Introduction

Brazil has four research reactors in operation: the IEA-R1, a pool type research reactor of 5 MW; the IPR-R1, a TRIGA Mark I type research reactor of 100 kW; the ARGONAUTA, an Argonaut type research reactor of 500 W; and the IPEN/MB-01 a critical facility of 100 W.

Research reactor utilization has more than fifty years in Brazil. The first three reactors, constructed in the late 50’s and early 60’s at university campus in Sao Paulo, Belo Horizonte and Rio de Janeiro, had their utilization for training, teaching and nuclear research. The IPEN/MB-01, designed and constructed in IPEN in the late 80’s, is utilized for the development and qualification of reactor physics calculation for PWR core application.

The IEA-R1 had its application and utilization increased along the years. It is presently used for radioisotope production, neutron beam application, neutrongraphy, neutron activation analysis, and limited fuel and material irradiation tests, besides the regular use for training and teaching. The low power of the reactor and the lack of hot cells for post irradiation analysis limit its technical application for the nuclear fuel industry.

Brazil has two nuclear power plants in operation, one unit starting construction and four more units planned for the next two decades. Brazil has significant quantities of uranium ore and has expertise in all the fuel cycle steps, including uranium enrichment, and produces the fuel assemblies for the nuclear power plants. These industrial activities demand the need of material and fuel irradiation tests.

IPEN produces radiopharmaceutical kits attending more than three million patients each year. The majority of the radiopharmaceutical kits is produced from imported radioisotopes. The increasing price and shortage of world supply of $^{99m}$Tc leads also to the need of increasing the radioisotope production in Brazil.

Due to these new demands, the Brazilian Nuclear Energy Commission is analyzing the costs and benefits of developing and constructing a new Research Reactor in Brazil, which besides radioisotope production and material testing can be a new tool for neutron beam application to the scientific community as well.

This paper presents the actual research reactor utilization in Brazil, and the perspectives of developing and constructing a new multipurpose research reactor.

ARGONAUTA Research Reactor

The ARGONAUTA Reactor is an Argonaut type reactor (Argonne National Laboratory Nuclear Assembly for University Training) installed in 1965 at the Nuclear Engineering Institute (IEN) of the Brazilian Nuclear Energy Commission located at the Rio de Janeiro University Campus. It has 500 W of maximum power, and uses $\text{U}_3\text{O}_8$-Al MTR dispersion fuel type with 20% uranium enrichment. The main use of the reactor is for teaching and training in reactor physics, neutrongraphy and neutron activation analysis. Nuclear engineering post-graduated courses at the University of Rio de Janeiro use the reactor for practical laboratory classes in reactor physics.
The IPR-R1 research reactor is a TRIGA MarkI type reactor, constructed by General Atomic Company, USA, and installed in 1960 at the previous Radioactive Research Institute (IPR), today the Nuclear Technology Developing Center (CDTN) of the Brazilian Nuclear Energy Commission, located at Belo Horizonte, Minas Gerais Federal University Campus. It has 100 kW of maximum power for continuous operation, and uses U-Zr-H TRIGA pin type fuel with 20% uranium enrichment. The main use of the reactor is for the production of specific radioisotope for applications in industry, medicine, agriculture and engineering, neutron activation analysis and teaching and training in reactor physics. The reactor is one of the training tools for licensing the Brazilian nuclear power reactor operators. The reactor has been refurbished along the operating years and now will have its maximum power license increased to 250 kW for improving its application.

The IPEN/MB-01 is the first reactor designed and constructed with Brazilian technology. Installed at the Nuclear and Energy Research Institute (IPEN) of the Brazilian Nuclear Energy Commission site, in Sao Paulo, inside the Sao Paulo University Campus, had its first criticality
in 1988. The reactor is a critical facility, with a maximum power of 100 W, and has the objective of validating reactor physics methodology and nuclear data associated for PWR core analysis. UO$_2$ fuel pins with 4.3% uranium enrichment, arranged in a rectangular array, compose the reactor core. The international community recognizes some experiments performed at this reactor as benchmarking data. The experimental data obtained at the reactor are: integral and differential reactivity worth of control rods; power calibration by foils activation and noise analysis; temperature and void reactivity coefficients; spatial and energetic flux distribution by foils activation and fission chambers detectors; reaction rates and spectral index measurement inside fuel rods; buckling measurement with different “baffle” material and thickness; and criticality tests with different burnable poison among other tests. The reactor is also used for teaching post-graduated students at IPEN, and for nuclear power reactor operators training as well. The reactor has recently obtained authorization to increase its maximum operation power to 1 kW in order to improve the quality of the measurements in experimental tests.

IEA-R1 Research Reactor

IEA-R1 is the largest research reactor in Brazil, with a maximum power rating of 5 MW. Installed at the previous Atomic Energy Institute (IEA), nowadays the Nuclear and Energy Research Institute (IPEN) of the Brazilian Nuclear Energy Commission site, in Sao Paulo, inside the Sao Paulo University Campus, the reactor achieved its first criticality on September 16, 1957. The reactor originally used 93% enriched U-Al fuel elements, but now it uses 20% enriched uranium U$_3$Si$_2$-Al fuel produced at IPEN.

The IEA-R1 reactor is a multidisciplinary facility used extensively for basic and applied research in nuclear and neutron related sciences and engineering. The reactor produces some radioisotopes with applications in industry and nuclear medicine, performs miscellaneous irradiation services, and has been used for training as well. Several departments of IPEN routinely use the reactor for their research and development work. Many scientists and students at universities and other research institutions in Brazil also use it quite often for academic and technological research. However, the main user of the reactor is the staff of the IEA-R1 Research Reactor Center (CRPq) with interest in basic and applied research in the areas of nuclear and neutron physics, nuclear metrology, and nuclear analytical techniques.

Besides the main radioisotope production for the IPEN Radiopharmacy Center, some of the products and services offered by the CRPq find their application in the petroleum industry, aeronautical and space industry, medical clinics and hospitals, semiconductor industry, environmental agencies, universities and research institutions.

The reactor produces $^{131}$I routinely for radiopharmaceutical kits manufactured at IPEN, produces also special radioisotopes such as $^{41}$Ar and $^{82}$Br for industrial process inspection, $^{192}$Ir and $^{198}$Au radiation sources for brachytherapy, and $^{153}$Sm for EDTMP used in pain palliation in
bone metastases. The reactor also produces $^{99}$Mo by activation under demand from the IPEN Radiopharmacy Center, as they can produce $^{99m}$Tc generator kits by the gel process (with lower specific activity compared to the fission route).

The reactor has a neutron diffractometer that includes nine position sensitive detectors (PSD), a rotating oscillating collimator and an elastically bent silicon single crystal focusing monochromator. The PSD stack permits simultaneous measurement of neutron intensity in an angular interval of 30 degrees. The monochromator permits the choice of three different neutron wavelengths.

The CRPq offers regular services of non-destructive testing by real-time neutron radiography installed in a beam hole of the reactor. Multi-element trace analysis by neutron activation analysis supported by a radiochemical laboratory is an important activity developed by CRPq. Neutron irradiation of silicon single crystals for doping with phosphorus was developed at IPEN in the early 1990’s. A simple device for irradiating silicon crystals with up to 12.7-cm diameter and 50-cm long, located in the graphite reflector, was installed in the reactor for commercial irradiation.

The CRPq offers miscellaneous neutron irradiation of samples for research applications. The reactor permits irradiation tests of fuel for research and power reactor. An irradiation rig is used for testing MTR fuel type mini plates. A pressurized loop for testing mini rods of PWR fuel rod type was manufactured and is planned to be installed in the reactor in the near future. An irradiation rig for structural material test is also available for specific test at temperatures up to 300 °C. As the IEA-R1 installation does not have any hot cell, the post irradiation analysis are only non-destructive tests (NDT) performed inside the reactor pool. These tests are: visual inspection, dimensional inspection, gamma scanning and sipping test.

During the last several years, many changes in the reactor systems and components have been made in an effort to extend the lifetime of the reactor and guarantee its safe and sustainable operation. IEA-R1 is one of the oldest reactors of its kind in the world and has been operating for nearly 51 years with excellent safety records. Some of the important improvements made in the reactor systems during the last decades are: (a) modification of the reactor core from 6x5 to 5x5 using LEU fuel elements; (b) installation of a central beryllium element for samples irradiation; (c) replacement of 10 graphite reflectors with beryllium reflectors; (d) installation of four isolation valves in the primary cooling system; (e) repairs in the cooling tower and pipelines; (f) installation of a new ventilation and air conditioning system; (g) improvement in the control instrumentation; (h) replacement of the old radiation monitoring system; (i) and installation of an emergency core cooling system. With these modifications introduced an authorization from the Brazilian regulatory body was obtained in September 1997 for continuous operation of the reactor at 5 MW.

Aging management and refurbishment program for the IEA-R1 reactor components and systems is a continuous and on-going activity of the Research Reactor Center. For example, the reactor pool water treatment and purification system was replaced in 2004. The older control and safety elements of the reactor began to show signs of aging and were replaced in 2004 with identical elements, (fork type Ag-In-Cd) fabricated at IPEN. The infrastructure modernization efforts include the Technical Cooperation (TC) project BRA/04/056: “Modernization of the IEA-R1 research reactor to secure safe and sustainable operation for radioisotope production,” supported by IAEA during 2005-2006. The project contemplated several training programs for the reactor operation and maintenance personnel as well as improving the technical infrastructure of the reactor. Some of the goals achieved through the TC project were: (a) replacement of some electrical and refrigeration systems; (b) radiometric analysis system for water and air samples; (c) reactor control instrumentation; (d) radiation monitoring equipment; (e) neutron flux mapping facility using self-powered neutron detectors; (f) improved computational facility for neutronic calculations; (g) a highly radioactive sample handling facility; (h) training of personnel engaged
in electrical and mechanical maintenance, water chemistry, and irradiation services; (i) and installation of a continuous vibration monitoring system for rotating machinery. Today, ongoing new projects are the instrumentation and control room modernization and building maintenance. The current phase of the reactor modernization program is estimated to be completed by 2009.

In the year of 1999, all the spent fuel elements stored in the reactor pool since its first criticality (a total of 127 elements) were transferred to USA under a bilateral agreement (DOE-IPEN/CNEN). Transfer of an additional batch of 40 spent fuel elements to USA took place in 2007 under the same agreement. The reactor pool at present has storage space for more than 130 spent fuel elements. The available pool storage space should be sufficient for about 7-8 years of reactor operation at 5 MW, 120h/week. A new project for spent fuel management and storage was initiated in 2001 at IPEN to verify the possibility of an alternate dry storage space. This activity received active support from IAEA in the form of a regional project. A prototype of a dry storage cask for 21 spent fuel elements is under qualification testing.

The reactor modernization program, introduced several years ago at IPEN, and its effective implementation during all these years with solid investments, guarantees safe and continuous operation of the reactor. The improved operational regime of the reactor has stimulated renewed interests in other applications, which are currently in experimental stages, such as boron neutron capture therapy (BNCT) and coloration of topaz. Neutron beam research will benefit due to availability of more intense neutron beams. A viability study has recently been made for the possibility of installing a low angle neutron scattering (SANS) facility at the reactor. It should be emphasized that academic research and postgraduate teaching at the Reactor Center are very important programs in the effective utilization of the reactor. Research scientists, students, and professors from universities and other research institutions and their students have free access to the research facilities at the CRPq.

IEA-R1 Research Reactor
Future Perspective

In 2006 the Brazilian government created a working group, composed by the top managers of the nuclear area sectors, for reviewing the Brazilian nuclear program (PNB). The working group proposed some guidelines and projects for the development of the PNB. An Advisory Group of 11 Ministers analyzes the actions proposed for the PNB before addressing them to the Brazilian President decision. This program is based on the fundamental principle of pacific and non-proliferation use of nuclear energy consonant with the Brazilian Constitution and International Treaties and Agreements. The PNB identifies that the nuclear energy will continue to be used in Brazil for electricity production and for several applications in the benefit of the society.

Brazil has around 90 GW of electricity production installed capacity. From this 70 GW is of hydraulic origin, and only 2 GW comes from nuclear power plants. The Brazilian 2030 energy plan envisages a total of 216 GW of electricity production installed, from which 164 GW of the total is from hydraulic origin and only 7.3 GW from nuclear power plants. Today Brazil has two nuclear power plants in operation, Angra I and Angra II, with a total of 2 GW electrical power. A new nuclear power plant, Angra III, 1.3 GW, is resuming construction, and four more nuclear power units are planned up to year 2030. The new four units will certainly be from the generation 3+ PWR reactor type, as the ones that are being designed and licensed around the world. Seven nuclear power plants is a significant number for a nuclear program of any country, but it still represents a very modest participation in the electricity production matrix (3.3%) in the case of Brazil.

Brazil has the sixth known reserve of uranium ore in the world. This reserve may increase considerably by detailed soil prospecting along the country. There are two mines being exploited nowadays, and produce enough uranium quantities for all the Brazilian nuclear program needs. Brazil dominates the fuel cycle technologic steps, being one of the few countries that have the autonomous technology for uranium enrichment. INB (Industrias Nucleares do Brasil) is the company in charge of producing the fuel assemblies for the Brazilian nuclear power plants. Nowadays INB imports some of the fuel manufacturing steps (UF\textsubscript{6} conversion and enrichment steps), but the PNB proposes that all nuclear fuel manufacturing steps for the 2030 energy plan shall be made by INB.

The two industrial activities shown before, nuclear power plants construction/operation and nuclear fuel manufacture, lead to the necessity of technological development in the area of reactor and fuel engineering. In this autonomous development there is the technical need of fuel and material testing under irradiation and post irradiation analysis as well.

IPEN produces the majority of the radiopharmaceuticals used in Brazil. The radiopharmaceuticals produced in IPEN are distributed to more than 300 hospital and clinics attending more than 3 million patients per year. The base radioisotopes used are imported or produced at IEA-R1 research reactor. The $^{99m}$Tc generator kits have activities varying from 250 mCi to 2,000 mCi and are produced from the fission of $^{99}$Mo isotope imported from Canada, due to the low flux of the IEA-R1 reactor for the desired activity. The $^{99m}$Tc generator kits production is continuously increasing, with the current production of about 20,000 Ci of $^{99m}$Tc per year. Historically the $^{99m}$Tc generator kits application is increasing 10% per year in Brazil and there is the perspective of continuing this figure in the near future. Different from $^{99}Mo$, the $^{131}$I radioisotope is partially imported from Canada and partially produced at IPEN. The one from Canada is produced from fission and the one from IPEN is produced by activation. An amount of 2,000 Ci of $^{131}$I is distributed by IPEN per year. The potential increase to the $^{131}$I radiopharmaceutical utilization is higher than the $^{99m}$Tc kits.

There is today a big concern on the future perspectives on the radioisotope availability for medical use. The main radioisotope commercial producers in the world have their reactor
facilities getting older, and in the second semester of 2008 there were a shortage of these products in the market. The prices are increasing, and the perspective for the future depends on new reactors construction. In the case of IPEN, the increase in the radioisotope production depends on the power scale up of the IEA-R1 research reactor. But due to limitations on the reactor design and the site licensing, the reactor can not increase its power beyond 5 MW or IPEN can not construct any hot cell for $^{99}$Mo processing from fission. These limitations lead to the need of a cost-benefit study concerning the construction of a new reactor.

As pointed before, either the industrial application of power reactor and nuclear fuel technology or the radioisotope production for radiopharmaceuticals application requires, for an autonomous development, the need of a new research reactor. Besides these needs, the actual utilization of neutron beams in Brazil, for fundamental and technological research, also requires a higher powered research reactor with appropriate installations as neutron guides using cold and hot neutron sources.

Based on these facts, the CNEN (Brazilian Nuclear Energy Commission) started to analyze the costs and benefits of developing and constructing a new research reactor in Brazil. The study has to take into account all the aspects evolved in the design and construction of a research reactor as well as the supporting installations needed for its application and operation. The figure below summarizes the points that have to be addressed in the scope of the reactor. One important point in the case of the Brazilian project decision is the aspect of multipurpose utilization. The neutron flux of the reactor has to be compatible to the needs described above. The studies will finish in 2009 for submission to the PNB advisory group.

**Multipurpose Research Reactor Scope**

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