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NUCLEAR RESEARCH REACTORS IN BRAZIL

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ABSTRACT

The rising concerns about global warming and energy security have spurred a revival of interest in nuclear energy, giving birth to a "nuclear power renaissance" in several countries in the world. Particularly in Brazil, in the recent years, the nuclear power renaissance can be seen in the actions that comprise its nuclear program, summarily the increase of the investments in nuclear research institutes and the government target to design and build the Brazilian Multipurpose research Reactor (BMR). In the last 50 years, Brazilian research reactors have been used for training, for producing radioisotopes to meet demands in industry and nuclear medicine, for miscellaneous irradiation services and for academic research. Moreover, the research reactors are used as laboratories to develop technologies in power reactors, which are evaluated today at around 450 worldwide. In this application, those reactors become more viable in relation to power reactors by the lowest cost, by the operation at low temperatures and, furthermore, by lower demand for nuclear fuel. In Brazil, four research reactors were installed: the IEA-R1 and the MB-01 reactors, both at the *Instituto de Pesquisas Energéticas Nucleares* (IPEN, São Paulo); the Argonauta, at the *Instituto de Engenharia Nuclear* (IEN, Rio de Janeiro) and the IPR-R1 TRIGA reactor, at the *Centro de Desenvolvimento da Tecnologia Nuclear* (CDTN, Belo Horizonte). The present paper intends to enumerate the characteristics of these reactors, their utilization and current academic research. Therefore, through this paper, we intend to collaborate on the BMR project.

1. INTRODUCTION

In 1942, in a pioneering experiment coordinated by Fermi at the University of Chicago, the first criticality in the first reactor of the world, the Chicago Pile N. 1 (CP-1), was observed. Since then, new research reactors with different topologies were built, particularly in the 60s and 70s, when 373 of these reactors were operating in 55 countries [1]. Nowadays, there are 239 research reactors in operation, 13 temporarily shut down, 419 off, decommissioned or canceled, three under construction and two only planned, according to the database of the IAEA (International Atomic Energy Agency) on present date [2], in about 70 countries.

In the last 50 years, research reactors have been quite often used for research and training in reactor technology; for isotope production; for characterization of materials using scattering, diffraction of neutron and neutron radiography; and for neutron activation analysis (NAA). Moreover, the research reactors are used as laboratories to develop technologies in power reactors, which are evaluated today at around 450 worldwide [3]. In this application, those reactors become more viable in relation to power reactors by the lowest cost, by the operation at low temperatures and, furthermore, by lower demand for nuclear fuel (hence, far fewer fission products build up as the fuel is used) [4].

In Brazil, four research reactors were installed: the IEA-R1 and the MB-01 reactors, both at the *Instituto de Pesquisas Energéticas Nucleares* (IPEN, São Paulo); the Argonauta, at the *Instituto de Engenharia Nuclear* (IEN, Rio de Janeiro) and the IPR-R1 TRIGA reactor, at the *Centro de Desenvolvimento da Tecnologia Nuclear* (CDTN, Belo Horizonte). The present paper intends to enumerate the characteristics and the utilization of these reactors and the current academic research. Therefore, through this paper, we intend to collaborate on the Brazilian Multipurpose Reactor (BMR) project, predicted in current government of Brazil action plans.

2. UTILIZATION OF RESEARCH REACTORS

The International Atomic Energy Agency (IAEA) categorizes the applications of research reactors into four broad classes, namely, human resource development; irradiation of materials into reactor; beam works; and nuclear fuel tests and experiments in loops running through the reactor core [5]. In order to develop human resource, the IAEA foments the use of research reactors as teaching and training environment. Thus, the IAEA encourages the scientific community training as a way to attract future customers and users. The IAEA also foments the general public access to the facilities on scheduled visits.

In the others classes, research reactors are summarily used for production of radioisotopes and for performing neutron activation analysis (NAA). In addition, it is used in methods for dating minerals (geochrolonogy) and in gemstone coloration. Further, research reactors are availed to perform general instrumentation/nuclear fuel tests and services of non-destructive testing by neutron radiography. Among these applications, the NAA is the most simple and widely used because it requires no high power levels (just a few tens of kilowatts are capable of irradiating samples for some sort of NAA), in conjunction with the fact that many of the uses of trace element identification can be directly linked to potential economic benefits.

In the last 50 years, research reactors have promoted advances for a wide range of areas, from lifesaving cancer treatment to electronic gadgetry. Nevertheless, it is expected that over the next 15 years, less than 40 research reactors remain in operation, due to obsolescence of the facilities (over two-thirds of today's research reactors have been operating for over 30 years, close to the end of their typical 40-year lifespan) [6]. In the present context, the discoveries and innovations that can be made by most of current research reactors, considering their possibilities, have already been consolidated. New research needs the incorporation of newer tools and functionalities, which make them more powerful.

Thus, some countries have undertaken reforms and upgrades in their reactors or have even built new ones. Finland, for example, has adopted an innovative approach to use its TRIGA reactor, the FiR 1 (250 kW), for pioneering research in the treatment of brain cancer via boron neutron capture therapy (BNCT). On the other hand, Australia follows the project of construction of a multipurpose research reactor to benefit agriculture, energy, mining and environment sectors. It also guarantees the country's supply of medical isotopes, thus minimizing the importation costs and reliance on few foreign suppliers of vital radionuclides [6]. Other countries, such as Canada, have also built new reactors that are entirely devoted to the production of radioisotopes for medical diagnosis and treatment. Besides that, some of which are related to exclusively commercial purposes. In the same direction, the Brazilian government proceeds with the design of the Brazilian Multipurpose Reactor (BMR). The

RMB project aims primarily at the production of radiopharmaceuticals, at miscellaneous irradiation services and, in general terms, at research involving neutron beams.

3. NUCLEAR RESEARCH REACTORS IN BRAZIL

3.1. The IEA-R1 Reactor

At the end of 50s, the IEA-R1, the first research reactor of the southern hemisphere, was installed at the current *Instituto de Pesquisas Energéticas e Nucleares* (IPEN) – on that occasion, it was called *Instituto de Energia Atômica* (IEA), name from which derives that designation. The IEA-R1, at the *Centro do Reator de Pesquisa* (CRPq/IPEN), is a swimming pool type research reactor, with light water as coolant and moderator, with beryllium and graphite as reflectors. This reactor achieved its first criticality in September 1957. Despite the original design, which defines the operation at 5 MW thermal power, the IEA-R1 operated from 1957 to 1961 at between 200 kW and 2 MW, when was summarily used for commissioning and nuclear physics tests. During that period, the reactor operated five days a week, in less than eight hours per day. In 1961, the production of ^{131}I was established, so it was found necessary to maintain the reactor power continuously on 2 MW, and also to adopt an operational cycle of 40 hours per week. On that date, the radioisotopes ^{32}P, ^{198}Au, ^{24}Na, ^{35}S and ^{51}Cr had already been produced. In the 80s, the IPEN started the production of ^{99m}Tc generator kits via fission of ^{99}Mo, imported from Canada [7]. In 1995, a program defined the start of ^{153}Sm production, as well as the preparation for ^{99}Mo production in IEA-R1. Thus, the current operation cycle was increased to 64 hours per week and the power to 3.5 MW [7].

Since then, new design changes were performed to allow operating at 5 MW (power authorized by regulatory body in 1997), on 120 hours a week. Currently, however, it still remains with thermal power of 3.5 MW. Even so, IEA-R1 is the largest power research reactor in Brazil, and hence, the reactor with the largest range of potential uses. Under current conditions, the IEA-R1 provides neutron fluxes up to 8.5×10^{13} n.cm^{-2}.s^{-1} and epithermal and fast neutrons of about 10^{13} n.cm^{-2}.s^{-1} (using an array of 24 standard fuel elements, manufactured in IPEN) [7].

The IEA-R1 has 144 positions for irradiation in the core, distributed in 15 elements for long irradiation and a pneumatic system for short irradiations (up to 5 minutes). The IEA-R1 further has nine horizontal irradiation tubes ("Beam Holes"), from which emerges a beam of neutrons used for applied nuclear and solid-state physics experiments, for research in cancer therapy by boron neutron capture (BNCT) and for neutrongraphy [8].

Concerning security, the IEA-R1 incorporates a multiple barrier system to protect against the release of radioactive material and a system for reactor shutdown and cooling in an emergency. The core has one control rod and three security rods. The first of these rods is constituted by absorbing material (Ag-In-Cd), in order to ensure fast shutdown by gravity (in less than 1 s), in case of any abnormality [9]. This core is also characterized by negative temperature coefficient, which is intrinsic safety condition of the IEA-R1. The project provides the reactor shutdown when it exceeds some previously specified conditions. In case of some failure of electric motor and/or power cut, the primary cooling circuit pumps have a flywheel, which provides, for a sufficient period of time, a coolant forced convection in the core, thus reducing the decay heat (under normal conditions, only powers greater than

200 kW lead to a coolant forced circulation). Furthermore, in case of emergency, there are remote control valves in the coolant pipes, which enter (cold leg) and leave (hot leg) the core. Moreover, the operation and maintenance carry out rigorous methodology, thus ensuring quality and reliability and minimizing the probability of human error.

The IEA-R1 is fueled with plate type fuel, enriched to 20%. There are 20 fuel elements and four control elements, with 18 and 12 plates, respectively, arranged in arrays. In each control element, there are two plates of absorbing material. On the periphery of those arrays, reflector elements of graphite and beryllium are distributed. The fuel quality ensures the reactor criticality. In order to compensate for the negative effects of reactivity, there is an excess of reactivity, controlled by the operator via insertion/removal of control and safety rods. The drive mechanisms for the rods are linear, fault intolerant, radiation-resistant and with quick action. In manual mode, the rods move with linear speed. In automatic mode, the speed is controlled via the speed reducer.

The instrumentation of the reactivity control system (RCS) includes a linear channel and a N^{16} channel. In the linear channel, there is a compensated ionization chamber, doped with B^{10}. There are also power supplies and a linear multitrack pico-Ammeter, which sends signals to the control unit and to unit record [10]. The N^{16} channel measures the gamma radiation released from the reaction O^{16} (n, γ) N^{16} and, hence, indirectly assesses the global power of the core. In automatic rods operation, a signal comparator circuit evaluates three entries (namely, the power demand, the power read from linear power channel and the reactor period) and then performs the position adjustment of the control rod [9].

On the other hand, the instrumentation of the reactor protection system (RPS) consists of a wide channel wide-range, or Campbell (with fission chamber that monitors the neutron flux in a range of 10 decades and the reactor period) and of three security channels. There is also a reactor cooling system (RCS), with primary and secondary cooling circuits. The primary circuit consists of the pool, the reactor core, the hydraulic pumps, the valves and also of the primary side of heat exchangers. The secondary one, on the other hand, consists of the secondary side of heat exchangers, the pumps, and also of two cooling towers. The instrumentation of cooling system includes two subsystems, one of them used to measure the flow in those two circuits, with orifice plates of nozzle flow type and with differential pressure transmitter; and another one to measure temperature, with 24 thermocouples [9].

Nowadays, the IEA-R1 is used extensively for basic and applied research in nuclear and neutron related sciences and engineering. It has also been used for training and for producing radioisotopes to meet demands in industry and nuclear medicine. Miscellaneous irradiation services and academic or technological research are also performed in the IEA-R1. For this last use, universities or other research institutions often use the facilities of the reactor. However, the IEA-R1 is mostly used by the staff of the *Centro de Pesquisa do Reator,* for research and development in the areas of nuclear and neutron physics, nuclear metrology and nuclear analytical techniques [9].

Presently, the IPEN is testing and commissioning a fuel miniplate thickness measurement system for dispersion fuel swelling evaluation. In addition, an instrumented standard fuel element with U_3Si_2-Al dispersion (manufactured by the *Centro de Combustível Nuclear*, CCN, under orientation of the *Centro de Engenharia Nuclear*, CEN) has been tested. Further, experiments for simulation of the irradiation conditions in a fuel rod in pressurized water reactors (PWR) have been performed in the IEA-R1 [8].

3.2. The IPEN/MB-01 Reactor

Also in the IPEN, the IPEN/MB-01 reactor, at the *Centro de Engenharia Nuclear* (CEN), is a zero power reactor, with first criticality achieved in 1988. The design reactor and its execution were accomplished by researchers and engineers of IPEN, financed by Brazilian Navy, hence, the MB-01 is envisioned as the first genuinely Brazilian reactor. Originally, the design reactor intended to test a typical core for use in naval propulsion, in which the reactivity was controlled by the degree of control rods insertion (as opposed to some critical units, where the reactivity is defined by the water level in moderator tank) [10].

The first MB-01 core is composed of a 28x26 array of fuel rods and 48 guide tubes to insert the control/security rods. There is a reactivity excess of 2415 pcm. The core design enables the assembly of distinct critical arrangements in a 30x30 array plate with holes spaced at 15 mm. The whole reactor core, as well the drive mechanisms and the rods drop absorber, are assembled in a support structure, which is fixed at the top by a metal platform and at the bottom kept suspended in a tank with the moderator (treated and demineralized water). The reactor fuel rods consist of stainless steel tubes, containing inside a column of 52 UO_2 fuel pellets enriched to 4.3%, with active height of 54.6 cm (each pellet has a height of 1.05 cm). The non-active ends of the rods are filled with Al_2O_3 pellets. Among the 48 guide tubes for the neutron-absorbing rods, arranged in four groups of 12, two groups are composed of safety rods and two of control ones. These groups of rods are arranged in a central body (spider), connected to a drive mechanism, which is indirectly connected to energized magnets. The full control/security rod reactivity (about 3200 pcm) is enough to provide the reactor shutdown [9]. In the case of a power cut in the magnets, the four rods fall by gravity into the reactor core, resulting in reactor shutdown (called first level shutdown). Furthermore, there is the shutdown for moderator loss (second level shutdown), when two quick opening butterfly valves are opened, thus emptying the moderator tank in about 4 s. In case of shutdown, the fluid is drained to reactor underground (storage tank), where it is stored until next reactor operation, when it returns to tank moderator, or until it is removed for filtration routines or for control of the conductivity level and temperature.

The nuclear instrumentation for control and safety is composed of ten nuclear channels, namely two startup channels (BF_3 detectors); two power channels (compensated ionization chambers, CIC), two linear ones (uncompensated ionization chambers, CINC); three security ones in the power range (two and a detector CINC B-10); and a safety one in the startup range (BF_3 detector). All of these channels are located inside the moderator tank in sealed aluminum tubes, around the core. This instrumentation process each signal sent by the nuclear detectors, which is then sent to the power and period reactor indicators, all of them located in control desk and to signal comparators. The last ones comprise the reactor protection logic [10].

In order to achieve the minimum count rate in linear channels and thus start the reactor, an Am-Be neutron source with an activity of 1 Ci and an intensity of $2.5x10^6$ $n.s^{-1}$ is used. Usually, this source is stored on the second underground reactor and is moved to the lower base of the moderator tank (where it can sensitize the nuclear channels). Therefore, the neutron population growth levels observed in the reactor operation may sensitize startup and safety channels detectors. Without the minimum count rate of 2 cps in the startup channels and in their respective safety channels, the reactor operation is not enabled. Other operational set points also act on nuclear channels. For example, in supercritical conditions, periods of neutron population growth less than or equal to 17 s cause the involuntary shutdown (first level "scram") and periods less than or equal to 14 s lead to second level "scram". Furthermore, several other events may lead to reactor shutdown, such as the bad conditions of the moderator water and the opening of the access door to the Critical Cell (hall where is the core reactor) [10].

Together with the IEA-R1 reactor, the MB-01 reactor has been used in IPEN graduate programs. In the last two years, more than 50 postgraduate works (among theses and dissertations) were related directly to the two IPEN reactors. In addition, this reactor avails to perform general experiments, which obtain, for example, the integral and differential reactivity worth of control rods; the temperature and void reactivity coefficients; power calibration by foils activation and noise analysis; spatial and energetic flux distribution by foils activation and fission chambers detectors; and reaction rates and spectral index measurement inside fuel rods and buckling measurement with different "baffle" material and thickness. Furthermore, the reactor is used for nuclear power reactor operators training [11].

3.3. The IPR-R1 TRIGA Reactor

The TRIGA IPR-R1 reactor, acquired in 1960 by the *Instituto de Pesquisas Radiativas* (IPR), the current *Centro de Desenvolvimento da Tecnologia Nuclear* (CDTN), was the second research reactor installed in Brazil, with first criticality notified in 1960. The IPR-R1 reactor is a typical TRIGA Mark I and was fabricated by General Atomics, the supplier of all TRIGA reactors, which are presently the most widely used research reactors in the world. The TRIGA reactor is the only research reactor that offers true "inherent safety", rather than relying on "engineered safety" [12]. The basic parameter which allows TRIGA reactors to operate safely during either steady-state or transient conditions is the prompt negative temperature coefficient due to the TRIGA fuel and core design. This temperature coefficient allows great freedom in steady state and in transient operations.

In general terms, the IPR-R1 is light-water and open pool type reactor, with graphite as reflector and with fuel composed of a metallic alloy of uranium and zirconium hydride moderator (U-ZrH), containing 8% to 8.5% by weight of uranium enriched to 20%. Figure 1 shows the pool and the core when the IPR-R1 TRIGA reactor is in operation.

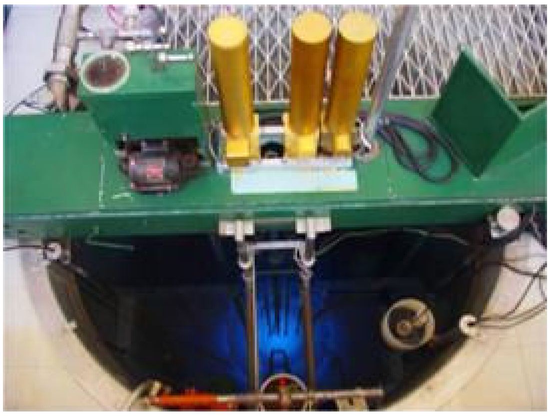

Fig. 1. IPR-R1 TRIGA reactor pool and core

The IPR-R1 reactor core forms a cylindrical lattice with 63 fuel-moderator elements (59 original elements, coated with aluminum and four recently inserted elements, coated with stainless steel). The core is placed at the bottom of an open tank of about 6 m height and of 2 m diameter. This tank is filled with approximately 18 m^2 of water, thus assuring an adequate radioactive shielding. The reactor core cooling is done by water natural circulation. The cooling water passage through the top plate is provided by the differential area between a triangular spacer block on top of fuel element and the round hole in the grid. A heat removal system is provided to remove heat from the reactor pool water. The water is pumped through a heat exchanger, where the heat is transferred from the primary to the secondary loop. The secondary loop water is cooled in an external cooling tower.

The TRIGA fuel rod has about 3.5 cm diameter, with active length of about 37 cm closed, at the top and bottom ends, by graphite slugs, which act as axial reflector. The moderating effects are mainly caused by the zirconium hydride in the mixture and, on a smaller scale, by light water coolant. The power reactor is controlled with three independent control rods, namely, a regulating rod, a shim rod, and a safety rod.

The IPR-1 operated at 30 kW before new elements were incorporated into the core, enabling the operation at 100 kW. In 2002, the core is reconfigured in order to allow the operation at 250 kW. Nevertheless, it is still operating at the power of 100 kW (waiting for the definite license to operate at 250 kW).

In recent years, the IPR-R1 TRIGA reactor has been operated sporadically, mainly for neutron activation analysis, on about four hours per week. Occasionally, the TRIGA IPR-R1 reactor has been served to postgraduate programs of CDTN. In the last 50 years, 17 dissertations and 4 theses about this reactor were developed in CDTN.

3.4. The Argonauta Reactor

The Argonauta reactor, at the *Instituto de Engenharia Nuclear* (IEN), was the third research reactor installed in Brazil (1962) and the first built by Brazilian companies (MicroLab and CBV). Its first criticality was achieved in 1965. In general terms, the Argonauta reactor (whose name derived from Argonne National Laboratory, which projects this reactor) provides maximum power of 500 W and of 10 kW in continuous use and is moderated by deionized water and graphite. Furthermore, this reactor is characterized as being inherently safe, due to the negative temperature and void reactivity coefficients [13].

The Argonauta reactor original design is attributed to the ANL. The Brazilian researchers only adapted the American design to the possibilities of national industrial park and the availability of materials in the national market. Later, once the Department of Instrumentation and Control was consolidated, a program to upgrade the reactor instrumentation was initiated. It aimed essentially at the replacement of the vacuum tubes of the original design by solid-state components. This program initiates the development of nuclear reactor instrumentation in Brazil [13].

Presently, the Argonauta reactor core summarily consists of two concentric aluminum cylinders, which are called "external thermal column" (external cylinder) and "internal thermal column" (internal one). The last one, with smaller diameter, is filled with graphite. In the ring between the two cylinders, immersed in demineralized water, are allocated the fuel elements, consisting of flat plates coated with aluminum. The fuel elements can be arranged in several ways, namely, in lateral orientation (in which the elements are positioned in a single arc segment), bilateral (two elements placed in two arc equal and symmetrical segments), uniform (elements uniformly distributed around the ring) and in alternate orientation (elements grouped two by two, making six sets symmetrically distributed). The fuel elements orientation directly affects the average neutron flux and critical mass, conditioning the reactor possibilities [14].

Usually, the reactor is charged with four fuel elements (each of them containing 17 plates with 21 g of ^{235}U per plate) or with two elements (each containing 11 plates with 21 g of ^{235}U per plate, associated with 6 other plates with 9.84 g of ^{235}U per plate). Furthermore, another use of two elements is common, with each element containing only seven plates with 9.84 g of ^{235}U per plate, in conjunction with half graphite prism [14]. The plates that make up the fuel rods are fixed by two pins transposing them at the ends, keeping spacing between them. The elements can be assembled with false plates, consisting only of aluminum, instead of the fuel plates. All fuel plates are numbered for identification and a catalog with descriptions of each one, as well as their distribution in the elements, is kept on files.

At the region of the reactor core with greatest length (external thermal column), the samples are introduced in drawers. Graphite blocks stacked involve the whole of the reactor core. In this configuration, the graphite acts as neutron moderator and as neutron reflector. The water acts as neutron moderator and coolant of the reactor core [14].

Although the design reactor allows operation at up to 5 kW, it usually operates at lower powers (170 W or 340 W), and was licensed for continuous operation at only up to 500 W. Under these conditions, the Argonauta reactor provides, in the core reactor, maximum thermal neutrons flux up to 10^9 n.cm^{-2}s^{-1}. The reactivity control is done by six rods, three security rods and three control ones, consisting of cadmium metal plates coated with aluminum. These rods move vertically into existing channels in the graphite reflector, parallel to the axis of external cylinder, around the core. Moreover, reactivity control can be done via the water drainage and also via nitrogen bubbling, which introduces "voids" in the water, thus inducing a negative reactivity in the reactor core [14].

Presently, the Argonauta reactor is summarily used for miscellaneous neutron irradiation services, research in reactor Physics, staff training, services of non-destructive testing by neutron radiography, and also to perform general material tests [14]. Furthermore, this reactor is used in postgraduate programs of several institutions and universities in Brazil. In 2005, more of 70 students concluded their theses or dissertations using the Argonauta facilities [15].

4. CONCLUSIONS

Presently, four research reactors have been operating in Brazil, in three research institutions (IPEN, IEN and CDTN). Among those reactors, three have been operating for over 45 years, which means they turned out exceeding the typical 40-year lifespan expected for research reactors. Despite the reforms and upgrading routines, which have been undertaken since their first criticalities, their instrumentations exhibit a large gap from the state-of-the-art. The obsolescence of these reactors restricts the applications to the limited possibilities of their instrumentations, thus restricting the range of their potential uses. Hence, the extending of utilization, in all of those cases, requires, at least, instrumentation upgrades. In addition, the incorporation of newer tools and functionalities and/or the increasing of reactor power could also enlarge the scope of services and applications resulting from use of these reactors.

In the future, these research reactors, after those upgrades and reforms, together with the Brazilian Multipurpose Reactor, may possibly meet for the increasing demands of industry and of the academic community in Brazil. Furthermore, in these conditions, these reactors may provide support to Brazilian power reactors, thus allowing for the increase of the use of nuclear energy in Brazil.

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