Brazilian Journal of Physics
ISSN: 0103-9733
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Sociedade Brasileira de Física
Brasil

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Brazilian Journal of Physics, vol. 41, núm. 2-3, septiembre, 2011, pp. 107-112
Sociedade Brasileira de Física
Sâo Paulo, Brasil

Braz J Phys (2011) 41:107–112
DOI 10.1007/s13538-011-0028-z

NUCLEAR PHYSICS

News and Views: Nuclear Power in Brazil

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Received: 9 May 2011 / Published online: 22 July 2011

Abstract No energy, whether renewable, clean or known by any other name can possibly be relied upon as the only solution for ensuring a supply of electricity compatible with a nation's economic and social development. Brazilian consumption and installed capacity of electric power generation per capita indices are still inadequate and below the world average—this crucial fact must be considered. It obliges Brazil to take the most advantage of all resources available to increase its electricity generation capacity as rapidly as possible, thereby enabling consumption to reach levels compatible with the quality of life the Brazilian population aspires to. The planning of a country's electric system requires efficient management of a diversified portfolio of energy sources. In Brazil, hydroelectricity will continue for many years yet to be the main component of its portfolio of electric power generation sources, but it must be supplemented by thermal sources—uranium, coal, biomass, natural gas, and oil by-products derived from petroleum—in this order of importance, keeping in mind aspects related to local availability, cost, environmental impacts, and use in other applications.

Keywords Nuclear energy · Energy sources · Reactor technology

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1 Introduction

Nuclear energy provides roughly 3% of the Brazilian electricity. In 2010, for instance, a year in which 445 TWh were produced and 39 TWh had to be imported, nuclear power plants accounted for 12.4 TWh, or 2.8%, while 84% came from hydro, 3.5% from gas, 4% from biomass, and slightly more than 5% from coal and oil. For the current and future years, progressively larger energy totals are projected, since the per capita consumption has risen steeply—from 1,500 kWh/year in 1990 to 2,200 kWh/year in 2010.

Among the actions planned to meet the growing demand, in February 2010 the Brazilian government approved investment in the new 11.2 GW Belo Monte hydro complex, which will flood 500 km^2 of the Amazon basin and ultimately supply around 11% of the electricity. The construction tending to increase the already high dependence on hydro resources and the consequent vulnerability to climatic stresses, the perspectives for additional hydroelectric development are now perceived as narrow. Alternatives must be studied.

2 Why Does Brazil Need Nuclear Power?

The predominance of hydroelectricity, a unique feature of the Brazilian energy network, can either be regarded as a blessing of nature or as a curse leaving the country at the whims of the weather. Against the curse, the system is protected by reservoirs, the capacity of which has therefore capital importance in this discussion.

Small until the late 1950s, the volume of the hydroelectrical reservoirs expanded rapidly in two well defined periods, the first in the 1960s and the second ranging from the second half of the 1970s to the early 1980s. Since then, the volume has increased marginally, out of pace with the rising installed capacity, and the disproportion between rates has fueled the risk of deficits. As a result, notwithstanding the adequate installed power, the operators fear droughts that could lead to supply crises analogous to the shortage of 2001.

The storage capacity of the dams, once equivalent to 2 years of energy, dwindled to 5.8 months in 2003. This was already close to critical, given that 5 months of stored hydroelectric energy are needed to cope with a dry spell as severe as that of 2001. To make matters worse, environmental restrictions having severely limited the size of reservoirs, only hydroelectric plants with 2-month accumulation-to-production ratios will start to operate in the near future. The overall ratio will drop. Thermal plants are, therefore needed, and not only because the hydro potential is expected to become exhausted in the medium run.

The national electric power system is transitioning from practically 100% hydro to a balance between hydro and thermal. In the new setting, while still dominant, hydroelectric generation will operate in tandem with a major thermoelectric component. The combination will allow the reservoirs to reach a level sufficient for a number of years and reduce the hydrological risk. Thermal plants will moreover supplement the installed capacity to meet the demands of sustained economic development.

The consumption of electric power is expected to grow faster than the GDP of the country. Over the next 10 years, a growth in the 4–5% per-annum range has been projected in the 2006–2015 Decennial Plan for the Increase of Electric Power, a study conducted by the Ministry of Mines and Energy. On the basis of this projection, the installed capacity should reach 150 GW by 2015. Comparison with the current 100 GW capacity, plus the amount that can be imported from neighboring countries, indicates that Brazil will have to strain its natural resources in an effort to install approximately 50 GW in the next 5 years.

It is more difficult to predict the growth rate in the subsequent decade, which depends on a number of unknowns. If, as an exercise, a 4% per-annum average is considered, an installed capacity of 230 GW can be projected for 2025, 80 GW above the 2015 level.

These numbers define one of the greatest challenges facing the country in the next 20 years. The nation must choose. The thermal sources offer numerous alternatives, which can be ranked on a scale defined by four practical aspects: abundance within the country, potential for integration to the grid, cost, and environmental impact. Easiest to apply, the first criterion leads to a list comprising uranium, coal, biomass, natural gas, and oil by-products derived from petroleum, in that order.

The geographical aspects come next. The concentration of reserves privileges coal in the southern region. In the southeastern and northeastern regions, whose hydroelectric potentials have been practically exhausted, nuclear energy is an attractive alternative. There is also room, here, for biomass, in the form of sugar cane and other vegetable residues, sources that would also help to regulate the system, given that their production peaks in the dry months. Unfortunately, the required arable land severely limits the supply of biomass, 3,000 to 5,000 km^2 being needed to generate 1 GWh of electricity.

The economic and environmental aspects have also to be considered, and they advise against burning oil or natural gas. The limited national reserves of these two sources should be assigned to sectors of the economy in which they cannot be replaced, such as transportation and the chemical industry; this is especially so since their massive environmental impact goes beyond the emission of greenhouse gases. From this viewpoint, nuclear energy offers a very different perspective, since the Brazilian uranium reserves, one of the largest in the world, find application only in the generation of electric power.

Wind, solar and other renewable energies cannot, of course, be discarded. Excellent options for off-the-grid locations with modest power demands, these alternatives become less attractive as the scale grows, because they are expensive and occupy much space: an installed capacity of 1 GWe, for instance, requires 50 to 60 km^2 of solar panels or wind turbines. And because they are intermittent, solar and wind powers can only offer subsidiary contributions to the continuous generation of electricity required by the national system.

3 Development of Nuclear Industry in Brazil

In 1970, the Brazilian government decided to seek bids for an initial nuclear plant. The turnkey contract for Angra 1 was awarded to Westinghouse, and the construction started in 1971, at a coastal site between Rio de Janeiro and São Paulo.

In 1975, resolved to become self-sufficient in nuclear technology, the government signed an agreement with West Germany to acquire eight 1.3 GW e nuclear units over a period of 15 years. The first two of these, Angra 2 and 3, were to be immediately built, with Kraftwerk Union (KWU) equipment. The transfer agreement ensured the technological content of the other six units to be 90% Brazilian. A state-owned company, *Empresas Nucleares Brasileiras, S. A.* (Nuclebrás) was set up, with a number of subsidiaries focused on particular aspects of the nuclear fuel cycle and the associated engineering. Soon, however, economic difficulties forced the country to interrupt the construction of the first two Brazilian-German reactors.

A decade later, the whole program was reorganized. In 1988, a new company, Indústrias Nucleares do Brasil (INB), took over the front-end fuel-cycle subsidiaries of Nuclebrás. Responsibility for the construction of Angra 2 and 3 was transferred to an utility company, *Furnas Centrais Elétricas, S. A.* (Furnas), a subsidiary of Eletrobrás, although Nuclen, a former Nuclebrás subsidiary with KWU participation, remained in charge of nuclear-plant architecture and engineering. Construction of Angra 2 was resumed in 1995, and in 1997, the nuclear branch of Furnas merged with Nuclen to form *Eletrobrás Termonuclear S. A.* (Eletronuclear), a new subsidiary of Eletrobrás that is responsible for the construction and operation of all nuclear power plants.

Heavy-equipment manufacturing remained in the hands of the former Nuclebrás subsidiary *Nuclebrás Equipamentos Pesados, S. A.* (Nuclep). Both Nuclep and INB are subsidiaries of the *ComissÃčo Nacional de Energia Nuclear* (CNEN), the national nuclear-energy regulator. Their administration is nonetheless independent of the CNEN, and all three report directly to the Minister of Science and Technology. Eletrobrás, which owns Eletronuclear, is under the Ministry of Mines and Energy.

4 Current Status of the Brazilian Nuclear Power Industry

In its first years of operation, Angra 1 suffered continuously from steam-supply malfunctions and had to be shut down for extensive periods. Over the first 15 years, its lifetime load factor was only 25%. Since 1999, however, the availability has improved substantially, a cumulative factor of 78% being recorded in the 1997–2009 period.

Table 1 Operative Brazilian power reactors

Reactor	Model	Gross capacity	First power	Commercial operation
Angra 1	PWR	1,657 MWe	1982	Jan 1985
Angra 2	PWR	1,350 MWe	2000	Dec 2000
Total		2007 MWe		

Table 2 Brazilian power reactors under construction

Reactor	Model	Gross capacity	First started	Commercial operation
Angra 3	PWR	1,405 MWe	Jun 2010	2016

Angra 2 was inaugurated much more recently, in 2000. Begun in 1976, its construction was delayed by scarce funding and lower-than-expected demand. Since it became operational, however, the plant has performed impressively: with a 1997–2009 cummulative availability of 86%, it occupies the first quartile in the international ranking of nuclear power plants (Tables 1 and 2).

Angra 3 was planned to be a twin of Angra 2. Work on the project started in 1984, only to be suspended in 1986, before construction began, even though 70% of the equipment lay on site. Twenty years later, in November 2006, the federal government announced its plans to complete the power plant. In June 2007, the National Energy Policy Council approved the construction, an act ratified by the President in July 2007. Following environmental (March 2009) and other approvals (July 2009), the CNEN issued a construction license in May 2010. The first concrete load was poured one month later, and the plant is expected to become operational by the end of 2015.

The new nuclear power plant is expected to push network prices down. Typically, the power delivered by nuclear plants is 1.5 times more expensive than that from established hydroelectricity. Compared with old hydros, Angra 3 is expected to charge slightly more than twice-higher prices. Compared with coal, about the same prices, and compared with natural gas, smaller prices.

Two new nuclear power plans are currently being planned for the northeast region, and two more near Angra, in the southeast. Eletronuclear initiated siting studies in the northeast and southeast regions at the end of 2009; a report should be presented to the Ministry of Mines and Energy in 2012, and sites and technology are expected to be selected in 2013. The models under study are defined by the Westinghouse AP1000, the Areva-Mitsubishi Atmea-1, and the Atomstroyexport VVER-1000.

5 Uranium Resources and Fuel Cycle

Active exploration in the 1970s and 1980s led to the discovery of 278 000 tons of uranium, or 5% of the world total known resources. Three main deposits were found in Poços de Caldas, State of Minas Gerais, Lagoa Real or Caetité, State of Bahia, and Santa Quitéria, State of Ceará. The mine in Poços de Caldas was closed in 1997, after 15 years of operation.

Mining is now active only in Caetité, the production amounting to 340 t/year. The INB has announced plans to expand that rate to 670 t/year and to add 680 t/year from Santa Quitéria, to reach a production of 1,360 t/year in 2013. To further increase the yield in Santa Quitéria, to 1,270 t/year, the INB has signed an agreement to recover uranium from the phosphate that is mined by Galvani, a company specialized in fertilizer production.

Currently, the mined uranium is converted and enriched abroad and shipped back to INB's fuel fabrication plant in Resende, in the State of Rio de Janeiro, less than 100 miles away from the Angra site. The plant is a Siemens design with 160 and 280 t/year pellet and fuel-assembly production capacities, respectively.

Starting in 2012, an enrichment plant, also located in Resende, is expected to supply 60% of the fuel required by the Angra 1 and 2 power plants. The string of technological advances bringing that goal within reach dates from the early 1980s, when the Brazilian Navy started its nuclear propulsion program. Following the 1988 development of a centrifugal enrichment prototype, a pilot unit was constructed at the Aramar Experimental Center in Iperó, State of São Paulo, which still produces 5% enriched fuel, for the nuclear-submarine project.

The Resende plant was built to exploit the technology developed at the Experimental Center. The INB officially opened its first stage in 2006, which comprises four modules—four or five 5,000–6,000 SWU/year cascades each—totalling 115,000 SWU/year. In its first year, 2009, the plant produced 730 kg of 4% enriched uranium with domestically developed centrifuges based on all-magnetic bearing technology. A second stage is planned to raise the capacity to 200,000 SWU/year.

6 Radioactive Waste Management

The CNEN is responsible for management and disposal of radioactive waste. Legislation passed in 2001 provides for site selection, construction and operation of repositories to store low- and intermediate-level wastes. A long-term solution for the waste-management problem must be found before Angra 3 is commissioned, and a long-term interim storage facility, implanted by 2030. Until then, the spent fuel will be stored in Angra.

7 Regulation and Safety

Since 1962, when the *National Policy on Nuclear Energy* was enacted, the state has had control over nuclear materials. The CNEN was set up even before that, in 1956, and became the nuclear regulator 18 years later. One of its Directorates is in charge of licensing and supervising nuclear facilities. Since 1989, when the Institute of the Environment and Renewable Natural Resources, an organ of the Ministry of the Environment, was created, the responsibility of the CNEN on nuclear licensing has been limited to the technical aspects of radiation and safety.

8 Research and Development

Five nuclear research centers maintain R&D programs focused on radioisotope, fuel cycle, reactor and related technologies, one of the Directorates of the CNEN coordinating their work. In particular, the Nuclear-Energy Research Institute (IPEN), located in São Paulo, maintains two research reactors—one of these is a 5 MW unit of the pool type—and is planning to construct a third one. The IPEN also operates a cyclotron to produce isotopes.

Also located in São Paulo is the Navy's Technology Center. Here, a prototype 11 MWe reactor for naval propulsion is being developed, expected to be critical by 2014. Safeguards on the prototype would be applied by the International Atomic Energy Agency (IAEA) and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC).

9 Non-proliferation

In 1998, Brazil acceded to the Nuclear Non-proliferation Treaty as a non-nuclear-weapon state. Since 1967, it has subscribed to the Tlatelolco Treaty. As established in its 1988 Constitution, the country renounces the development of nuclear weapons. In 1991, the ABACC was organized and in 1994 it was enabled, under the auspices of the IAEA to apply full-scope safeguards. In 1996, Brazil joined the Nuclear Suppliers Group.

10 The Fukushima-Dai-ichi Accident: Lessons Learned so Far

At 14:46 on March 11, 2011, local time, northeastern Japan was hit by a 9.0° earthquake, in the Richter scale. With an epicenter close to the coast and only a few kilometers below the crust, the quake was the strongest to affect a highly industrialized, highly populated area. A tragedy followed. Japan has responded to its history of frequent strikes with remarkable cultural and technological advances towards minimizing seismic damage. Nevertheless, the preventive measures proved insufficient to face an event with once-in-a-millennium chance of occurrence.

Constructions were not engineered to resist events of that magnitude. Most buildings and industrial facilities in the affected region collapsed at once. Among them were oil refineries, fuel deposits, thermoelectric plants, and chemical industries, deposits of hazardous materials that released toxic fumes under the thunder of explosions. Dozens of thousands died in an apocalyptic scenery of environmental devastation.

Fourteen nuclear plants were sited in the affected area, 14 boiling water reactors (BWRs) grouped in three centrals: three units in Onagawa, four in Fukushima Daini and six in Fukushima Da-ichi, and one in Tokai. Equipped with automatic closure, all of them resisted the seismic forces and switched into safety refrigerated mode after external power was lost. At the end of the earthquake, the 14 electric powerhouses stood out against the scenery of rubble.

Nearly 1 h later, however, came an aftereffect of unlikely magnitude. A 10-m-high tsunami wave swept the flat coastal area and plowed several kilometers inland dumping rubble and other debris upon the hundreds of thousands that the earthquake had left homeless.

The nuclear powerhouses had not been designed to withstand the destructive wave. Although the Onagawa, Tokai, and Fukushima Daini plants were able to resist, the Fukushima-Dai-ichi complex proved less resilient. Over a dozen diesel generators and their fuel tanks were damaged. The backup cooling system, which had responded so well to the earthquake, was now impaired, and its failure triggered a chain of occurrences that pushed the reactors below safe operational levels.

In response to the problems initially detected in the Fukushima Dai-ichi unit 1, the Japanese government activated the External Emergency Plan for Centrals and evacuated the already homeless population from a 5-km circle around the damaged reactor. Later, given that plural units presented serious problems, the authorities decided to extend the evacuation radius well beyond the limits set by international standards, which recommend evacuation within 5 km and, beyond that, sheltering within 15 km. By evacuating 140 000 people from the high-risk area in only a few days, the Japanese government warranted safety even in the worst imaginable circumstances.

The accident has taught two lessons; more will be learned in the future. First that, as demonstrated by the Onagawa, Tokai, and Fukushima Daini centrals, nuclear plants rank highest among the human constructions designed to resist natural events of extraordinary magnitude. Second, that nuclear plants in seismic areas, especially those near seashores exposed to tsunamis, are insufficiently robust. Of course, only a small fraction of the nuclear plants around the world belong to this risk group.

More will be learned from technical analyses of the accident and not only about BWR plants. More strict requirements will be imposed on plants under construction, and safety will be elevated to a higher plateau. Reactor technology has benefited even from the study of insignificant mishaps, and the investigation of more serious events, such as the one at hand, has led to major advances. So it was with the 3-mile island accident, in the USA, 1979, and with the Chernobyl disaster, in the former USSR, 1986.

The negative record from Chernobyl is incommensurate with the tally from Fukushima Dai-ichi. The Chernobyl reactor encased graphite; hundreds of tons burned for days and claimed dozens of lives until the fire could be controlled. The released energy hurled large amounts of radioactive materials into the atmosphere, which were dispersed over an enormous area. By contrast, water-based reactors, such as the BWRs in Fukushima, store no chemical energy that might be released explosively.

Out of the 442 power plants in operation around the world, 25% are BWRs and 65% are pressurized water reactors (PWRs). Angra 1 and 2, for instance, are PWRs. In the worst-case scenario, the dispersion of radioactivity around them would be limited to the evacuation radius, and to a lesser extent, to the shelter radius.

In the aftermath of the earthquake, inflamed speeches were heard demanding a ban on nuclear energy. Such demands were provoked by the doomsday depictions dominantly found in the media coverage of the Fukushima accident, reports finding no support in technical reasoning. Suffice it to recall that, notwithstanding the magnitude of the two successive cataclysms that struck northeastern Japan, most of the nuclear stations in the devastated area remained safe. Only a few plants succumbed to the tsunami wave, and around them, an external emergency plan efficiently protected the population.

A few technical arguments are, obviously, insufficient to close the debate. The problem under discussion has numerous facets and different opinions will be voiced on each of them. Nonetheless, two general notions stand out as self-evident: it seems clear, first, that the promotion of safer nuclear industry is in the Brazilian agenda, and second, that hasty decisions made in the heat of emotion of opportunism are to be avoided, here included the decision to close operating plants or to abort the construction or the planning of new units.

11 Conclusions

Some may feel that Brazil turned to nuclear power much before it was necessary, at a time when other bountiful supplies of energy were available. Nonetheless, given that nuclear technology requires advanced qualifications, the early decision to invest in reactors has had beneficial consequences. In particular, the country is now ready to expand its nuclear park at lower costs.

The expansion of a countrywide electric power system raises questions analogous to the uncertainties in portfolio investment. The solutions to both problems should be based on the same principles; in particular, they should follow the guidelines of risk management, which call for diversification. In the long run, no country can rely on a single source of energy. The recent evolution of the Brazilian electric system, from almost exclusively hydro to an assortment including such thermal sources as nuclear power, is an example speaking loudly in favor of this strategy. Notwithstanding its position as one world's top generator of hydroelectric power, Brazil cannot keep up with demand. Thermal and, in particular, nuclear sources of energy are, therefore, necessary.