THE IEA-R1 62 YEARS OF OPERATION: EXPERIENCES AND LESSONS LEARNED

F.A. Genezini, A.J. Fernandes, G. S. Zahn
Nuclear and Energetic Research Institute – Brazilian National Nuclear Energy Commission. IPEN-CNEN, São Paulo, Brasil
E-mail contact of main author: fredzini@ipen.br

Abstract Early in 1956, the Atomic Energy Institute (IEA, from the acronym in portuguese) was founded with the aim of installing the nuclear research reactor purchased from the American company Babcock & Wilcox in the framework of the "Atoms for Peace" program. The start-up was on September 16, 1957, where the first criticality in the Southern hemisphere was achieved. The IEA-R1 is a pool type, light water cooled and moderated, beryllium and graphite reflected research reactor. Although designed to operate continuously at up to 5 MW, it operated at 2 MW for 40 years and only rather recently started operating at 5 MW. This year IEA-R1 completed 62 years of operation. The reactor is the core of the Nuclear and Energy Research Institute – IPEN (former IEA) – with its laboratories working for radiopharmaceutical applications, in the areas of radiological protection, nuclear fuel cycle, nuclear engineering, and radiation applications among others. Throughout this period it underwent several reforms, renovations and changes of management. In 2000 an Integrated Management System (IMS) has been structured, based on ISO-9001, in order to keep the operation safe, which implied certain procedures together with a continuous modernization program, and to comply with the regulatory requirements at the date as well. The first certification dates to 2002 and since then the reactor has been successfully renewing its ISO certification. The history, experiences and lessons learned during the 62 years of the IEA-R1 operation are described and shared in this paper.

Key Words: IEA-R1 Research Reactor, Modernization, history.

1. INTRODUCTION

IEA-R1 was the first reactor to operate in South America, built in the late 1950's as part of the *Atoms for Peace* program. Since its first criticality, the reactor underwent several modifications, both in its structure, in the fuel used and in the operating schedule. Along these years, several distinct applications were developed in the reactor, both in basic science, medical or industrial applications, and so on. The following sections intend to tell some of that story.

2. THE IEA-R1 REACTOR

2.1. The Construction

With the advent of the mastery of nuclear fission process, the end of World War II and the start of the Cold War, the development of nuclear industry has become a crucial issue. In 1953 the United States President delivered his famous speech called "Atoms for Peace", which marked the beginning of the USA program that supplied equipment and information to schools, medical facilities and research institutions within the U.S. and throughout the world. In this regard, a Brazilian representative attended the first meeting for the peaceful use of atomic energy in 1955, where a research reactor has been offered to Brazil as a part of this program. In order to take care of the reactor, IEA was created in 1956, marking the beginning of the construction of the facility.

The main objectives of IEA-R1 project included developing research on peaceful uses of nuclear energy; producing radioisotopes for various applications and contributing to the human resources formation in the fields of nuclear science and technology. The reactor was designed and built by Babcock & Wilcox Co., in accordance to the requests of the IEA. Reactor construction started in the second half of 1956 and the first criticality was reached in

September 16th, 1957; thus, a period of just one year and sixteen days separated the beginning of reactor construction and the date of its first operation [1].

2.2. General Description of IEA-R1

The IEA-R1 research reactor of IPEN is situated in the main campus of the University of São Paulo. The reactor building has a total area of ~2 000 m2 in its 5 floors, as shown in figure 1. The pool goes from the first floor (bottom of the pool) to the third floor (water surface). The primary cooling system, the water treatment system and the heat exchanger are located in the basement level. The neutron experimental hall is located on the first floor. At this floor an airlock gate allows the passage of large sized equipment or vehicles, e.g. forklifts. The main access to the reactor, also through an airlock chamber, is located on the second floor and so is the ventilation system. The third floor houses the pool hall and the control room, whereas and the fourth floor contains the air conditioning system.

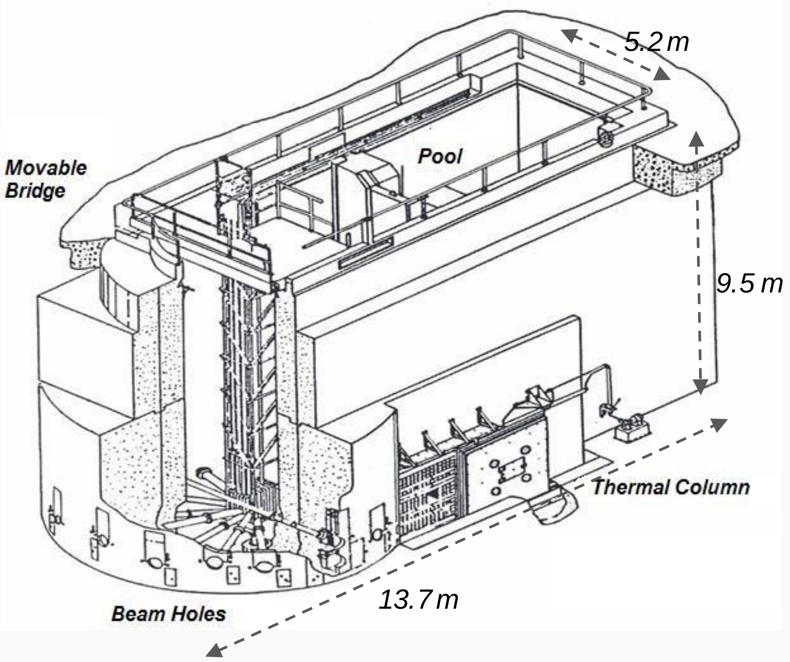

FIG. 1. Drawing of the IEA-R1 Research Reactor

.

The reactor is an open pool type, as previously mentioned, cooled and moderated by water, with a nominal power of 5 MW. The pool has 272 m^3 capacity (5.2 m x 13.7 m x 9.5 m) and the wall thickness is 2.40 m in the core region and approximately 1.5 m above it. The reactor core is linked to a movable bridge, approximately 8 meters deep. When the core is operating in the regular position, the forced cooling system is coupled to it, so that 13 kL of water are passing through it per minute.

The pool can be divided in two compartments, the principal one, where the core is located, and a smaller one that houses spent fuel elements. Also, in the main part of the pool there are 10 beam tubes, two radial and 8 tangential, positioned around the core for neutron experiments, and a graphite thermal column, but its use requires that the core is repositioned and then the reactor can only operate at up to 100kW due to the lack of forced cooling system at that position.

2.3. Operating Regime

Since the first criticality, for two years IEA-R1 operated at 1 MW and in the next 35 years (from 1960 to 1995) the operation regime of the reactor was of 8 hours per day, 5 days per week at 2 MW. In 1995, with the increasing need for ^{131}I, IEA-R1 started to operate continuously from Monday 8:00 a.m. to Wednesday 12:00 p.m. (in total, 64h per week), and an upgrade project was launched in order to reach safe operation at 5 MW. On September 16, 1997, 40 years after its first criticality, IEA-R1 was operating at 5 MW, 60 h per week, until the middle of 2015.

2.4. Nuclear Core

The core is mounted on the grid plate linked to the movable bridge with aluminum truss structure, ~8 m deep. This plate has an 8x10 matrix allowing for different configurations of fuel elements, irradiation devices and reflectors. The control and safety bars driving mechanism is also linked to the bridge, and above the core inside the one-side sealed pipes ionization chambers, fission chambers and other control instruments are positioned.

The first configuration of the IEA-R1 core was a 5x6 arrangement with of curved plate type Low Enriched Uranium (LEU) of U-Al alloy with 1.9 g/cm^3 of U (the first load produced by Babcock & Wilcocx), but shortly after these exhibited pitting corrosion and were changed. In 1968 the fuel elements were changed to flat plate type with 93 % of enrichment and with 0.6 g/cm^3 of U, also made with an U-Al alloy (produced by UNC/USA and NUKEM/Germany) [3].

In the beginning of the eighties with the core conversion from high enriched (HEU) to LEU, five elements (produced by NUKEM with U-Alx alloy - 19.75 %) were placed in the core matrix of IEA-R1. At the same time IPEN started developing its own fuel elements. In 1985 two prototypes (U_3O_8-Al, 1,9 g/cm^3 of U – 19.75 %) were examined in the IEA-R1 and in 1988 the first Brazilian fuel elements were placed in IEA-R1 core matrix. After this first production of 18 fuel elements in 1997, the U density was increased to 2.3 g/cm^3, and since 1998 IEA-R1 started using fuel elements of U_3Si_2 with 3.0 g/cm^3 density until the complete substitution of the U_3O_8-Al. The current standard fuel element is composed of 18 plates with around 10g of ^{235}U each, and the control fuel elements are composed of 12 plates in the center and two channels at the tips.

The safety and control elements were changed in 1968, from oval type based on B_4C to fork type made with Ag-In-Cd alloy. The original control bars entered through open central channels of each of the 4 control fuel elements. This geometry was replaced by the one with two channels per control element situated at the element side borders available for a two-blade control bars.

Current configuration of the core is 5x5 with 24 fuel elements and Beryllium Irradiation Element (EIBE) in central position, a beryllium trap device with 16 irradiation positions for high neutron flux irradiations (up to 10^{14} n.cm^{-2}.s^{-1}). On the grid plate, around the core, are located two Water Cooled Graphite Irradiation Elements (EIBRA), a rectangular aluminum profile with beryllium reflector (22 irradiation positions each) and another one similar with 8 irradiation positions but used only for Iridium wires irradiation (EIF). Another 5 elements with two concentric aluminum tubes called Water Cooled Irradiation Elements (EIRA) with 16 positions each remain in the fixed positions. Another core cell is occupied by a pneumatic irradiation system for short irradiations (up to 5 mins). The core is surrounded by graphite and beryllium reflectors. Since its first start-up 265 core configurations have been installed. Figure 2 illustrates the 265 core configurations.

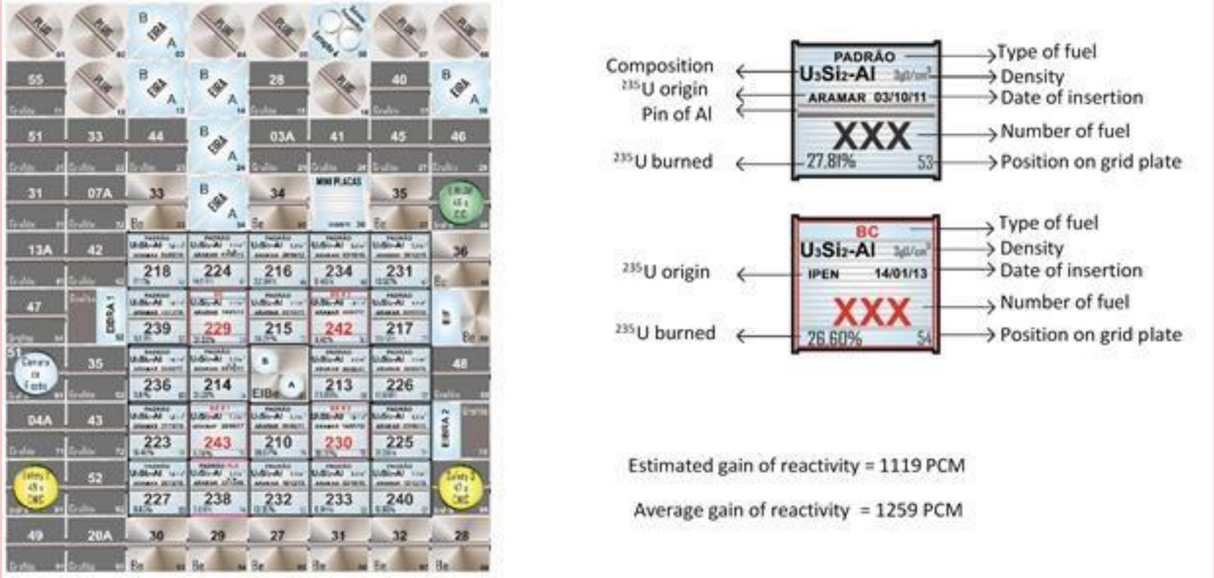

FIG. 2. The 256 core configuration

2.5. Upgrades Required for 5MW Operation Regime

To implement the 5MW upgrade project several difficulties were solved, among them core management issues, adaptations related to safety aspects and staff training. The core management, as described in the section 2, consisted of adopting the technological know-how of IPEN, namely, production of higher U density (3 g/cm^3) fuel elements and installation of irradiation devices with beryllium trap for neutron flux enhancement.

Certain safety issues had to be solved in order to get the license for 5 MW operation in accordance with the “Guidelines for the Review of Research Reactor Safety” (IAEA Services Series Nº 1). Among the main changes, the “Guidelines” highlights the improvement of Instrumentation and Control, the radiation monitoring setup and the electrical system; the assessment and adequacy of the cooling system and the exhaustion, ventilation and air conditioning system; installation of the emergency cooling system and of the fire protection system.

The protection system and safety related instrumentation have been improved. Specifically, interlocks were installed to perform the primary circuit isolation and the emergency core cooling system valves actuation, as well as to protect the core from power excursion at lower power levels. The reactivity control system was installed, based on ^{16}N detection and consisting of two channels: the linear (a compensated ionization chamber doped with ^{10}B) and a ^{16}N channel. As for the radiation control equipment, replacement of old monitors and introduction of gaseous effluent monitors were performed.

The assessment and tuning of the cooling system and of the exhaustion, ventilation and air conditioning system were performed and both cooling towers were refurbished and repaired. The exchange of the alpine cooling tower was planned but its execution only occurred in 2012. The whole secondary circuit was changed. The primary and secondary pumps were completely overhauled and a Vibration Monitoring System was commissioned in order to predict maintenance requirement[6]. The Heating, Ventilation and Air Conditioning (HVAC) System was changed with separation of the reactor building in cold and hot areas, according to radiation exposition criteria. These areas were isolated from each other by placing interlock chambers between them so that the hot materials are handled in hot areas only. A new set of filter batteries, shutoff dampers, fan coils, blowers, isolated air ducts and instruments were installed. In the electric system, the distribution of power from main switchgear and emergency generators directly to the set of consumers and motor control centers became possible due to the installation of new power panels.

With the increase of power the regulatory body has requested an Emergency Core Coolant System (ECCs). The ECCs consist of two raised reservoirs, piping, valves and a distributor with spray nozzles, as well as the necessary instrumentation for measurement, actuation and monitoring, and a line for periodic tests. It is a fully passive system for removing residual radioactive decay heat from the reactor core preventing the fusion of the combustible elements in events such as the Loss Of Cooling Accident (LOCA). The two water reservoirs have 75 m^3 each, which ensures a minimum of 3 m^3/h (0 83 kg/s) flux at core position for at least 14h [11]. Also, a new fire protection system was installed composed of fire detection and extinguishing system, initially covering only the areas with greater fire risks, and later the whole building.

The operation team was reinforced with new trainers in such a way that in 2010 it was composed of 6 senior operators (supervisors), 11 operators and 7 trainees. The training program was improved with the addition of hands-on sessions and a two-week internship at each reactor system. In the present IEA-R1 training program, after the candidates complete the course they take a number of internal tests; if the individual notes are greater than 7 and the mean note greater than 8, the candidate is able to apply for regulatory agency test in order to get the operator certificate. All the operator groups should be a part of the Fire Brigade, and as part of the training process, a quota was established for two fire exercises per year conducted by Sao Paulo City Fire Department (2008). Other parts of the team now include radiological protection, electronic and mechanic technicians and irradiation service staff who receive the samples, prepare the irradiation devices and communicate with clients.

2.6. The Ageing Program

As mentioned previously, the increased demand for radioisotope production resulted in changing the reactor operation schedule and technical tuning for its safe operation at 5 MW. Several modifications were implemented as described above. However, a course was taken to a continuous modernization. As a result, only the aluminum trusses and the grid plate are now original parts of the reactor. Some modernization procedures are ongoing, among them the installation of digital control console acquired from RADIY in 2017, the enhancement of the storage for spent fuel assemblies, etc. The main modernization tasks performed over the years are summarized in Table 1.

TABLE I: MAIN REPLACEMENT OR MODERNIZATION TASKS PERFORMED IN IEA-R1.

Year	**Modernization / Refurbishment**
1971	Change of the ventilation system, assuring negative pressure inside the building
1974	16N decay tank installation
1977-1978	Replacement of the original ceramic tiles of pool by stainless steel plate lining.
	Change of the reactor control console, designed by G.A.
1985	Improvement in the control instrumentation
1987-1988	Implementation of two separate areas inside the reactor, hot and cold.
	Installation of new cooling tower
1988	Change of the core size from 30 to 25 fuel assemblies with 2.3gU/cm3
1991	Water treatment system boundary covered with lead radiological shield
1996	New fire-detection and fighting equipment (smoke detectors, sprinklers, hydrants)
	Major maintenance in the old cooling tower
1997	Replacement of area and duct radiation monitors
	Installation of new ventilation and air conditioning system.
	Installation of an emergency core cooling system to prevent meltdown in LOCA.
	Isolation valves in Primary circuit to prevent accidental drainage of the pool water
1999	Original HEU fuel elements returned to USA totalizing 127 spent fuel assemblies in 1999 and additional 33 in 2007.
	Introduction the beryllium irradiation device at the center of reactor core
2000	Implementation of an online data acquisition system with full capabilities
2001	Vibration monitoring system
2004	Substitution of the former safety rods by new absorbing devices fabricated on-site
2005	Replacement of 13 graphite reflectors with Beryllium.
2007	Replacement of primary heat exchanger.
	New pneumatic irradiation system.
2011	Replacing all auxiliary instrumentation racks at the reactor control room
2012	Exchange of the secondary circuit pumps
2014	Exchange the primary cooling circuit pipe.
2015	New meteorological tower that provides real time data of atmospheric conditions
2019	Change of 220V electric generator
2020	**Change of the control console**
	New rack made of BORAL for spent fuel assembly storage
	New pneumatic irradiation station
	Change of 440 V electric generator
2021	**Change of 4 control bars**
	Pneumatic transfer systems for irradiated samples.
	New storing of liquid waste system and modernization of the reactor holding tank.

2.7. The IMS System

In 2000 the Research Reactor Center – CRPq was established as the department in IPEN responsible for operation and maintenance of the IEA-R1, as well as improving its utilization. At the same time, the discussion about Strategic Planning and Quality Management System of CRPq, based on ISO-9001, started. The main directions were safety and turning the reactor operation client-oriented. Other motivations included the necessity to satisfy the requirements of the regulatory agency [8] and to develop a more efficient management system capability that would fit the modern business strategies. The system has been improved. Examples include the implementation of a computerized scheme to control the periodic tests, and preventive - even predictive - maintenance, or the formalization of periodic meetings devoted to modernization that are now held at a regular basis. It should be highlighted that the system is based on ISO9001 but complies with norms of the regulatory agency for nuclear facilities [8] and is prepared to absorb other ISO standards, e. g. environmental or occupational ones. The system has a three-level structure organized as follows. The documents such as the “Business Plan” and “Quality Assurance Manual” are associated with the strategic level, the “Action Plan” and “Safety Analysis Report” with tactical level, and procedures and work instructions belong to the operational level. At present, the architecture evolved to an Integrated Management System (IMS), based on three processes: reactor operation, maintenance and irradiation service. These processes are strongly interrelated and have an assigned manager whose responsibilities are defined clearly. For each process, risk assessment using different tools are performed periodically.

The first certification dates to 2002 in “Reactor Operation and Irradiation Services,” and since the reactor has been successfully renewing its ISO certification, so that now it is certified according to ISO 9001:2015 version.

3. REACTOR UTILIZATION

Since its first operation, several different activities have been developed in IEA-R1. In neutron science, today, only three beam hole stations are in use: one for neutron imaging, one for high resolution neutron diffraction, and there is also a multipurpose one, for neutron detector testing, assessment of neutron damage in electrical and electronic circuits, and for Boron Neutron Capture Therapy. Other installations devoted to time-of-flight spectroscopy, photofission measurements and triple axis scattering are now decommissioned, due to personnel retirements. The beam holes setup is shown in figure 3.

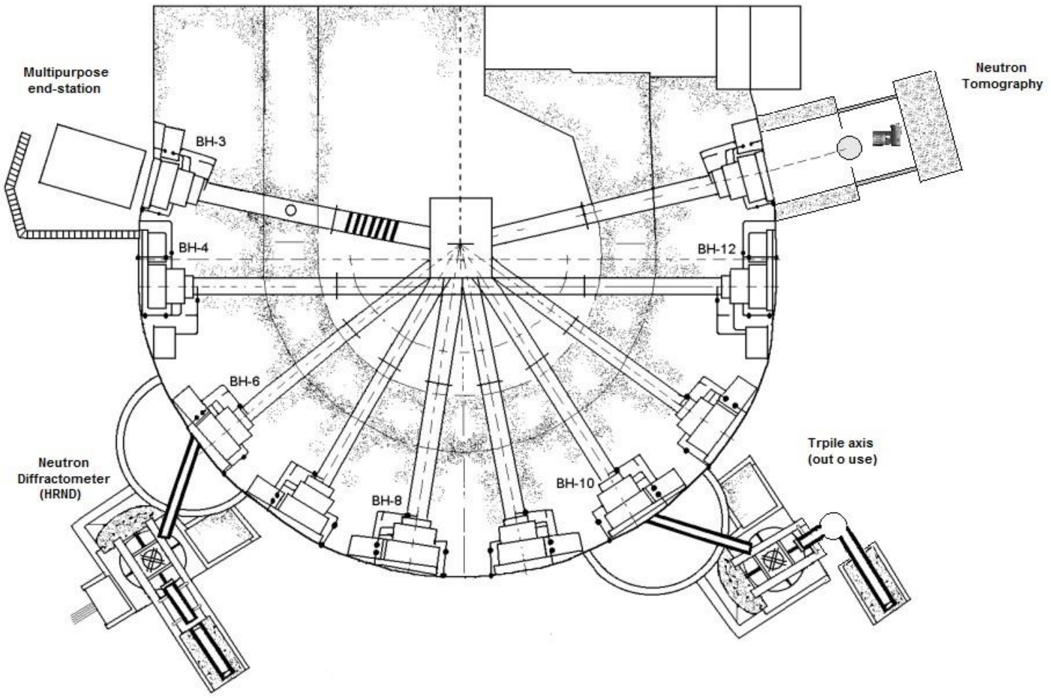

FIG. 3. IEA-R1 beam holes setup.

In-core irradiation related research and development carried out today include irradiation of fuel miniplates, fuel elements studies in a closed loop with individual cooling, and monitoring and control system for irradiation of fuel pins. Also, an instrumented fuel element was produced for collecting thermal parameters inside and outside cladding. This element was irradiated for a period and then put outside of water. Several samples are also irradiated, with or without cadmium cover, for Instrumental Neutron Activation Analysis (INAA). The associated laboratories have a set of 13 Ge detectors, and for short half-live, the pneumatic station, close to these laboratories, is used. Nuclear data related to neutron-induced nuclear reactions, including the radioactive decay of nuclei therein produced are also studied. Material studies based on hyperfine interactions applying the Perturbed Angular Correlation (PAC) are also performed with nuclides as ^{139}La or ^{181}Hf produced in IEA-R1. Other important line is the use of thermal neutron irradiation in apatite of zircon samples for geochronology studies.

Related to products and services, in addition to radioisotopes for nuclear medicine, there is a growing demand for radiotracers as ^{79}Kr or ^{41}Ar, specially for oil industry plants. Other radioisotopes for this applications have been produced during the years as ^{203}Hg. ^{131}I, ^{82}Br, ^{192}Ir, ^{198}Au, and ^{140}La. Doped silicon was also produced using a device that allows optimal axial and radial uniformity of the neutron dose - the uniformity and doping accuracy, determined by resistivity measurements, shows an excellent doping quality.

An important role of the IEA-R1 activities is to contribute to education and training of human resources for the country's nuclear program. IPEN and University of São Paulo have a joint graduation course in Nuclear Technology, and IEA-R1 was used by hundreds of students for their Master of Science and/or PhD degrees.

3.1. Radioisotope Production

The first production of radioisotope for medical application in IEA-R1 was of ^{131}I, beginning in 1959, in the first two years in trial basis. The production was based on $^{130}\mathrm{Te}(n,\square)^{131m}\mathrm{Te}$

reaction, that decays with 30 h of half-life to ^{131}Te which then decay to ^{131}I. The radioisotope was sent to radiopharmacy unit in order to separate iodine from tellurium by dry distillation, and used only in diagnosis, due to the low specific activity. Until 2015, the amount of ^{131}I produced by IEA-R1 was 2700 Ci per year but this year due to leaks in the hot cell, the production was suspended.

Other radioisotopes used in nuclear medicine have been produced during the years of IEA-R1 operation, but not in a regular mode. Sulphur for diagnosis of testicle disease, by ^{35}Cl(n,p)^{35}S reaction or ^{32}S(n,p)^{32}P for bone disease, and also ^{50}Cr(n,□)^{51}Cr for marking cells techniques For therapy, ^{153}Sm for palliative bone pain relief is also produced in regular schedule, by gamma capture in samarium oxide; Iridium wires for brachytherapy application are also frequently produced. The amount of these radioisotopes are 60 Ci of ^{153}Sm and 31 Ci of ^{192}Ir wires per year, on average.

4. CONCLUSION

Over the last 62 years, IEA-R1 has been excelling at its original role of fomenting the knowledge, science and technology related to the peaceful use of nuclear energy. From the production of radioisotopes for health management uses to studies on atomic and nuclear properties; from the understanding of the nuclear cycle to research on environmental pollution; from the assessment of electronic systems to be used under strong neutron fields to the dispersion of knowledge, IEA-R1 has been a cornerstone of the Brazilian nuclear field. This mission demanded great refurbishment and modernization of the reactor, which is a never-ending process aiming to improve the safe, solid operation of Brazil’s largest nuclear research reactor for the years to come.

REFERENCES

[1] SANTOS, M. D. DE S., TOLEDO, P.S. DE Description of the Brazilian Research Reactors, PROCEEDINGS OF 2ND U.N. GENEVE CONFERENCE, vol. **10**, Geneve (1958) 2274.

[2] SANTOS, M.D. DE S. et all Preliminary Results of 5 MW Operation With the Brazilian Swimming Pool Reactor PROCEEDINGS OF 2ND U.N. GENEVE CONFERENCE, vol. **10**, Geneve (1958) 2279.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Isotope Guidelines for the Review of Research Reactor Safety: Revised Edition Reference Document for IAEA Integrated Safety Assessment of Research Reactors (INSARR), Services Series Nº. 25, IAEA, Vienna (1997) (CD-ROM).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Code on the Safety of Nuclear Research Reactor Design, Safety Series Nº. 35-S1, IAEA, Vienna (1994) (CD-ROM).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Code on the Safety of Nuclear Research Reactor Operation, Safety Series Nº. 35-S2, IAEA, Vienna (1994) (CDROM).

[6] E. de L. BENEVENUTI Metodologia para monitoração e diagnóstico de vibração das bombas moto-operadas do circuito primário de refrigeração do reator IEA-R1”, F Dissertação de Mestrado, IPEN/USP, |São Paulo (2004), CD-ROM and https://bdpi.usp.br/item/001377463.

[7] INSTITUTO DE PESQUISAS ENERGÉTICAS E NUCLEARES, Relatório de Análise de Segurança do Reator IEA-R1, IPEN-CNEN/SP, Rev. **1**, São Paulo (1996).

[8] BRAZILIAN NATIONAL NUCLEAR ENERGY COMMISSION, Garantia da Qualidade para a Segurança de Usinas Nucleoelétricas e Outras Instalações, CNEN, Rio de Janeiro (2000), in http://appasp.cnen.gov.br/seguranca/normas/pdf/Nrm116.pdf.