

## THE UTILIZATION AND OPERATIONAL EXPERIENCE OF IEA-R1 BRAZILIAN RESEARCH REACTOR

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### Abstract

IEA-R1 was the first research reactor (RR) to operate in the southern hemisphere (September, 1957) and now days it is one of the oldest RR still operating in the world. Since its first criticality it had been used in research, non commercial production of radioisotopes (RI), Neutron Activation Analysis (NAA), Material Testing and Training. This paper will describe the operational experience along its life including the conversion from HEU to LEU, the recent power upgrade from 2 MW to 5 MW and the continuous modernization program, mainly the aging management program. Its present utilization in Neutron Scattering (NS), NAA, Neutron Transmutation Doping (NTD), commercial production of RI ( $^{99}\text{Mo}$ ,  $^{131}\text{I}$ ,  $^{192}\text{Ir}$ ,  $^{153}\text{Sm}$ ), Material and Fuel Testing, Gems irradiation and a facility for research in NCT (Neutron Capture Therapy) will be described. The main conclusion is that even an old RR of middle power in a developing country can have multipurpose utilization if investments are made in its operational performance.

### 1. INTRODUCTION

During the fifties many RR were built around the world ( $\cong 286$  were commissioned at that time), however now days it is a fact that many RR are being shutdown, mainly in developed countries. Thus from a total of around 500 RR built, still only half of this figure are operating. The tendency is not to build small RR at universities, zero power reactors and even demonstration or pilot reactors at research institutes, but to build multipurpose RR, such as HANARO (Korea), ETRR-2 (Egypt) and FRM-II (Germany), with power in the range between 20 to 30 MW, or very intense neutron sources, as the French Jules Horowitz, which can substitute all other RRs of the country, and even have its utilization shared among several users. However if this rule is valid in developed countries, in developing country the situation in general is not the same with exception of countries with an advanced nuclear program, as China and India. In these countries most of RR were built in the frame of the Atoms for Peace Program (USA) as in the Western countries or by the former Soviet Union in Eastern Countries. In general they were not built with a clear purpose, or need, being in that time a kind of fashion for any called “civilized” country to have a RR, no matter how poor it was. Today many of RR in the developing countries are facing problems related with aging, safety and even utilization. This paper describes how a developing country, as Brazil, is modernizing its main RR in order to face the challenge to increase the utilization, safety, management and operational performance of an old RR with a restricted budget (IEA-R1 is 42 years old, being one of the oldest RR still operating in the world).

TABLE I. RESEARCH REACTORS IN BRAZIL [1]

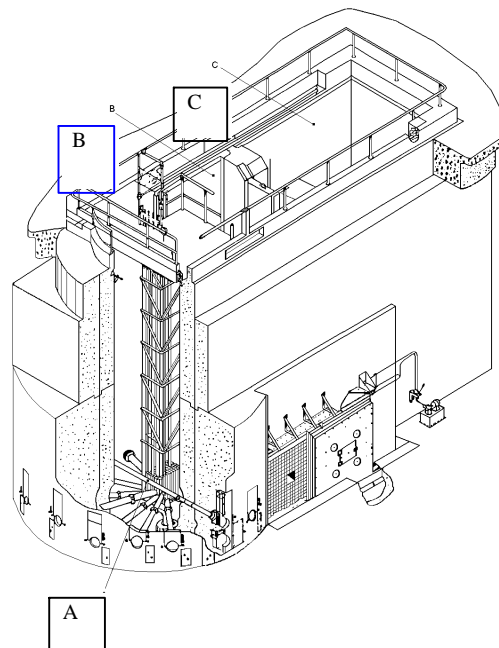
Reactor/Place/ Criticality Date	Type	Power (kW)	Utilization
IEA-R1/São Paulo/1957	Open Pool	5,000	RI production, Neutron Scattering, NAA, NTD, Material and Fuel Testing, Training
IPR-R-1/Belo Horizonte/1960	TRIGA-MARK-I	100	NAA, Training, Radio Tracers production
IEN-R-1/Rio de Janeiro/1965	ARGONAUTA	0.2	Training, Research
IPEN-MB-01/São Paulo/1988	Critical Assembly (Tank Type)	0.1	Zero Power Simulation of small LWR (Nuclear Propulsion), Research in Reactor Physics

Brazil has 4 RR in operation, as listed in Table I, and from this table one can notice that IEA-R1 is the only one with power suitable for multipurpose applications.

## 2. GENERAL DESCRIPTION

The IEA-R1 is a pool type, light water cooled and moderated, graphite reflected RR. It was designed and built by Babcock & Wilcox Co. in the US Atoms for Peace. Its first startup was on September 16<sup>th</sup>, 1957, being the first criticality in the southern hemisphere. During the 2<sup>nd</sup> UN Geneva Conference the description [2] of the IEA-R1 was first reported, and since then several publications were published describing the reactor as well as its utilization [3, 4]. Even so, here we wish to review a general description, mainly to update this information given the modifications done along its life and to describe the irradiation devices.

The reactor building is located at IPEN in the campus of São Paulo University. The reactor pool is located in a steel lined concrete structure (5.2 m × 13.7 m × 9.5 m) inside the reactor building, as illustrated in Figure 1. There are three position where the reactor core can operate, in position A, the heat is removed through forced water circulation from up to down, in position B, by natural circulation (100 kW), and position C is used to transfer burned fuel elements to the storage racks.



*Figure 1. General view of the reactor pool structures.*

The reactor core, the reflector (graphite) and the irradiation elements are assembled in a  $8 \times 10$  grid plate which is suspended by an Al structure linked to a bridge located on the top of the pool. Presently the core is a  $5 \times 5$  array of fuel assemblies (FA) with 18 plates, LEU oxide ( $U_3O_8Al$ ). The control elements (4) are fork type of Ag-In-Cd. Figure 2 illustrates a typical configuration of IEA-R1, including the pneumatic system used for NAA and irradiation elements which are used for in-core irradiation.

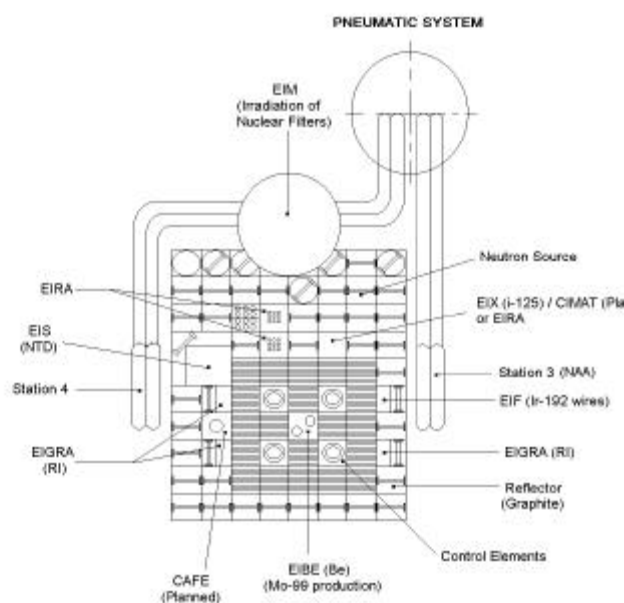


Figure 2. Typical grid configuration of IEA-R1.

The following irradiation elements are available:

- EIRA — Water Cooled Irradiation Element consisting of two concentric tubes. The external tube has holes which allows the cooling, and the internal tube has 8 position to lodge standard water proof aluminum capsules. It is used for RI production and others eventual irradiation.
- EIGRA — Water Cooled Graphite Irradiation Element consisting of a rectangular Al profile with a shelf in the interior having 24 receiving positions for capsules. It is fixed in the grid plate using another rectangular Al profile which is filled with graphite. It is also used for RI production.
- EIX — Water Cooled Irradiation Element used to irradiate pressurized capsules of Xe to produce  $^{125}I$ .
- EIF — Similar to EIGRA, used to irradiate Iridium wires.
- EIS — Silicon Irradiation Element (NTD).
- EIC — Al tube fixed in the matrix plate used to irradiate nuclear micro filters.
- CICON — Irradiation loop with cooling, monitoring and control system for irradiation of fuel mini plates.
- CAFE — Pressurized loop with capsule for irradiation of small LWR fuel pins.

Beam holes (BH) are available at the two core position. In front of thermal column position, are located 2 BH which are not used anymore, and at the main-core position there are 8 radial BH, and 1 tangential. The utilization of these BH will be described later on.

The primary system has two heat exchangers, each with 5 MW thermal capacity, and the secondary has also two independent cooling towers with a capacity to dissipate 5 MW of heat each. The main change in the cooling system was made when the upgrade of power from 2 to 5 MW was done. The most representative was the introduction of redundant isolation valves to avoid a LOCA due to a break of the primary pipeline. Also all the secondary pipelines were completely changed to a new over ground system to facilitate inspection. Finally a passive emergency core cooling system (ECCS) of spray type was introduced. Figure 3 illustrates a simplified flow sheet of the cooling system and the ECCS. Besides these systems, the reactor has auxiliary systems, such as water make up, purification, ventilation and air conditioning, electrical, etc., which had been modified during the reactor lifetime.

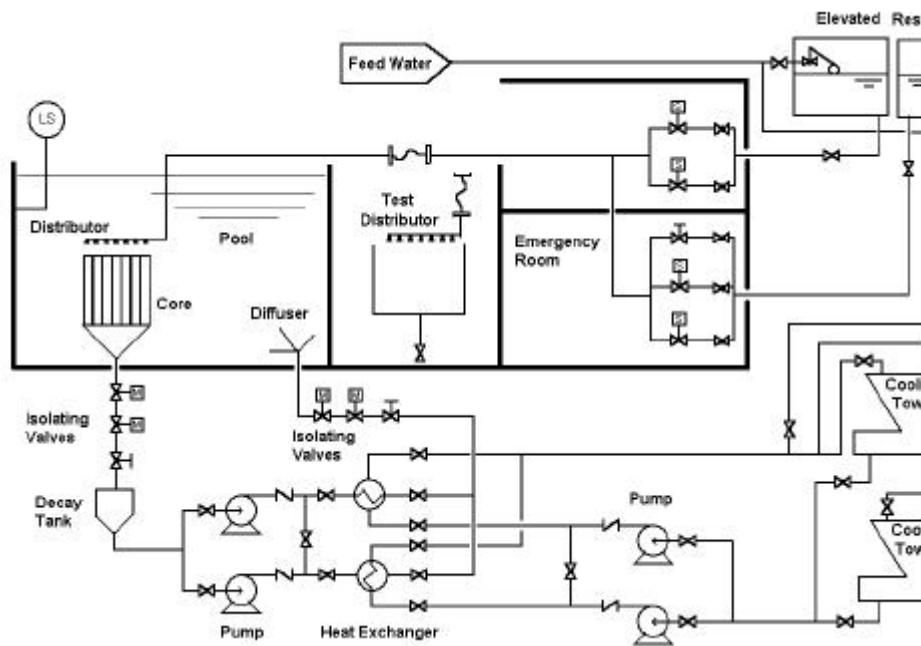


Figure 3. Simplified flow sheet of the cooling and ECCS systems.

### 3. OPERATIONAL EXPERIENCE

The IEA-R-1 was designed by Babcock & Wilcox Co. and start its construction in 1956. After one year, the construction was finished and in September 16, 1957 the first criticality was achieved, the first in the Southern Hemisphere. During the first years of operation, the reactor operated at 1 MW. From 1960 to 1995 the reactor operated at 2 MW, 5 days per week, 8 hours/day. After 1995, it started operating continuously from Monday to Wednesday (64 hrs/week), and start an upgrading of power project to 5 MW, and in September 16, 1997, 40 years after its first criticality it start operating at 5 MW. Now days, the reactor is starting a continuous operation (120 hr/week) at 5 MW. This session will describe the operational experience of IEA-R1 regarding core management, including spent fuel management and improvements in systems, components and structures, including the power upgrading.

#### 3.1. Core management

The first IEA-R1 core was a 5x6 arrangement of LEU, U-A1, with 19 curved plate fabricated by B&W and had been used for a short time, when fuel failure occurred (pit corrosion). These first load (total of 40 FA, including control), were replaced by the same type as the early one but with improvements in the fabrication. Today the first failed load is storage in dry tubes located in the 1<sup>st</sup>

floor the reactor building and are sending back to the USA in the RR spent nuclear acceptance program of the US DOE. Since the first configuration, 206 core configuration were assembled in the reactor grid, using different types of fuel. Although, the fuel history of IEA-R-1 had been described during the RERTR meetings [5, 6], here we summarize this information. In 1968, a load of HEU FA, U-Al flat fuel plates (18) was bought from USA, and many of them were kept in the core configuration until two years ago. Also at this time the control elements were changed from oval type (B<sub>4</sub>C), to fork type (Ag-In-Cd) to be inserted in control FA fabricated by CERCA (4).

The core conversion from HEU to LEU, starts in the beginning of eighties, when 5 LEU of U-Al<sub>x</sub>-Al, 18 plates FA fabricated by NUKEN were introduced in the core. Also at this time research was initiated to fabricate locally FA, and in 1985 two prototypes partial fuel elements were introduced in the core for performance tests and qualification. With the good performance of the Brazilian fabricated LEU prototypes, the first complete LEU was introduced in the core in 1988, and since then an average of two new LEU FA were introduced per year in the core, including control elements, converting gradually the HEU to LEU core, and at the same time when the reactor was ready to operate with 5 MW, in September 1997 a complete LEU 5 × 5 core configuration was introduced. Since the first Brazilian made FA (number 130) up to now, 34 FA were introduced in the core configuration, with an average burn up of 30% and peaks burn up of 50%. The qualification of the IEA-R1 FA was well described by Perrotta et al. [7]. Finally, it is worth to mention that a production of U<sub>3</sub>Si<sub>2</sub>-Al FA have already started, and will be introduced in the reactor core in this year.

The in-core fuel management is proposed by calculation (LEOPARD-UM, or HAMMER-TECH for cell calculation, 2 DB-UM, or CITATION for reactor and burn up calculations, and COBRA-RERTR for thermal hydraulics [8]). The calculated results are submitted for the approval of a safety committee, and if the results do not violate the technical specification, as described in the Safety Analysis Report [10], the proposed core configuration is approved. Finally, it is worth to mention that in view of the new power level and continuous operation planned (120 hrs/week), a core inspection program is under way (visual inspection of core components with under water camera system, flow and temperature measurements, etc.).

The spent fuel is stored in racks, located in the wet storage (position C, in Figure 1). It is interesting to mention that two new Al racks were introduced in the wet storage. Also, the spent fuel of American enriched uranium is going to be returned to the USA (127 HEU and LEU in dry and wet storage). The status of this operation was reported in the 21<sup>st</sup> RERTR [9], and it is planned to occur in October, 1999. Finally, once the spent fuel is returned to the USA, it is planned to clad the old SS racks by Al, mainly to avoid the galvanic pits of corrosion already observed in the fuel plates.

### **3.2. Systems, components and structures management (power upgrading)**

Although the IEA-R1 basic structures continues almost the same as the original project, several improvements and changes in its systems, components and structures had been made along its life, such as: i) duplication of the capacity of the primary cooling system (5 to 10 MW) with the introduction of new heat exchange (5 MW), a fly wheel and pump (1974); ii) installation of N-16 decay tank (1974); iii) installation of motor generator, with a renovation of the electrical system (1974); iv) introduction of a steel liner in pool walls replacing the old tile liner (1978); v) substitution of the original control console by a new console fabricated by General Atomic; vi) physical separation of internal areas of the reactor building, separating hot areas from cold areas, and isolating the control room from the operational top of the pool, with construction of antechambers (1987); vii) installation of a new cooling tower (1987); viii) construction of shielding in the purification water system (1991). All these modifications contributed to increase the safety and operational performance. However, the power level (2 MW), and the operating cycle (8 hrs/day, 5 days/week) limited the utilization of IEA-R1 only to research, NAA, and non commercial production of RI.

In 1995, in view of the priorities to produce radioisotopes, mainly Mo-99, Sm-153, as will be discussed in the reactor utilization, a project starts to upgrade the power to 5 MW and 120 hrs/week. In fact, just changing the cycle of operation to 64 hours continuous per week, which started in 1996, allowed the commercial production of Sm-153. As operational experience the first step was run the reactor at 5 MW, without any adequacy, in order to perform tests, mainly radiation level assessment. This experiment gave many subsidies for the entire project. One lesson learned from this experiment was that the design of a hot layer was not needed, as previously planned, saving effort and money.

To accomplish safety requirements demanded by the Brazilian Regulatory Body to upgrade the power of IEA-R1, a set of actions were made which consist mainly of the adequacy of old systems and design of new ones, involving engineering, analysis, safety evaluation and licensing. The most representatives adequacies are :

*Reactor Core:* The Core configuration was changed from mixed (HEU, LEU) 5x6 array to a LEU 5 × 5. The new core configuration provide thermal fluxes of magnitude  $5 \times 10^{13}$  n/cm<sup>2</sup>.s. Also a Be irradiator is going to be used to produce <sup>99</sup>Mo in the center of the core.

*Primary Cooling System:* Four isolation valves type ball and gate electrically actuated were installed at the inlet and outlet primary piping to isolate the reactor pool within one minute in a case of primary system piping break (LOCA). Pumps also had components changed due aging, and are monitored in operation by a new Vibrating Monitoring System.

*Secondary Cooling System:* The cooling towers were revised and all secondary piping completely changed. The new piping were installed on the ground to facilitate inspection. Also the pumps are monitored by a vibration monitoring system

*Spent Fuel Wet Storage:* Two new aluminum racks were installed, to increase the spent fuel storage capacity.

*Fire System:* A new detection and extinguish fire system was installed covering all areas of risk, according evaluation previously performed.

*Ventilation and Air Conditioning (VAC):* A new system had been installed with the separation of reactor building into two distinct and isolated areas (cold and hot). The cold area will be completely free of radioactivity contamination risk. A new set of filter batteries, shutoff dampers, fan coils, blowers, isolated air ducts and instruments were installed.

*Electrical System:* New power panels were provided to distribute power from main switch gear and emergency generators directly to set of consumers and motor control center. All wiring was checked, revised, and distributed into new cable trays, making possible the isolation of instrumentation and power cables for new systems.

*Instrumentation and Control:* Improvements were made in the reactor protection system and in safety related instrumentation. New interlocks were introduced into 2 out 3 logic, specially to drive primary circuit isolation and emergency core cooling system valves using pool level signals from new sensors as initializing events. An interlock to protect core against power excursion at lower power level was also installed. Also new panels were installed in the control room, and in the emergency room for the new systems and radiation protection systems.

*Radiation Monitoring System:* Old monitors were replaced and new gaseous effluent monitors were installed. Also new panels in the control room were installed.

*Emergency Core Cooling System (ECCS):* It is a fully passive system, employing two redundant trains with four automatic valves designed to work in fail safe concept, spraying water directly from reservoirs into uncovered reactor core, and avoiding fuel element melting. ECCS was designed to continuous operation during 26 hours after reactor shutdown.

Besides these systems small changes were done in the reactor infrastructure. Also a formal licensing process was realized with the regulatory branch of the Brazilian Nuclear Energy Commission, and a new version of the Safety Analysis Report was prepared [10]. The project started on July 1995, when a proposal was presented and approved by the competent authority. The reactor

operated at 5 MW in September, 1997, after a series of commissioning tests were performed. The financial resources to realize the upgrade of power was around US \$2 million.

Finally, aging, inspection and modernization programs are under way. The Aging management program is being conducted as a coordinated research project of the regional IAEA, ARCAL XLIV, titled "Safety of Research Reactors", with the participation of Argentina, Chile, Mexico and Peru. The first phase of this project is a self-evaluation of the systems, components and structures, based in the IAEA guides [11], and will result in a diagnosis to instruct actions related to maintenance, test and inspection, and operational plans. Also it is included in this project a construction of "on line" Monitoring and Diagnosis Systems for the main pumps and for the plant operational condition based on advanced data processing techniques (e.g. artificial intelligence). The modernization includes changes in all nuclear channels, a new digital control console, and replacement of aged components. Also it is planned to change the graphite reflector by Be reflector, and a compact core configuration with 20  $U_3Si_2$ -Al fuel assemblies, in which will be possible to achieve neutron fluxes up to  $10^{14}$  n/cm<sup>2</sup>.s.

#### 4. REACTOR UTILIZATION

The IEA-R1 had been used for basic and applied research, non commercial production of RI, and NAA. Presently, the reactor is increasing its utilization to include commercial production of RI, and several other applications. This session will describe the reactor utilization, as well the planned ones.

##### 4.1. Beam utilization

Since the beginning of its operation IEA-R1 has been used as a neutron source to basic and applied research in the field of Nuclear Physics using thermal neutrons extracted from the beam holes. Today, the experiments underway at IEA-R1 BH are illustrated in Figure 4.

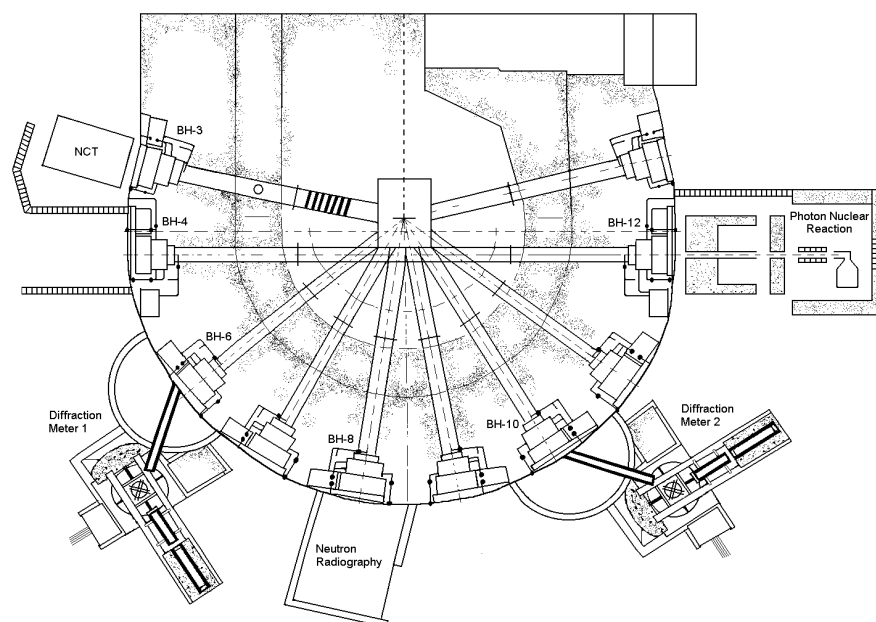


Figure 4. Schematic view of beam utilization at IEA-R1.

The experimental facilities located at the beam holes allows research to be conducted in several fields. In the tangential BH, ( $\gamma, n$ ) cross-sections are being measured for light and heavy nuclides using up to 30 mono energetic gamma with energies between 5 and 11 MeV. Photon fission cross section is measured by fission track technique for actinides, and for others light and heavy nuclides by a high efficiency long-counter neutron detector. Another research field is the study of angular distribution of gamma induced nuclear reactions, as  ${}^7\text{Li} (\gamma, {}^3\text{H}) {}^4\text{He}$ . Neutron Scattering experiments are being conducted in two neutron diffraction meter which allow to obtain monochromatic wave length of 1.14 Å. These experiments includes studies for determination of crystalline structure in mono and multiphase crystals, multiple diffraction, etc. It is worth to mention that the modernization of the neutron diffraction meter is underway having as goal to improve the resolution and decrease the time for data acquisition by a factor of 600. This project is being conduct in cooperation with Missouri University, and includes the substitution of  $\text{BF}_3$  neutron detector by 9 He-3 detectors, and the substitution of the Cooper monochromatic crystal by a Silicon crystal, which will allow select 3 beams of different wavelengths. A paper to be presented in this symposium will describe with more details the Neutron Scattering activities [12].

Neutron Radiography is a well established technique at IEA-R-1, with direct conversion method (gadolinium plates) as well as indirect method (dysprosium plates). The main characteristics of the facility are: thermal flux of  $3 \times 10^6$  n/cm<sup>2</sup>.s; thermal to epithermal ratio of 5.7; cadmium ratio of 150; n/ $\gamma$  ratio of  $5 \times 10^5$  n/cm<sup>2</sup>.mrem; beam diameter of 20 cm. Neutron radiography at IEA-R-1 has been used for material inspection, and a modernization to include real time neutron radiography will allow to realize inspection of samples in motion.

Finally an experimental facility for NCT is being installed for irradiation of “in vivo”, “in vitro” of biological samples, and phantom. The samples will be placed in a irradiation cell located after a set of filters which can be removed from the BH by a mechanical device [13]. The facility will allow studies with different combination of filters to assess neutron spectra, dose rates, etc., suitable for use in NCT. Also the facility will allow internal dose meter studies through phantom irradiation in the “irradiation cell”, as well as will allow assays of cell growing curves (gliomas and melanomas) in presence of  ${}^{10}\text{B}$ , and tumor regression assays in mice. It is worth to mention that there is no intention to use IEA-R-1 to treat humans, but only to develop an R&D program in NCT.

#### 4.2. Radioisotope production

Although IEA-R-1 was not used as commercial producer of RI, it had been used for experimental production of medical and industrial RI. Thus since 1959 IEA-R-1 starts experimental production of  ${}^{131}\text{I}$ . In the sixties the production of  ${}^{32}\text{P}$ ,  ${}^{198}\text{Au}$ ,  ${}^{24}\text{Na}$ ,  ${}^{42}\text{K}$ ,  ${}^{35}\text{S}$ ,  ${}^{51}\text{Cr}$  were done at experimental level. This radioisotopes allied with the Radio Pharmacy, introduced the utilization of Nuclear Medicine in Brazil. In the beginning of the 80's IPEN had decided distribute commercially radio pharmaceuticals to the medical centers. However due operational limitation of IEA-R-1 in that time, the decision was to import primary RI, mainly  ${}^{99}\text{Mo}$  to produce  ${}^{99\text{-m}}\text{Tc}$  generators. Due to the growing of the utilization of radio pharmaceuticals in Brazil, IPEN decides to upgrade the power and the modernization of IEA-R-1, in order to produce locally primary RI, mainly  ${}^{99}\text{Mo}$ ,  ${}^{153}\text{Sm}$ , and  ${}^{131}\text{I}$ .

Although there was a R&D effort to produce  ${}^{99}\text{Mo}$  by fission of HEU, budge restrictions and difficult in HEU supply, allied to the success obtained by countries like China in developing gel generator, which allows the utilization of low specific activities  ${}^{99}\text{Mo}$  had changed our strategy. Today,  ${}^{99}\text{Mo}$  is going to be produced by capture, irradiating capsules of natural  $\text{MoO}_3$  in a Be irradiator located at the central core position during 120 hours continuous at 5 MW. Experimental production had show that generators from 250–750 mCi/gMo can be obtained, however R&D effort are concentrated to produce generators up to 1 Ci. This production will allow to substitute more than



50% of the today imported  $^{99}\text{Mo}$ . More ever, the new operational condition of IEA-R-1 will allow to produce all  $^{131}\text{I}$  imported, and already started the commercial production of  $^{153}\text{Sm}$ . Other medical RI produced by IEA-R-1 are wires of  $^{192}\text{Ir}$ ,  $^{35}\text{S}$ ,  $^{24}\text{Na}$ ,  $^{198}\text{Au}$ , and  $^{45}\text{Ca}$ . Finally there is a future potential to produce  $^{166}\text{Ho}$ ,  $^{165}\text{Dy}$ ,  $^{51}\text{Cr}$ , and  $^{186}\text{Re}$ , and a planned in-core pneumatic system to produce short lived RI ( $^{18}\text{F}$ ,  $^{78}\text{Se}$ ).

Besides the production of medical RI, IEA-R-1 has been used to produce RI for industrial application ( $^{203}\text{Hg}$ ,  $^{82}\text{Br}$ ), and is planned to produce  $^{192}\text{Ir}$  for gamma radiography sources.

Recently, studies were conducted to irradiate gems, and the results were encouraging. A project to build an irradiator covered with cadmium with capacity to irradiate stones per batch is under way.

### 4.3. Neutron transmutation doping

Silicon crystals can be irradiated at IEA-R-1 using EIS, which consist of two parts, one fixed on the grid is a square Al guide tube, and the other is a freely rotating Al tube, which serves as the irradiation tube. NTD at IEA-R-1 has a capability of irradiation of the order 1 ton/year, and is used by international clients [14].

### 4.4. Neutron activation analysis

NAA is realized at IEA-R-1 using the pneumatic system (see Figure 2), where the samples in “rabbits” are irradiate under thermal fluxes between  $2.5\text{--}5.0 \times 10^{12}\text{n/cm}^2\cdot\text{s}$ , and then dispatching pneumatically to a gamma spectrometry analysis laboratory. The irradiation time usually is 20 minutes, and the dispatching time is around 6 seconds. Although NAA is used as an analytic technique for external clients, it is more used as a tool for R&D in life sciences, environmental studies, agronomy, geology, etc.

### 4.5. Materials and fuel testing

In the past IEA-R-1 was used for studies of radiation damage using an in-core irradiator (GRESIL-cooperation Grenoble-Brasil), however this program was stopped. Nowadays, the utilization of IEA-R-1 for materials and fuel testing are starting again, mainly driven by the Navy Nuclear Program, which is involved in post-irradiation to qualify fuel to be used in nuclear propulsion. From this program, a pressurized loop of irradiation with capsules for PWR pin type will be used at IEA-R-1 (CAFE). The loop was designed by a Research Institute of the Brazilian Nuclear Energy Commission (Center for Development of Nuclear Technology), and is already in cold test. Besides this utilization, IEA-R-1 is being used for studies of metallic material testing using a in-core irradiator (CIMAT), with temperature control up to  $700^\circ\text{C}$ , and for irradiation of mini plates, using another loop (CICON).

## 5. CONCLUDING REMARKS

As presented in this paper, now days IEA-R-1 RR is being utilized, or in advanced planning stage for almost all possible applications in which a RR of middle power (5 MW) can be used. This effort to increase the utilization of an old RR was possible, mainly due to the continuous reforms in systems, components, and structures which have been made along the reactor life time, with an emphasis in the recent power upgrade. Although another multipurpose RR (20 MW) is planned to be built at a new Research Center in Northeast of Brazil [15], due the present time economical situation, this new reactor will be a “reality” only in the next decade. Therefore, IEA-R-1 still have at least ten years to continue contributed to enhance the quality of life of the Brazilian Society, through the production of RI, irradiation services, or helping to develop science and technology. In order to continue to offer services with quality and safety demanded by the society, it is necessary a continuous modernization, aging management and quality assurance programs.

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