Nuclear Power Energy Development in Brazil - Future Perspectives

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Abstract. This paper deals with the implementation of nuclear energy in Brazil from the 50's up to present time. Today the country has two pressurized water reactors in operation – ANGRA 1 (626 MWe) and ANGRA 2 (1,275 MWe). A third unit – ANGRA 3 (1,224 MWe) – had its construction interrupted many years ago; nowadays the re-start of its construction works is under consideration by federal authorities. The country has also developed sufficient installed capacity for supplying main nuclear power components. Pursuing fuel supply self-sufficiency for these three reactors, considerable expansion has also been accomplished on all stages of the fuel cycle such as uranium mining, conversion, enrichment and fuel fabrication. The country has also been engaged in relevant international co-operation and initiatives aiming the development of advanced and new generation of nuclear reactor systems.

1. Introduction

Nuclear activities in Brazil have been initiated through initiatives of state governments, first with the creation of the Center for Nuclear Technology Development (CDTN-CNEN/BH), earlier named Institute for Radioactivity Research (IPR), in 1954, in Belo Horizonte – Minas Gerais and two years later, in August 1956, with the foundation in São Paulo of the Institute for Atomic Energy (IEA) whose current name is Institute for Energy and Nuclear Research (IPEN-CNEN/SP). In October of 1956 the federal government created the National Nuclear Energy Commission (CNEN) with its headquarters in Rio de Janeiro. Currently both institutes are managed by CNEN.

Still in 1956, it was initiated the construction of the IEA-R1 research reactor in São Paulo. This reactor is a pool type, light water moderated and graphite and berilium[1] reflected research reactor, built by Babcock & Wilcox Co., in accordance with specifications furnished by CNEN and financed by the U.S "Atoms for Peace" program. Its first start-up was on September 16th , 1957, being the first criticality achieved in the Southern hemisphere. Although designed to operate at 5 Mw, this reactor had been operating until 1997 at a power level of 2 Mw mainly for basic and applied research, as well as in experimental production of radioisotopes for medicine, industry and life sciences applications. Due to the recent growth of radioisotope demand in Brazil in the 80's for medical diagnosis and therapy, it was decided to increase the power reactor level to 5 Mw and to operate the reactor continuously. To achieve this goal, it was necessary to perform some systems modifications and introduce new safety systems as the Emergency Core Cooling System-ECCS in order to obtain the licensing from Brazilian Regulatory Body. In September 16th , 1997, the IEA-R1 was licensed to

[1] - Berilium reflector was an improvement introduced recently in 2002.

operate at 5 Mw [1]. Three more research reactors are also in operation in the country: a TRIGA reactor (250 Kw) in Belo Horizonte at CDTN-CNEN/BH, an ARGONAUTA reactor (500 w) in Rio de Janeiro at IEN-CNEN/RJ and a critical unit (Zero Power Reactor) at IPEN-CNEN/SP in Sao Paulo.

Since the fifties, the role of nuclear science and technology in Brazil has experienced some ups and downs but a considerable growth has been achieved. Today nuclear applications are widely spread within the country in the areas of medicine, agriculture, industry, environment, bioengineering and production of electrical energy [2]. Specifically on the sector of nuclear medicine, initiated in 1959 at IPEN-CNEN/SP with the production of ^{131}Iodine for thyroid diagnostic and therapy, our country has had an outstanding development. Today, ^{99m}Tecnetium generators, primary radioisotopes, labeled radiopharmaceuticals, radioactive kits and some other products are routinely produced and widely distributed all over the country by the research institutes of CNEN, mainly by IPEN-CNEN/SP. Its worthwhile to mention, as an example, that from 1995 to 2003, CNEN's production of radioisotopes and radiopharmaceuticals increased 175%, which represents identical increase of the medical procedures performed annually. In the year of 2003, nearly 2.2 million procedures were carried out in nuclear medicine, satisfying the demand of the more than 300 clinics and hospitals existing throughout the country. It is foreseen that nuclear medicine will continue to expand its activities all over the country at an expected rate of 6 to 7%/year.

A similar pattern of success has been achieved by almost all other non power nuclear applications on industry, agriculture, environment, health, food irradiation, materials and instrumentation [2], due mainly to a reasonable good industrial and R&D installed basis in the country, however, considering that the main objective of this paper is to deal with nuclear power developments, as shown in the following sections, we shall not extending this matter any further.

2. Initial nuclear power developments

Brazil has a population over 176 million people, distributed in an area of 8.5 millions of square kilometers. As can be seen in Table I, during the seventy's and eighty's before the introduction of nuclear power, about 90% of the electricity consumed in the country was of hydroelectric origin. Although Brazil had one of the largest hydroelectric potentials in the world, the interest in nucleoelectrical energy comes from the end of the 50's derived mainly due to the considerable uranium and thorium reserves existing in the country (today Brazil holds the sixth uranium geological resource in the world) and the huge distances between the hydroelectric plants and consumer centers. From 1955 to 1960 – the Center for Nuclear Technology Development in Belo Horizonte (CDTN-CNEN/BH) – established the "Thorium Group" to demonstrate and establish the technical basis for the development of a nuclear reactor fueled with thorium in the country. As a result from such activities a conceptual project of a nuclear reactor fuelled with thorium was elaborated.

At that time scientists, decision makers and politicians were often involved in exasperating and provoking discussions in which the supporters of the natural and enriched uranium as well as thorium fans usually expressed strong opposing opinions, both based on political, technical and economical considerations. As a consequence the thorium program was interrupted and the working group dismantled in 1960.

By the end of the sixties and first half of the 70's the country - through the National Nuclear Energy Commission, CNEN, by means of its research institutes IPEN-CNEN/SP (Institute for Energy and Nuclear Research) in São Paulo and IEN-CNEN/RJ (Institute for Nuclear Engineering) in Rio de Janeiro - established a strong R&D programs related with gas cooled reactors (HTGR), liquid metal reactors (LMFBR) and light water reactors (PWR) by using either natural or enriched uranium. These programs gave origin to important and highly capable research groups in knowledge areas related to thermohydraulics, materials, reactor physics, nuclear technology and design, instrumentation and control, safety analysis, structural analysis and many others. At same time, fundamental research facilities have been implemented such as a helium loop up to 800 ^{0}C, a 70 atmospheres pressurized water loop, low pressure water loops, fuel processing and fabrication installation and a critical facility, among many others.

3. Pressurized Water Reactors Program

3.1 PWR ANGRA 1 reactor

Due to a mix of technical, political and economical considerations, in the early 70's, a turn-key contract with Westinghouse Electric Corporation of the United States of America was signed to install in Angra dos Reis, half way between São Paulo and Rio de Janeiro – the largest cities in the country – the first Brazilian nuclear power reactor – ANGRA 1, a 626 Mw(e) PWR reactor. ANGRA 1 construction started in 1971, and the first criticality was achieved eleven years later.

General data and operational experience of ANGRA 1 are summarized in Tables II and III. Location of ANGRA nuclear power plants is shown in Figure 1.

It should be pointed out that during the period 1982-1995 the availability factors of ANGRA 1 were considerably low if compared with international standards. This was due to the occurrence of many technical problems in relevant equipment of the plant. Among these, can be mentioned the following: (i) main condenser sea water tubes had to be changed due to corrosion problems (1986); (ii) main electrical generator (1997/1998) and (iii) failure on fuel elements spacer grid (1993/1994). However, it is important to emphasize that along all its 20 years of operation of ANGRA 1 none of the problems presented had origin or showed any deficiency on the plant safety systems. As can be seen in Table III since 1997 ANGRA 1 has had a notable level of availability and regularity.

3.2 ANGRA 2 and ANGRA 3 nuclear power plants

ANGRA 2 is a PWR reactor with a net capacity of 1,275 Mw(e) fabricated and constructed by SIEMENS/KWU from Germany. Civil engineering works begin in 1976 and originally it was planned to be operational by 1983. Due to several problems, most of them economical, the construction of ANGRA 2 had to be interrupted several times. Fortunately, after many setbacks, construction of ANGRA 2 nuclear power plant re-started on the second half of the 90's and finished in July 14, 2000.

Operational experience of ANGRA 2 since year 2000 is shown in Table III. As can be seen this unit has had a high factor of availability comparable with those of similar reactors all over the world. It should be pointed out that ANGRA 2 has had an exceptional performance during the last three years with an availability factor superior to 91%, well above the WANO average availability factor (82.7% in 2001), [3]. This fact place ANGRA 2 among the best 20 nuclear power plants in operation around the world in terms of energy generated.

As shown in Table I, in 2002, ANGRA 1 and ANGRA 2 together were responsible for the delivering of 13,836. GWh to the electrical grid of the country. This corresponds to nearly 4% of the total electricity produced in the country.

A third nuclear plant – ANGRA 3 – was contracted together with ANGRA 2 as part of the Agreement Brazil-Germany. Like ANGRA 2, ANGRA 3 is a PWR reactor with SIEMENS/KWU technology with a net capacity of 1,224 MW(e) as shown in Table II.

Local preparation and excavation work of ANGRA 3 was initiated also in 1976. Originally it was expected that such reactor would be operating in 1984. However similarly to ANGRA 2, its construction was halted many times due to economical problems. In 1996 when the Brazilian government decided to re-start ANGRA 2 it was decided also interrupt all activities related to the construction of ANGRA 3 and this is the situation today. However, it is important to mention that about 70% of the imported major components are stored on site under a program of surveillance and maintenance in order to guaranty its utilization conditions.

A recent shortage of hydroelectric energy (year 2000 drought) caused by very low levels on the majority of water dams all over the country demonstrated the convenience of ANGRA 3 as an additional source of electricity in the Southeast region of the country. As a result although the construction resumption of ANGRA 3 is still pending, being under consideration by the National Council of Energy Policy (CNPE), there is good probability of a positive outcome once a reliable financing mechanisms is found.

3.3 Brazilian – Germany Cooperation Agreement and the Parallel Program

In an effort to become self-sufficient in nuclear power generation, a comprehensive agreement was signed with Federal Republic of Germany in 1975 to built eight 1,300 Mw(e) PWR reactors and all needed installations for a full technology transfer package. The first two units (ANGRA 2 and ANGRA 3) were scheduled for construction on the following years with most of their components imported from Kraftwerk Union's (KWU) shops in Germany. For the remaining plants it was aimed to reach a level of 90% Brazilian-made components. The Empresas Nucleares Brasileiras (NUCLEBRAS) was then created as the Brazilian stated-owned nuclear holding company to be responsible for this enterprise which together with several joint companies should promote nuclear technology transfer from Germany on all aspects of PWR reactors and fuel cycle technology. Among these subsidiaries can be mentioned: NUCLEP – Heavy Components Manufacture, NUCLEI – Enrichment by Jet-Nozzle Process, NUCLEN – Nuclear Power Plant Architect and Engineering, NUCLAM – Uranium Prospecting, FEC – Fuel elements Manufacture, NUCON – Nuclear Power Plant Construction, NUCLEMON – Rare Earth's Production, CIPC – Mining and Yellow Cake Production. Likewise the holding NUCLEBRAS, only some of these subsidiaries had considerable development as it was the case of NUCLEP, NUCLEN and FEC [4].

Concerning the process of uranium enrichment transfer technology, the expectation was to have the ultracentrifuge process technology in the transfer package. However when the agreement was signed the enrichment technology included in it was the jet-nozzle process. From the beginning it was clear that this process didn't have technical or economical viability as demonstrated by the first developments and experiments made.

The alternative sought was to establish an R&D parallel program (name given to differentiate this program from that one officially coordinated by NUCLEBRAS) to guarantee to the country the complete domain of all stages of the fuel cycle. Thus in the early 80's the Brazilian Navy, interested in the development of a nuclear propulsion program, together with IPEN-CNEN/SP started a consistent R&D program to develop all the stages of nuclear fuel cycle. The Navy's main activity has been the development of uranium enrichment by using ultracentrifuge process. By the end of the decade all fuel cycle stages, including uranium enrichment by ultracentrifuge, had been dominated. Such success was continued with further developments through the 1990's.

Due to several problems the technology transfer program foreseen under the Brazilian-German Agreement didn't succeed properly. Due to foreign debts and considerable economical difficulties with added pressures from a privatization program proposed by federal government and strong budget cuts, the Brazilian nuclear program had to be revised at the end of the 80's. Thus, in 1988 both programs – official and parallel - were unified and a complete reorganization on the Brazilian nuclear sector was made. From the eight reactors originally programmed in 1975 only ANGRA 2 would be completed (as it was, although 17 years after the planned date). ANGRA 3 construction as previously commented was stopped (a re-start construction is still pending but with concrete perspectives). Beyond ANGRA 3 there wasn't any real commitments of plants at the time of program unification.

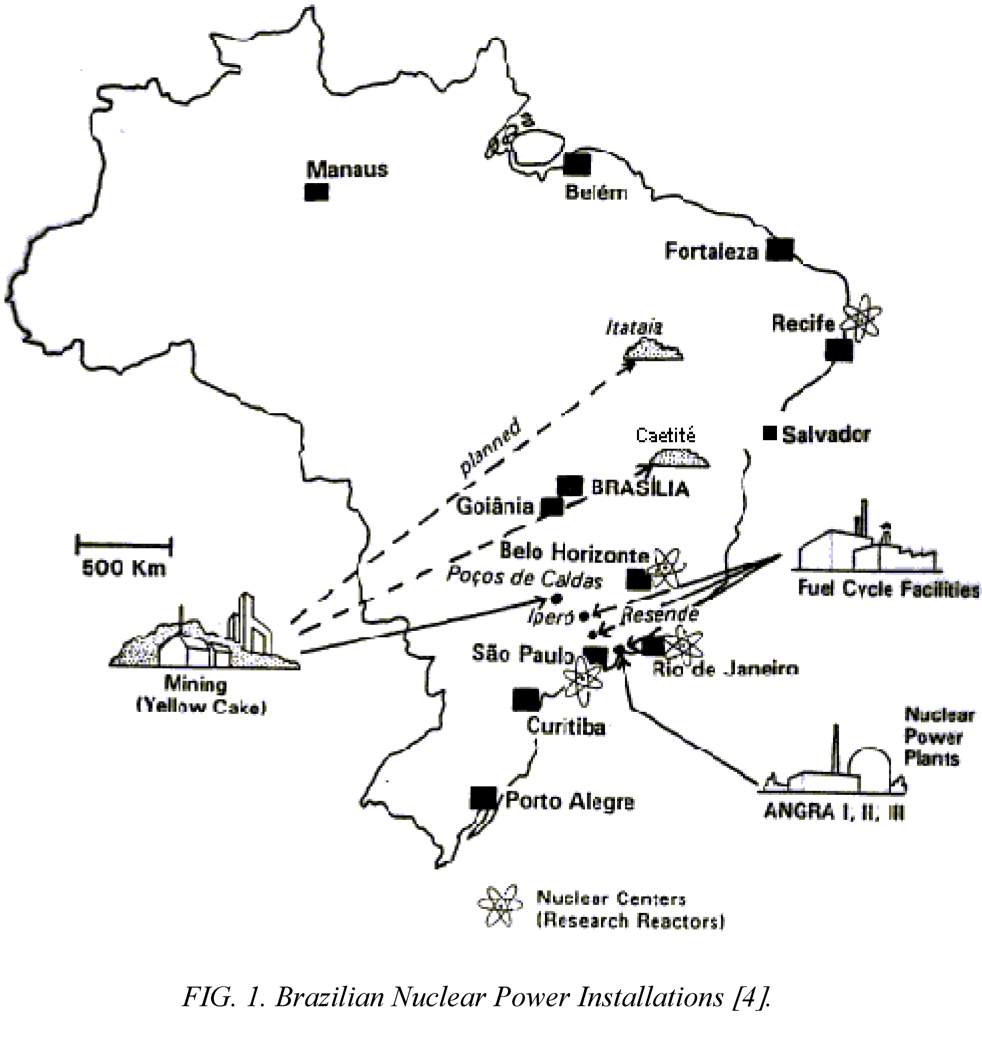

FIG. 1. Brazilian Nuclear Power Installations [4].

3.4 Organizational structure of nuclear sector

In 1988 a new company, named Industrias Nucleares do Brasil SA (INB), replaced NUCLEBRAS and its subsidiaries, with limited authority. INB became responsible for rare earth's production, mining of nuclear minerals and yellow cake and nuclear fuel production assuming FEC, NUCLEMON and CIPC activities. FEC, renamed as Nuclear Complex of Rezende, was transformed in an INB Directorate. It was assigned to CNEN the majority of the shares of INB and NUCLEP, this one responsible for heavy equipment fabrication. However, both companies, INB and NUCLEP, report directly to the Ministry of Science and Technology and are administratively independent from CNEN. Responsibility for the construction of nuclear power stations was transferred to the state-owned utility, FURNAS/ELETROBRAS, incorporating NUCON activities. NUCLEN was maintained responsible for nuclear power plant architect and engineering.

In 1997 there was another reorganization on the Brazilian nuclear structure. As a result the architect engineering company NUCLEN merged with the nuclear directorate of FURNAS in a utility responsible for the bulk supply of nuclear electricity. The new company named ELETRONUCLEAR - ELETROBRAS Termonuclear S/A. is responsible for design, procurement & follow up of Brazilian and foreign equipment's, management of construction, erection and commissioning of nuclear power plants and is the sole owner and operator of nuclear power plants in the country. Siemens sold its 25% holding in NUCLEN to ELETROBRAS when ELETRONUCLEAR was formed. NUCLEI and NUCLAM were disbanded.

Today the Brazilian nuclear structure organization is the following: ELETROBRAS, responsible for all power plants planning, construction and operation, ELETRONUCLEAR continues responsible for all nuclear power plant architect engineering and operation. Both ELETROBRAS and ELETRONUCLEAR report to the Ministry of Mines and Energy. Reporting to the Ministry of Science and Technology are the National Nuclear Energy Commission (CNEN) responsible for licensing, inspection, safeguards, standards, R&D, training and human resources development activities, INB, responsible for development, construction and operation of the fuel cycles plants, including fuel elements manufacturing and NUCLEP, responsible for heavy equipment manufacturing including NSSS equipment.

Table I. Electricity production and installed capacity [4].

	1970		1980		1990		2002	
Electricity Production (TWh)								
- Total	45.46		139.49		222.82		363.14	
- Thermal	5.60	(12%)	10.58	(8%)	14.06	(6%)	39.14	(11%)
- Hydro	39.86	(88%)	128.91	(92%)	206.71	(93%)	310.17	(85%)
- Nuclear		-		-	2.05	(1%)	13.83	(4%)
Installed Capacity (GWe)								
- Total	11.23		33.37		53.05		76.74	
- Thermal	2.41		5.87		6.86		11.98	(82%)
- Hydro	8.82		27.50		45.56		62.86	(15.5%)
- Nuclear	-		-		0.63		1.90	(2.5%)

Table II. Brazilian Nuclear Power Reactors (ELETRONUCLEAR) [5].

Nuclear Plant	Type	Net Capacity Mw(e)	Status	Grid Date

ANGRA 1	PWR	626	Operational	April 1982
ANGRA 2	PWR	1,275	Operational	July 2000
ANGRA 3	PWR	1,224	Pending	-

Table III. Operational experience of ANGRA 1 and 2 [5] [6].

Year	ANGRA 1		ANGRA 2	
	Energy Generated (GWh)	**Annual Availability Factor (%)**	**Energy Generated (GWh)**	**Annual Availability Factor (%)**
1982 to 1994	14,818.8	-		
1995	2,520.7	92.8		
1996	2,428.9	57.6		
1997	3,161.4	71.0		
1998	3,265.3	79.6		
1999	3,976.9	96.2		
2000	3,423.3	80.8	2,622.6	-
2001	3,853.5	82.9	10,498.4	93.9
2002	3,995.1	86.3	9,841.7	91.5
2003	3,326.0	76.7	10,009.0	92.3

3.2 Fuel Cycle Development

All industrial stages economically important of the uranium fuel cycle have been implemented in the country. Industrias Nucleares do Brasil (INB) has as its main goals to implement industrial units related to nuclear fuel cycle for Brazilian nuclear power plants. Among such units can be mentioned: uranium mining and milling, enrichment, reconversion, pellets production and fuel elements assembling. General information concerning Brazilian nuclear fuel cycle facilities is shown in Table IV and its location can be seen in Fig. 1.

Brazil has one of the higher uranium geological reserves in the world. The mine of Lagoa Real (Caetite Unit) is the only commercial plant currently in operation with a capacity of 340 tU/year only for internal needs. Another site - Itataia – discovered in 1976, has phosphate as co-product. Although production start up date has not yet been set, Itataia site has a capability projected to 250 tU/year.

As part of its nuclear propulsion programme, the Brazilian Navy (Centro Tecnologico da Marinha do Brasil em São Paulo – CTMSP) installed in Iperó (100 Km from São Paulo) a demonstration enrichment centrifuge pilot plant. Recently the Brazilian Government decided to start the industrial implementation of the ultracentrifuge process developed by CTMSP in the Resende Industrial Plant in the state of Rio de Janeiro. Operation of the first section of unit one is scheduled to start in late 2004. The complete set of units is intended to be operating in eight years, to attend the ANGRA 1 needs and partially the needs of ANGRA 2 and 3 (~ 300,000 SWU/year) [7].

Concerning the conversion process development, a UF_6 pilot plant, with a nominal production capacity of 40 tons U/year, is under construction at CTMSP in Iperó. However, there are no plans to install a commercial plant in the near future [7].

The Fuel Fabrication Plant (FEC), also located at Resende Complex, comprises two units, and has a total production capacity of 280 tons of uranium per year. At present, the FEC was refurbished and produces at unit I the fuel rods and fuel elements for Brazilian nuclear reactors. The Unit II, responsible for pellets fabrication, is operating since June 1999 with a capacity of 120 tons of UO_2 pellets/year.

Table IV. Nuclear Fuel Cycle Facilities (INB) [7].

Facility	Current Status	Output	Licensing Status
Uranium Mine (Caetite Site)	Operating	340 t/yr U_3O_8	Temporary license
Enrichment Plant	Under construction	-	Construction license
Fuel Pellets Fabrication	Operating	120 t/yr UO_2 pellets	Licensed
Fuel Assembly	Operating	-	Licensed up to 3.4% enrichment
Fuel Fabrication (Reconversion)	Operating	140 t/yr UO_2 powder	Temporary license

The UO_2 powder production line, using the AUC process, is in operation since September 1999 with an overall production capacity of 140 tons of UO_2 powder/year. The fuel assemblies for ANGRA 1 are manufactured by INB using both Westinghouse and Siemens technology [7]. The fuel assemblies for ANGRA 2 are manufactured using Siemens technology and the first core of this plant has already been manufactured by INB. The Fuel Fabrication Plant also produces other fuel element components, such as top and bottom nozzles, grids and end plugs.

4. Future Developments and Perspectives

4.1 Nuclear Power Perspectives

As shown in Table I electricity output in 2002 amounted to 363.14 TWh – 85% originated from hydroelectric sources, 11% from fossil-fuelled plants and 4% from nuclear plants. Electricity consumption per capita increased from 1,653 KWh in 1990 to 2,235 KWh in 2002 and the nuclear energy share over the total electricity production increased from 1% to nearly 4% during the same period [4]. It is important to point out that despite of economical retraction, electricity consumption in Brazil has grown about 3.7% in 2003 in relation to 2002, establishing a new record after a stagnation period resulting from the rationing period the country experienced in 2001 [6].

In August 2002, the National Council of Energy Policy (CNPE) concluded a study related to the demand and offer of energy in Brazil for the next 20 years. Assuming a population increase of about 24% and a GDP (Gross Domestic Product) increase from the present value of 590,000 US millions to 1,590 US billions, the CNPE found that it will be necessary to roughly double the installed electrical capacity in the country by the year 2020. The same report claims that about 78% of this generation will be of hydroelectric origin, 15% natural gas and 2% of other sources (oil, biomass, wind, solar and nuclear). Today both reactors ANGRA 1 and ANGRA 2 correspond to about 2.5% of the electrical installed capacity in the country. As it was mentioned in a previous section, the construction resumption of ANGRA 3 is still pending of decision, however the perspectives are very good. Although there are other alternative energy sources to be considered, the nuclear option is a relevant alternative to the country for the next 20-30 years taking in account economical and technical aspects.

The nuclear community in the country, based on many international strong evidences, has the feeling that the next reactor after ANGRA 3 will not be a conventional PWR but a reactor of another generation. Today, is not clear how and which technologies are most suitable to answer the questions related to the nuclear power energy in the medium and long term future [8]. Therefore it is very appropriated to the country start a consistent R&D program on nuclear reactor systems to be developed in the medium and long term.

4.2 New technology developments

Envisioning defining the most promising technologies as well as their R&D needs to achieve deployment within the next 30 years, the country has been involved with some international initiatives. Two of them deserve to be mentioned due to their importance. The first one, launched in 2000 under the leadership of USA, is the Generation IV International Forum – GIF. Ten countries have been participating in this Forum, including Brazil. The second initiative was set for by the International Atomic Energy Agency – IAEA – in 2001 and was named INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycle). This project has the participation of 12 countries, including Brazil also. In short, both initiatives try to address the challenges for the future of nuclear energy which are: (a) to prove that nuclear energy is economically competitive in an environment ruled by market forces and (b) to get the public acceptance concerning safety, waste deposition, environmental and proliferation issues.

In a more direct involvement, Brazil is also participating in the IRIS design [9]. IRIS (International Reactor Innovative and Secure) is a small-to-medium power (335 MWe) integral type pressurized water reactor which has the significant characteristics of simplicity, enhanced safety, improved economics, proliferation resistance and waste minimization. The research institutes of CNEN are participating in specific activities related with pressurizer design, transient and safety analysis and desalination [10]. Besides CNEN, NUCLEP and ELETRONUCLEAR, to a less extent, are also involved in IRIS design and development. This participation, depending on some government decisions, is expected to increase in the next two years.

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