and intensified to the present day preserving more than 20 000 cultural artefacts.
Gamma radiation provides from the cobalt-60 acts an excellent alternative tool to the traditional preservation process mainly because it’s biocidal action and can even be used to consolidate fragile materials. When compared with conventional methods (e.g. chemical gases), radiation processing used for cultural Heritage disinfection has several advantages mainly related to the safety, efficiency, reliability, capacity, process time and safety for environment. Constitutive materials including paper, paintings, photographs, films, parchments, leather, textiles, wood, bones, etc. have been processed by gamma radiation with excellent results always respecting the limits of each material. Remarkable paintings were disinfected by using this technology from artists such as Anatol Wladyslaw and Wassily Kandinsky, as well as modern Brazilian painters such as Tarsila do Amaral, Anita Malfatti, Di Cavalcanti, Clóvis Graciano, Candido Portinari and Alfredo Volpi.

More than twenty institutions related to conservation or preservation activities such as National Museums and conservations Institutions, conservators-restorers, curators, etc. have been benefited for this technique and currently most of them maintain institution-
Museum of the Sao Paulo University – MAC, Visual Arts Museum – MAV of the University of Campinas – UNICAMP, Moreira Salles Institute, Tomie Otake Institute, Lasar Segall Museum, Santo Andre Museum, Libraries of the Sao Paulo University: Laws School, Communications and Arts School, Chemistry School, Integrated Library System SIBi-USP, City Co. - Planning and Development, etc.

Acting directions to promotion of disinfection of CH by ionizing radiation involve scientific research publications (e.g. side-effects studies), positive diffusion by TV and internet videos, etc. and strong interaction programs with restorers and conservation community supported by national an international organization (e.g. IAEA). Specifically, two IAEA promotional videos were made in collaboration of the CTR/IPEN:

Additionally, the 60 years edition of the IAEA Bulletin, March 2017 (www.iaea.org/bulletin) contains a special issue titled “Culture Meets Nuclear in Brazil” about the impact of the radiation processing of CH and the activities developed by the Multipurpose Gamma Radiation Facility at CTR/IPEN. Since 2013 to the present day, the CH preservation by ionizing radiation staff of CTR/IPEN have been actively participated of consulting and projects supported by IAEA. In 2016, the same team organized the first training in Latin America related to preservation of CH C7-RLA/0/058-001 “Using nuclear techniques in support of conservation and preservation of cultural heritage objects” at CTR/IPEN. In the same way, maintaining good irradiation practices is extremely important. Radiation processing of cultural heritage needs to be applied in qualified irradiation facilities as well as the preparation of pre-irradiation material protocols related to packaging, size limitation, etc. and recommendation to cleaning after irradiation.

Ionizing radiation is widely used to eliminate insects, fungi and bacteria. Desired results depend on the applied dose or the processing dose (Gray). The biological effects of gamma rays in living cells are well known and these depending on the radiosensitivity, exposition time, total dose, dose rate, etc. However, some of the results published in recent years have been misinterpreted. From the last studies, it can be concluded that to eradicate insects in paper and other cellulosic based materials, relatively low doses are necessary, between 0.5 to 1.0 kGy. Wooden materials usually need doses among 2-3 kGy to eliminate the larvae. Lethal doses to eliminate fungi are significantly higher than those used for insects. Doses between 6.0 to 10 kGy can be effective to disinfect of molds and other fungi in cellulosic based materials. Disinfection by radiation processing is a curative process not preventive without quarantine period or radioactive activation of the constitutive material of the CH objects, many actions should be taken to avoid recontamination. Decreasing on polymerization degree as a consequence of disinfection of gamma radiation on cellulose based materials is not reflected on macroscopic properties (e.g. mechanical resistance) of those materials. If applicable, minimization of side-effects of CH...
disinfection can be achieved at high rate doses and inert atmosphere conditions. Disinfection by ionizing radiation preserves DNA information.

Industrial processes applications

Industrial Process equipment troubleshooting with imaging technique improved gamma-ray absorption Scans

Column gamma scan is one of the most common nuclear techniques on troubleshooting industrial process equipments like distillation columns and reactors. With a very simple concept, the technique is easy to implement: consisting basically on a sealed radioactive source that moves parallel to a NaI(Tl) detector resulting on a 1D unidirectional density profile of the equipment. Searching for a competitive edge the industry has been long developing solutions to achieve better results. On the last decades, significant development has been done with the advent of new hardware, electronics, portable computers, and software. Continuous scanning and wireless detection systems are examples of successful field solutions, with new software’s aid on reporting and data presentations. However, the type and quality of the results themselves have not dramatically changed since their beginning. A scan profile is simple to understand, although the process to build it can be very complex as it requires a specific blend of knowledge and abilities. Process engineering, chemical engineering, internal hydraulic project, nuclear engineering, and field abilities are prerequisites for any scan specialist. Correct data gathering, interpretation and reporting are abilities often difficult to match or requires a long time of training. The industry faces a similar difficult on the customer side, as it is always necessary to train end users to understand a report and how to use its best. This scientific work, initially developed as a Nuclear Science Master degree project, describes our effort on developing a new approach on the gamma column scan test using image reconstruction techniques that would result on a two dimensional graphic image rather than a XY plot. Direct and easier to understand, a report with graphic images would also be accessible to a wider audience, not limited to the customers experience with gamma scan interpretation. The innovating technology, resulted on a patent register at Instituto Nacional de Propriedade Industrial (INPI), and recently received the 2013 Petrobras Technology Award, for Master Degree projects on refining and petrochemical area.

Strategic planning as competitive differential in the implementation of radioisotopes technology

Strategic planning is one of most important management tools for decision making. The Nuclear Area is a major segment in modern society not only in energy production but also in many other sectors of the economy. The ob-
Objective of this doctoral research was to propose the implementation of planning strategic tool, the BSC-Balanced Scorecard through relational performance indicators in order to facilitate the visualization in the simplest possible way for managers based on current and institutional strategic plans of the Sealed Sources Production Laboratory. The methodology used in this academic doctoral study was a case study, which considered the survey period from 2008 to 2015. The main results expected from this study can be cited as: a better view of the strategic plans, an additional tool in order to support management decision making, the ability to change the frequency of analysis and results and targets to be achieved among others. After the results that this research has achieved, it can be concluded that this study could be of great value to the Sealed Sources Production Laboratory if their managers choose to adopt this management tool. Finally, this proposal will enable this lab mapping directions in a more effective way using the resources it has. By doing so, it will bring benefits such as greater visibility and more effective action on strategic decision making process.

Development of an irradiation system for production of gaseous radioisotopes applied in industrial processes

Among the various applications of radioisotopes, the use of radiotracers is considered the most important in diagnosing operation and troubleshooting of industrial process plants in chemical and petrochemical companies.
The radiotracers are used in analytical procedures to obtain qualitative and quantitative data systems, in physical and physicochemical studies transfers. In the production of gaseous radioisotopes used as tracers in industrial process measurements, argon-41 (41Ar) and krypton-79 (79Kr) have low reactivity with other chemical elements. 41Ar is a transmitter range with high-energy (1.29MeV) and a high percentage of this energy transformation (99.1%), resulting in relatively small quantities required in relation to the other, for an efficient detection, even in large thickness components. Nowadays, the production of gaseous radioisotopes in nuclear research reactors is performed in small quantities (batches), through quartz ampoules containing natural gas 40Ar or 78Kr. In this sense, the aim of this study is to develop an irradiation system for gaseous radioisotope production in continuous scale, applied in industrial applications of emission tomography and flow measurement. The irradiation system may produce 41Ar with activity of 7.4x1011Bq (20Ci) per irradiation cycle, through the Reactor IEA-R1 with 4.5MW and average thermal neutron flux of 4.71x1013 ncm-2s-1 to meet an existing demand in NDT and inspections companies, and even needed by the Radiation Technology Centre, at IPEN/CNEN-SP. The irradiation system consists of an aluminium irradiation capsule, transfer lines, needle valves, stripy connections, quick connectors, manometer, vacuum system, dewar, lead shielding, storage and transport cylinders, among other components. The irradiation system was approved in the leakage and stability tests (bubble test, pressurization, evacuation and with leak detector equipment SPECTRON 600 T). In the experimental production, alanine dosimeters were distributed into various components of the irradiation system, obtaining 1.07x1011Bq (2.9Ci) of 41Ar. In addition, exposure rates were determined in the lead shielding wall, in which the liquefied radioactive gas was concentrated, and in the storage and transport cylinders after 41Ar was transferred, by the portable radiation meter Teletector ® Probe 6150 AD-t/H.

Sealed source production for gammagraphy and industrial process control

Radioactive sealed sources production for radiography and industrial process control. The gamma writing is an important non-destructive technique to analyze metallic components from small to large ones that need high performance and security in operation. The non-existence of internal failures is checked by gamma rays radiography, because of its great penetration characteristics that allow obtaining the photographic record of failures. This non-destructive analysis is used for quality control of welded components in chemical, nuclear, and mechanical industries, such as pipelines, turbines, reservoirs, and pressure vessels. According to the International Atomic Energy Agency (IAEA) information, the petrochemical and chemical process industries are the mains users and beneficiaries of the radioisotope technology. Radioisotope techniques are very competitive and are largely applied for troubleshooting and process analysis of tech-
nically complex, continuously operating industrial plants. Due to this fact, the application of sealed sources becomes more diversified, including gamma scanning of columns, vessels and pipes, level and interface detection. Since 1983, the Radiation Technology Center (CTR) has supplied industrial gamma sealed sources to more than 25 customers in Brazil and other countries in Latin America and Caribbean. Annually, the laboratory, (FIG -1) produces 280 sealed sources, with activities ranging from 740 GBq (20 Ci) to 4,444 GBq (120 Ci) of Iridium-192 and from 0.37 GBq (10 mCi) to 18.49 GBq (500 mCi) of Cobalt-60. The CTR has made 290 inspections in irradiators, command cables and guide pipes annually and also Selenium-75, Tantalum-182 and krypton-79 sources, loading services. These supplies allow taking more than 100,000 radiographies per year. The principal CTR’ customers are Arctest, ASNDT, Brasitest, CBC, JLM, Confab, Nuclep, TopCheck, Gamatron, Qualitec, Engisa, Capaz, Endlabor, NDT, Sperj, Polyteste, Usiminas, Real WDR, Nuclep, Radiolab, Voigth Hydro, Metaltec, Startec, Accend and Sertech.

Use of radioisotopes as tracers in the environmental and industrial process control

Radioactive tracers, as bromine 82, and dye tracer, as rhodamine WT, are applied to a grounded pipe flow rate measurements. Flow rate order of magnitude 0.1 m3/s up to 3.5 m3/s. Radioactive tracer, iodine 131, applications for mean residence time determinations in tank and digesters of domestic and industrial wastewater treatment plants. Volume order of magnitude: 7,000 m3 up to 12,000 m3.

Gemstones enhancement using gamma radiation

It’s estimated that 70% of the world’s production of gemstones have been submitted to enhancement process and have consequently increased in commercial value. Thus, the CTR performs research of process to induce or intensify the color in several gemstones using electron beam and gamma radiation. Enhancement services of colorless Brazilian quartz and other types of precious stones have been performed in the Gamma Multipurpose Irradiator and Electron Beam Accelerator for the companies Murta Gems Trade Gemstones (Minas Gerais State), Stoll Precious Stones of Brazil (Rio Grande do Sul State), Legep Mining (São Paulo State), Indobrás United (São Paulo State) and Geosciences Institute of São Paulo University (São Paulo State). The figures 51 and 52 show colored varieties of Brazilian quartz obtained to enhancement processes using gamma radiation and heating.

Environmental Recovery

Radiation processing of effluents and toxicity removal

Radiation processing of real effluents is the main target of this process being studied at Environmental Assay Laboratory (LEBA/CTR). The LEBA Laboratory rare living organisms applied for toxicity measurements mainly for liquid samples of industrial effluents and standard pharmaceutical solutions. Combining ecotoxicology studies and radiation tech-
Technology may guarantee that radiation may reduce toxicity of treated effluents, offering a safe technology or its combined processes for complex effluent.

In collaboration with some other groups which study alternative treatments for wastewater, LEBA participates of their work applying and developing suitable biological assays for measuring the efficacy of developing treatment processes such as polymeric membranes and other POAS (oxidative processes). They are textile industries, EPUSP, Instituto Butantan and SENAI.

Acute toxicity of pharmaceuticals was determined for fluoxetine, diclofenac, propranolol and their mixture, using two biological levels of aquatic organisms (V. fischeri and D. similis). All of them were also treated by radiation with Electron Beam Accelerator. Partial results are presented in Figure 53.

![Figure 53. Acute toxicity (in Toxic Units, TU=100/EC50) of diclofenac (DCF) and fluoxetine (FLX) individually and in mixture performed with V. fischeri. Data in triplicate. Initial condition: DCF concentration = 50 mg L⁻¹; FLX concentration = 5 mg L⁻¹; pH0 = 6.79 ± 0.77.](image-url)
Energy Production

Radiation effect on structure and composition of sugarcane bagasse

The structural and chemical modifications produced by ionizing radiation in the sugarcane bagasse are very important matter to be included in the second generation energy production and it depends on the combination of pretreatment technologies to transform these modifications into bioethanol production growth. The industrial application of electron beam accelerator on the second generation process is a challenging task and very feasible since the equipment could take part in the first generation installation. The radiation processing promotes an increase in the soluble portion that is related to hemicellulose and cellulose cleavage, and cellulose with high molecular weight (alpha) presented a total reduction. It is important to point out that the changes observed in the cellulose suggest some effects on the lignin structure, since the cellulose is protected by lignin and hemicelluloses. The obtained results show that radiation interacts initially on the surface of hemicelluloses liberating the arabinose, and then acts on the xylose polymers. The main byproduct liberated is acetic acid originated from the deacetylation of hemicelluloses; the removal of this acetyl group enhances the accessibility of the enzyme to the cellulose and can increase the enzymatic hydrolysis. This sequence of radiation interaction probably happens due to the location of xylose in the backbone of arabinoxylan, while arabinose is located in the branches of the macromolecules where the glycosidic bonds are easier to hydrolyze.
Radiation combined with hydrothermal treatment and enzymatic hydrolysis

The conversion of hemicelluloses reached 42% after thermal treatment by 40 minutes for sugarcane bagasse irradiated with 50 kGy. After the addition of diluted sulfuric acid (0.1% v/v), almost the totality of hemicellulose is converted in xylose and byproducts, mainly furfural. The enzymatic conversion yield of cellulose reached 72% in samples irradiated with 50 kGy and 60 min. of thermal treatment. When dilute sulfuric acid was added, it was observed an increase in the cellulose conversion, however the time was reduced, and the higher value (74%) was reached in 40 minutes of diluted acid treatment and 24 h of enzymatic hydrolysis.

Petroleum and diesel fuel desulfurization enhancement by ionizing radiation

Hydrodesulphurization, HDS, is currently the most common method used by refineries to remove sulfur compounds from petroleum fractions. However, it is not highly effective for removing thiophenes compounds such as benzothiophene. Additionally, this process generates high costs for the oil industry. In the present work, ionizing radiation was used as an advanced oxidation process in order to enhance the removal of sulfur contents from petroleum and diesel fuel. Samples of crude oil and diesel fuel, without any pretreatment, were irradiated using a Radiation Dynamics Electron Beam Accelerator in batch systems at 30 kGy and 50 kGy absorbed doses. The sulfur compounds were extracted and then analyzed by gas chromatography associated to mass spectrometry, GCMS, and by gas chromatography coupled with flame ionization detector, GC-FID. Furthermore, the petroleum and diesel fuel samples were analyzed by Fourier Transform Infrared Spectroscopy, FTIR, to detect chemical changes in sulfur compounds. It was observed a high efficiency of ionizing radiation on the degradation of sulfur compounds such as benzothiophene and benzenethiol and the formation of fragments, for instance 1,2-dimethylbenzene and toluene.

Study of the effect of ionizing radiation for utilization of spent cracking catalysts. Catalyst is a substance that changes the rate of a reaction. In the petroleum industry, the commonly catalysts are used for Fluid Catalytic Cracking (FCC) and Hidrocatalytic Cracking (HCC), which one applied in a specific stage. These catalysts are used to facilitate the molecular chains cracking which will generate a
mixture of hydrocarbons. However, the catalyst gradually loses its activity, either by changing its original molecular structure or by its contamination from other petroleum molecules. The application of ionizing radiation (electron beam and gamma rays) over these spent catalysts was studied to contribute with the extraction of metals or rare-earths of high added-value. Tests carried out with FCC catalysts used the techniques of 60Co irradiation and electron beam (EB) and had as a subject the extraction of lanthanum (La2O3), regeneration and utilization of these catalysts. However, the use of ionizing radiation has not contributed in these processes. Meanwhile with HCC catalysts, the irradiation used was electron beam and had as a subject the extraction of molybdenum (MoO3). In temperature around 750°C, these irradiated catalysts of the lower region have an extraction yield twice higher compared to non-irradiated ones, in other words 57.65% and 26.24% respectively.

Health applications of ionizing radiation and Radioactive Sources

Sterilization of Nile Tilapia (Oreochromis Niloticus) skin by ionizing radiation

The skin of Tilapia fish has been studied to be used as another alternative in the treatment of burns and for this type of use it is essential that it is sterile. To this end, several doses and rates of doses were studied in both the multipurpose irradiator and the electron beam in order to radiosterilize this material without significantly altering its physico-chemical structure. With the result of these studies, it was possible to establish the dose of 30 kGy as the ideal dose to radiosterilize these fish skins, already packed, in our gamma irradiator with 60Co source.

Radiosterilization for tissue banks

In Latin America, the industrial level ionizing radiation sterilization has been used for more than three decades in food and medical, pharmaceutical and cosmetics products. Later, this activity was extended to the sterilization of human tissues for graft and reinforced in some countries by the technical cooperation and International Agency of Atomic Energy - IAEA financial support. In the last few years, preserved tissue allograft, such as bone, cartilage, tendon, skin, amnion and other not viable tissues, have been used in reconstructive surgery by many clinical specialties, like orthopedic and plastic surgery. The transmission risk of infectious diseases by allograft, however, is a constant concern. To this end, many steps should be taken, including tissue sterilization. This technique is used to minimize the immunogenicity, to kill bacteria and to reduce the contagious diseases transferring risk. As an example, the skin glycerol preservation has a bacteriostatic effect after certain time, on the other hand, skin sterilization by ionizing radiation may reduce the quarantine period for transplantation in patients, and their safety is considered excellent. The ionizing radiation is a very efficient sterilization technique; nevertheless, its deployment is still contested since there are few data on its effects upon the tissue allograft. At the Radia-
tion Technology Center, procedures using two sources of ionizing radiation for sterilization of human skin allograft, and to evaluate the skin after gamma and electron beam irradiation, were established. Besides implanting the irradiation services routine to the tissue banks of the country, the researchers developed irradiation devices for human tissues; implanted dosimetry procedures for irradiation processes control; implanted the quality warranty program for tissue irradiation; optimizing type and dose to be supplied according to the preservation process which the tissue was submitted. Brazil was incorporated to the IAEA project in 1998 through the Clinical Hospital of Sao Paulo, where the Tissue Bank was installed and the Energetic and Nuclear Research Institute, where the tissues are being irradiated. Until 2012, Brazil was the coordinator of IAEA ARCAL CVIII “Consolidation of Tissue Banks In Latin America And Radiation Sterilization of Tissue Allograft” project with 12 Latin Americans countries participating and also, from 2010 to 2016, our group participated in the CRP 16119 “Safety and optimization of radiation sterilization in tissue banking: studies on functional properties of irradiated tissue grafts” and since 2014 we have taken part in another CRP 18283 project, “Development and Evaluation of Mesenchymal Stem Cell on Scaffolds for Skin Regeneration”, where we used tissue bank skins as the gold standard for our experiments. The research group has been collaborating with the implementation of quality systems of the Tissue Banks, as well as with experimental and clinical applications of irradiated tissues. Tissue samples were submitted to 15, 25 and 50 kGy doses and the impact of the irradiation on the mechanical properties was evaluated through the analysis of stress-strain and the morphology was accomplished by ultra-structure studies, immune histology and others histological tests. Also in our studies, we use non-destructives tests, like optical coherence tomography (OCT), with the Laser Applications Center collaboration, with excellent results.

**Development and production of radioactive sources for brachytherapy application**

The number of prostate cancer cases in Brazil is increasing and only a small part of the patients are submitted to brachytherapy treatment using Iodine-125 radioactive seeds. Nowadays, these seeds are imported at a high cost, restricting this application. The local production of these radioactive sources became a priority in order to reduce the problems of prostate cancer management for end users. Such action will permit to spread the use to a larger number of patients. Due to such reasons, the Nuclear Energy Research Institute established a program, in order to produce Iodine-125 radioactive seeds. In brachytherapy, small seeds with iodine-125 are implanted into the prostate to irradiate the tumor. The Iodine-125
seeds consist of a welded titanium capsule (0.8 mm diameter and 4.5 mm length) containing Iodine-125 adsorbed onto a silver rod. During the project execution, the following methods were developed: the seed core (silver) cutting, the titanium tube cutting, the iodine immobilization through its deposition in silver substrate and the sealing of the seeds through welding process, so that the classification of the seeds, as sealed sources, and the leakage tests can be done according to the international norms. In the moment, the routine production line is settling up. The production line consists in three gloves-boxes. In the first one, the Iodine-125 will be adsorbed in the silver core. In the second one, the titanium tube will be sealed. And finally, in the third one, all the assurance tests will be carried out. All the automation process of the welding glove and the quality control glove are finished.

Methods for Iodine-125 deposition in silver substrate

Among the different ways to treat prostate cancer, brachytherapy with Iodine-125 seeds is an option that provides good results and fewer side effects. In the present study, several methods of deposition of radioactive iodine in a silver substrate were compared in order to choose the most suitable alternative for the routine production to be implemented at IPEN’s laboratory. The methodology used was chosen based on the available infrastructure and experience of the researchers present. The better method will be implemented in the IPEN’s laboratory for brachytherapy sources production.

Development of methodology for the synthesis of Poly(Lactic Acid-Co-Glycolic Acid) for use in the production of radioactive sources

Iodine-125 seeds can be placed loose or stranded in bioabsorbable polymers. Stranded seeds show some advantages, since they reduce the rate of seed migration, an event that could affect the dosimetry of the prostate and cause unnecessary damage to healthy tissues or organs. For Iodine-125 stranded seeds, polyglactin 910 (poly(lactic-co-glycolic acid)) (PLGA), with a coverage of polyglactin 370 (Vicryl®) is used.

It was purposed, in this project, the study and development of the synthesis methodology for PLGA via ring-opening polymerization, as well as its characterization, with the objective of using the synthesized material to manufacture a material similar to RAPID Strand®. The results obtained show that it was possible to determine the optimal reaction parameters (time and temperature) for PLGA in 80/20 (lactide/glycolide) ratio. Using a temperature of 110°C and reaction time of 24h, a yield of 86% was obtained, and increasing the reaction time to 72 hours, the yield was higher than 90%. The molecular mass values obtained from the samples are still very low compared to those obtained by other authors in the literature (about 20%). Failures in the sealing of vials, leaving them vulnerable to moisture and oxygen, or lack of an efficient stirring system might be possible explanations for these results. A suitable chemical reactor could solve the problem. Regarding polymer characterization, all techniques used not only confirmed the expected structure of the polymer, but also showed the highest proportion of lactide units compared to glycolide units.

Study and parameters survey for Iodine-125 source dosimetry to be applied in brachytherapy

The objectives of this work are the development and the study of dosimetric procedures
associates with the experimental acquisition of the useful parameters for the Iodine-125 dosimetric characterization and to evaluate if the developed procedures, in this work, have the basic conditions to determinate the dosimetric analysis, that are fundamental for clinical procedures. The dosimeters selected for the analysis are the TLD-100 (LiF:Mg,Ti). Initially, these dosimeters were submitted to two selection steps to choose the dosimeters more reproducible for the dosimetric analysis. The two steps were the selection by the mass of the dosimeters and the reproducibility after four irradiation series in a Cobalt-60 irradiator (CTR-IPEN). After, the dosimeters were used to the irradiations with Iodine-125 seed, 6711 model, (GE-Healthcare). The irradiations and others analysis with Iodine-125 seeds yielded the useful values for the determination of the parameters suggested by the AAPM (American Association of Physicists in Medicine): constant of dose rate, geometry function, dose radial function and anisotropy function. The results showed good agreement with the values published by the literature, for the same Iodine-125 model. This fact confirms that the achieved parameters will be able to be used for the IPEN-CNEN Iodine-125 seeds dosimetry and quality control.

**Study and development of an iridium-192 seed for use in ophthalmic cancer**

Although ocular tumors are not among the cases with a higher incidence, they affect the population, especially children. The Institute of Energy and Nuclear Research (IPEN-CNEN/SP) in partnership with Escola Paulista de Medicina (UNIFESP), created a project to develop and implement an alternative treatment for ophthalmic cancer that uses brachytherapy iridium-192 seeds. The project arose since the Escola Paulista treats many cancer cases within the Unified Health System (SUS) and also because of the research experience of sealed radioactive sources group at IPEN. The methodology was developed from the available infrastructure and the experience of the researchers. The prototype seed presents with a core (192-iridium alloy of iridiumplatinum iridium platinum) of 3.0 mm long sealed by a capsule of titanium of 0.8 mm outside diameter, 0.05 mm wall thickness, and 4.5mm long. This work aims to study and develop a seed of iridium-192 from a platinum iridium alloy. No study on the fabrication of these seeds was found in available literature. It was created a methodology that involved: characterization of the material used in the core, creation of device for neutron activation irradiation, laser welding of the titanium coating and testing of quality control. The result proved the feasibility of the method. As a suggestion for future work, studies regarding metrology and dosimetry of these sources should be carried out, for future implementation in national scope.
Health Application of Ionizing Radiation and Radioactive Sources

Brachytherapy technique in nanoscale

Cancer is a global public health problem. The disease consists in an uncontrolled growth of anomalous cells that impair the functioning of the body. One of the treatments for cancer is the brachytherapy. In this treatment technique, the radiation is placed close or in contact with the region to be treated. The idea of using radiation sources to treat disease is as old as the discovery of radiation. With the association of modern medicine with computational methods for manufacturing, testing and certification, radiation sources for treatment are being produced with high efficiency at millimetric sizes. With recent advances in nanotechnology, the use of nanoparticles (NPs) instead of the traditional seeds is actively being investigated. Due to the minimal size of the NPs, the radiosensitization may be avoided, once this method may delivery a more precise dose only to the target volume, preserving adjacent tissues and organs at risk (OAR). The combination of nanotechnology with radiation sources created the new research field: nanobrachytherapy. There are several challenges to be considered when implementing this research such as characteristics of the radioisotope since not all isotopes can be used to treat cancer, radiation protection, characterization and animal tests issues. For the past two years, our group at IPEN, with a partnership with the University of Laval, was able to start a joint research and developed two new nanosources.