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On neutron generator applications in Brazil: current panorama and perspectives

Santos Filho[a], J. A.; Fonseca[b], E. S.; Dias[c], C. M.; Salata[d], C., Santini[d,e], E. S.; Lacerda, M. A. S. [a*]

[a] Centro de Desenvolvimento da Tecnologia Nuclear, CDTN, 31270-901, Belo Horizonte, MG, Brazil.
[b] Instituto de Radioproteção e Dosimetria, IRD, 22783-127, Rio de Janeiro, RJ, Brazil.

[c] Comissão Nacional de Energia Nuclear, CNEN, 70714-900, Brasília, DF, Brazil.

[d] Comissão Nacional de Energia Nuclear, CNEN, 20550-900, Rio de Janeiro, RJ, Brazil.

[e] Centro Brasileiro de Pesquisas Físicas, CBPF, 22090-180, Rio de Janeiro, RJ, Brazil.

*Correspondence: masl@cdtn.br ; madslacerda@gmail.com

Abstract: Techniques based on neutron beams are used in research, industry and medicine being especially suitable for the characterization of a wide variety of materials. Neutron radiation can be produced using nuclear reactors, isotopic sources, or particle accelerators. Since the number of reactors is in decline and isotopic sources are expensive and difficult to handle, neutron generator (NG) technology has experienced significant development. Neutron generators are safer than nuclear reactors and isotopic sources, and the use of NGs is increasing worldwide, including in Brazil. This article reviews the main applications of neutron radiation, neutron production techniques, and specifically the technologies used in neutron generators. An overview of the utilization of these techniques in Brazil is presented, along with studies on acquisition and start-up costs of neutron-generating equipment and perspectives for future utilization in various areas.

Keywords: Neutron generator, neutron activation analysis, prompt gamma neutron activation analysis, neutron sources, neutron source applications.

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Sobre aplicações de geradores de nêutrons no Brasil: panorama atual e perspectivas

Resumo: Técnicas baseadas em feixes neutrônicos são utilizadas em pesquisa, indústria e medicina sendo especialmente adequadas para a caracterização de uma ampla variedade de materiais. A radiação neutrônica pode ser produzida usando reatores nucleares, fontes isotópicas ou aceleradores de partículas. Como o número de reatores está em declínio e as fontes isotópicas são caras e difíceis de manusear, a tecnologia de geradores de nêutrons (GN) tem experimentado um desenvolvimento expressivo. Os geradores de nêutrons são mais seguros que os reatores nucleares e as fontes isotópicas, e o uso do GN vem aumentando em todo o mundo e até mesmo no Brasil. Este artigo revisa as principais aplicações da radiação de nêutrons, técnicas de produção de nêutrons e, especificamente, as tecnologias utilizadas em geradores de nêutrons. É apresentado um panorama da utilização dessas técnicas no Brasil, bem como estudos sobre custos de aquisição e inicialização de equipamentos geradores de nêutrons e perspectivas de utilização futura em diversas áreas.

Palavras-chave: Gerador de nêutrons, Análise por Ativação Neutrônica, PGNAA, fontes de nêutrons, aplicações de fontes de nêutrons.

1. INTRODUCTION

Neutron radiation has been used in a variety of applications since the 1930s. After the discovery of the neutron in 1932 by James Chadwick [1] further research on neutron-mater interactions was conducted by Enrico Fermi, Eugene Wigner, Lise Meitner, Otto Hahn, and Fritz Strassmann. Many discoveries in nuclear physics have been made [2,3] and in addition to basic research in matter investigation, several techniques using neutrons have been developed for applications in the field of medicine and industry.

In addition to a vast field of applications when it comes specifically to the characterization of materials, neutron analysis techniques have the advantage of being non-invasive and non-destructive. Additionally, element detection can be performed in minimal sample amounts, making it possible to discover small amounts of a given element in a large analyzed volume [4].

Although technologies that use neutrons have a wide range of applications and are in constant development, their use comes up against the relative difficulty of producing neutron beams with adequate fluence for the needs of use. A flux of neutrons useful for practical applications must be produced continuously, using techniques involving nuclear reactions. Obtaining neutron radiation is performed using one of the following methods: nuclear reactors, isotopic sources, or particle accelerators, in special a kind of accelerator called Neutron Generator – NG [2,5].

Techniques that use neutrons are becoming increasingly diverse as a result of the evolution of the electronics of sensors that interpret the interaction of neutrons with the investigated objects. This evolution increases the precision of the results, for example in the production of sharper and detailed images, making the interest in the use of techniques with neutrons grow. The evolution of electronics has also enabled the compactness of NG equipment so that its use goes beyond the structure of laboratories towards industries. This can be seen, for example, in the use of NG to control the composition of raw materials in the cement industry.

Another focus of interest in NG derives from the terrorist attacks on September 11, 2001, in the United States. After that traumatic event, special attention has directed to the detection of explosive materials and illicit drugs in ports, airports, and borders. This can easily be done using neutron beams from an NG because of its portability and ease of handling.

For the safe use of the NG is important to use properly calibrated neutron personal dosimeters and area survey meters. As these devices are generally quite energy-dependent in their dose equivalent response, this can result in an inaccurate estimate of the dose equivalent around workplaces with different neutron energy spectra and angular distributions from those of the reference radiation used for calibration [6]. To solve this problem, a possibility is to construct or adapt a calibration facility to produce a neutron field that simulates the energy spectrum found in the workplace [7]. NG can be successfully used for this purpose.

It is important to know the current status of using neutron sources in Brazil in various areas, and if there is an increasing use of neutron generators, in industry, scientific research, and surveillance industry, as observed worldwide. It is also worth studying the problems associated with acquiring an NG and the set-in-motion of a facility with this type of equipment. This paper treats these points, envisioning the future perspectives of NG use in various applications in Brazil. First, a review of the main applications of neutron radiation and neutron production techniques is made, focusing on the technologies used in NG.

2. APPLICATIONS OF NEUTRON RADIATION

Neutrons have no electrical charge, so their interaction with mater occurs through nuclear forces, which have a short range [2]. This fact makes them ideal probes for the nuclear structure of matter, especially sensitive to different isotopes of the same element. The kinetic energy of the neutron determines the probability and type of interactions that will occur. At high energies in the MeV range, inelastic scattering interactions mainly occur, while at thermal energies in the eV range, neutron capture interactions dominate [8]. In the absorption interaction, the neutron becomes part of the nucleus, which takes it to an excited state. Then, after a finite time, the nucleus decays emitting lighter fragments and/or electrons. Usually, the decay process is accompanied by the immediate emission of gamma radiation (prompt gamma). The residual nucleus may subsequently decay with beta emission followed by gamma characteristic radiation emission in an activation process [2].

2.1. Analytical techniques using neutron interaction

The analysis by neutron activation (NAA - Neutron Activation Analysis) or by "prompt gamma" method (PGNAA - Prompt Gamma Neutron Activation Analysis) are techniques already established and traditionally carried out in nuclear research reactors. In the NAA, the sample is irradiated with thermalized neutrons from inside a nuclear reactor and, subsequently, taken to another area of low background radiation (BG) where the gamma radiation intensities from the radioactive decay induced in the sample by the neutrons are measured. The gamma radiation spectrum provides information about the chemical composition of the sample. Although this technique can be used to measure concentrations of many elements with very high sensitivity (on the order of $< ng.g^{-1}$), it is not sensitive for about one-third of elements where no radioactive products are generated by neutron activation. In the PGNAA, the sample emits gamma radiation almost immediately, with a delay of the order of 10^{-14} s after the interaction. These are called prompt or immediate gamma radiation (prompt gamma) with energies of the order of 2 to 10 MeV [9], and are characteristic of the constituent elements of the sample. The gamma radiation emitted by the sample is registered by a gamma spectrometry system, consisting of a detector (scintillation or semiconductor), associated electronics and a multi-channel analyzer (MCA) connected to a computer. A software stores and displays the spectrum data [5]. This technique has sensitivities that allow detection of up to < 0.1 mg of any element except helium.

The NAA and PGNAA techniques can analyze simultaneously and accurately many elements, even in a small sample. Traditionally, the use of NAA and PGNAA was restricted to laboratories with research reactors, which, as will be discussed later, has had its accessibility continuously reduced [4]. The NG are an alternative to replace both reactors and isotopic sources. There are several neutron inspection techniques. Fast neutron analysis (FNA), fast and pulsed thermal neutron analysis (PFTNA), and thermal neutron analysis (TNA) are efficient techniques for detecting nitrogen (N), oxygen (O), and carbon (C), allowing the identification of many explosives [2]. Table 1 lists the characteristics of the main neutron sample analysis techniques.

Table 1 : Characteristics of the main techniques for analyzing samples with neutrons.

Technique	Radiation source	Probing radiation	Main reaction	Technique	Radiation source
TNA	252Cf; DD or DT STNG*	Thermalized neutrons	(n,γ)	Prompt γ from neutron capture	H, N, Cl (others)
FNA	DD or DT STNG*	Fast neutrons	(n,n'γ)	γ from neutron inelastic scattering	C, O, Cl (N, others)
PFNA	ns-pulsed accelerator	Fast neutrons	(n,n'γ)	γ from neutron inelastic nêutron scattering	C, O, Cl (N, others)
PFNTS	ns-pulsed accelerator	white spectrum of fast neutrons	All available	Source neutrons which are transmitted	H, C, N, O and others
API	STNG* DT e associated particle	14MeV neutrons with associated α particles	(n,n'γ)	γ in coincidence with α particle	C, N, O (others)
PFTNA	STNG* DT μs -pulsed	Fast neutrons during pulse, and then thermalized neutrons	(n,n'γ) + (n,γ)	γ from neutron inelastic neutron scattering, capture and activation analysis	H, C, N, O (others)
FNSA	ns-pulsed or DC accel.; STNG*	Monoenergetic fast neutrons	(n,n) + (n, n')	Elastically and inelastically scattered neutrons	H, C, N, O (others)

* STNG: Sealed tube neutron generator.

Source: Adapted from Buffler, (2004) [10].

2.2. Applications of neutron radiation in scientific research

Neutrons are fundamental in the functioning dynamics of reactors that operate with nuclear fission, whether they are power reactors, those that aim to produce energy, or those dedicated to research. It is not uncommon for these reactors to serve other purposes besides carrying out research and carrying out experiments in nuclear technology, such as the production of radioisotopes for medical and industrial use, neutron activation techniques for the characterization of materials, generation of images (neutrongraphy), training, teaching, material testing, etc. Controlling the speed of fission reactions and, consequently, the energy dissipated by the reactor is done by adjusting the density of neutrons that are naturally produced in the process. In normal operation, the reactors operate in a so-called "critical" condition in which, by controlling the neutron population, the chain reaction remains in a steady state. There are also research reactors that operate in a "subcritical" configuration in which an external source of neutrons controls the reaction speed [11,12]. The use of NGs in subcritical assemblies (SCA) has the advantage of providing an intense quasi-monoenergetic neutron flux, allowing the SCA operation under both pulsed and continuous modes [12].

Neutron applications can be found in almost all fields of scientific investigation, and most notably in the analysis of chemical elements in various samples. Although the result generated may resemble that obtained by conventional chemical analysis, the neutron analysis process is based on nuclear properties, which makes it especially advantageous in certain contexts, such as: (a) it is a non-destructive analysis process; (b) can analyze a large number of elements; (c) the sample is easy to prepare, requiring no reagents, which avoid contaminate during preparation and; (d) the analyzer equipment can be built in small dimensions, facilitating the application in the field where conventional analysis equipment could hardly be used [4].

Neutron radiation can also be used in the generation of tomographic images of objects of archaeological interest [13], in the reduction of the toxicity of waste radioactive substances through transmutation [14] and, in radiation metrology studies.

Accelerator-driven neutron sources have also been recently used for soft error test studies of semiconductor devices and to investigate the nanostructure of various materials (polymer, biomaterials, and metals). In this last case, it is used an experimental technique named Small-Angle Neutron Scattering (SANS) [15].

2.3. Applications of neutron radiation in industry

Neutrons can be used in mineral prospecting [16] and to control the composition of mixtures in the cement and coal industry [2]. At airports and border posts, neutron radiation can be used to detect illicit products such as explosives, drugs, hazardous chemicals [3], and radioactive materials. Buried landmines can be located using neutron beams [17]. Neutrons can be used to determine chemical elements such as hydrogen in metals [4] and for radioisotope production for industrial use.

- Neutron gamma logging system

Well profiling, especially for oil wells, is a technique used to determine the elements present in the soil inside the well, as well as its porosity, salinity, oxygen content, and water/hydrocarbon interface. This technique, called neutron gamma logging system, is carried out during drilling, so that a geological analysis of the data obtained can define the continuation or interruption of drilling. A logging system using neutrons consists of a neutron generator and a gamma radiation detector. During well drilling, the operation is periodically stopped and the bit removed. Next, the source and detector are lowered into the well.

There are drilling rigs in which the logging system is mounted directly behind the drilling head and the analysis is performed during drilling. In both processes, the generated neutrons penetrate the well wall surrounding the source and a detector measures the gamma radiation resulting from neutron interactions with the soil elements. Signals are sent to the outside of the well via a signal cable, in the case where the source is lowered, or via telemetry, when the system is mounted on the drilling rig. Interpreting the sensor signal using an electronic system provides information on the soil's constituent elements [18,19]. This technique was introduced in 1941 using an isotopic source of RaBe, and currently, those of AmBe are generally used. Neutron generators have replaced isotopic sources for a variety of reasons, which will be discussed later. Among them is the fact that certain measurements can only be made with pulsed neutrons, which is impossible with isotopic sources [18].

- Online analysis of bulk raw material

Conveyor-mounted analyzers are used for online analysis of bulk raw materials in industries such as cement, coal, iron ore, sinter, lime, industrial minerals for refractories, and blast furnace feeds, copper, iron ore, etc., helping to ensure material quality and process optimization [2]. Figure 1 illustrates an analysis system applied for raw material analysis in cement production. Online analyzers are tools that are becoming indispensable in the analysis of raw materials in cement and coal processing plants. In 2012, according to the IAEA [4], more than 400 online system analyzers by several manufacturers were operating in cement plants, monitoring the composition of the raw material circulating on conveyor belts. A typical analysis system is constructed from a neutron generator, a moderator (e.g. polyethylene), the belt with the material on it, and detectors (typically scintillators) above it. A box accommodates the set acting as a shield against radiation. An electronic multichannel analyzer card connected to a computer collects the spectral data. The spectra are compared to those of pure materials (SiO_2, Al_2O_3, $CaCO_3$, and Fe_2O_3) in a library of spectra. The great advantage of this method is that irradiation analyses, on average, about 90 % of the raw material, while the conventional process removes and analyses samples that represent about 0.0001 % of the raw material [4].

Figure 1: PGNAA analyzer situated directly on the conveyor belt.

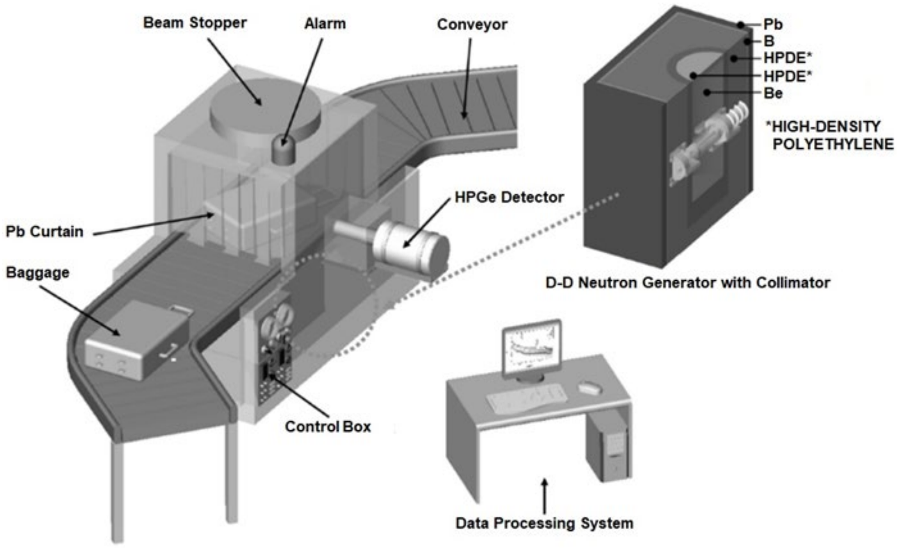
Source : Adapted from Chichester, 2012 [21].

- Detection of illicit substances using neutrons

Normally, the most used technique for the surveillance of goods and baggage in ports, airports, and borders is x-ray inspection. Although this technique is very useful in detecting solid objects such as weapons, it fails to detect low-density chemical elements, which are the main components of organic materials in general, explosives, and illicit drugs. The limitations of x-ray inspection have stimulated the development of other techniques including those based on neutrons [10].

An inherent characteristic of illicit drugs and explosives is that, although there are hundreds of variations in composition, most of these substances consist almost exclusively of the elements H, C, N and O. Their characteristics make them quite different from most common materials. High proportions of nitrogen and oxygen and relatively low proportions of carbon and hydrogen characterize explosives. Illicit drugs, on the other hand, are generally rich in hydrogen and carbon and poor in nitrogen and oxygen. This particular composition can be used to identify explosives and illicit drugs when hidden among other materials using techniques employing neutrons. The characteristic gamma radiations obtained after bombardment of the sample with neutrons, produce a "signature" that allows to identify its constituent elements and respective quantities and, ultimately, to individualize the substance inside a sample [10]. The Figure 2 illustrates the conceptual design of such a system for baggage inspection

Figure 2: Conceptual design of a baggage inspection system.



Source : Adapted from Im and Song, 2009 [9].

- Detection of anti-personnel landmines (APL)

Land mines for anti-personnel use are explosive devices buried in the ground, being hidden. When a victim interacts with its surface, the explosive is detonated, injuring or eventually leading the victim to death. As the device can remain active for years, even after the final of the conflicts, the areas where these devices were installed remain very dangerous. Setting up a mine is a simple process, but removing it is not, as there is normally no individual record of its location. For removal and deactivation, mines must first be located on the ground. Conventional techniques for this are location using metal detectors and natural sniffers [22]. Two detection methods using neutron beams have been developed, which can be used individually or together. One method is based on the fact that mines contain significantly more hydrogen atoms than the surrounding land. As the hydrogen atom is a very effective moderator, when the neutron flux directed towards the ground encounters a mine, the backscattered thermal neutrons will suffer an increase, and the measurement of these neutrons allows the location of the mine. Another method uses the PGNAA (prompt gamma) technique.

2.4. Applications of neutron radiation in medicine

Neutrons can be used in the study of bone densitometry [23] and in the treatment of cancerous tumours [24]. They also can be used to determine the concentration of various chemical elements in human bodies, animals, and biological material [4] and radioisotope production for medical use.

Boron Neutron Capture Therapy (BNCT) is a type of treatment for some types of cancerous tumours. It consists of administering a boron-based compound to the patient, in this case, ^{10}B, so that it is absorbed in greater quantity by tumour cells than by healthy cells. Subsequently, the patient is subjected to a beam of low-energy neutrons, and the unstable nuclide formed, ^{11}B, rapidly decays into an alpha particle and a ^{7}Li nucleus releasing an energy of 2.79 MeV per reaction [25]. The ^{7}Li nucleus remains in an excited state and emits a gamma photon of 0.48 MeV. The average stopping power of ^{7}Li ions with energy of 0.84 MeV and alpha particles of 1.47 MeV have high values (162 and 196 keV μm^{-1}, respectively). Thus, they are stopped at a short distance, 5.2 and 7.5 μm, limiting their action to the interior of the cell itself. If an adequate amount of ^{10}B is administered and concentrated on the surface, or preferably inside, the cancerous tumour cells, the neutron capture process will kill the tumour cells, largely preserving the healthy tissue. A substance used in clinical trials, as a vector for ^{10}B is boron phenylalanine (BPA), which is phenylalanine synthesized with a boron atom. The concentration of this substance in the tumour is approximately three times higher than the concentration in normal tissue. Currently, clinical trials of BNCT and BPA have been carried out for the treatment of recurrent brain cancer, head and neck cancer, and superficial cancer [26].

A higher-intensity neutron source is normally preferable for BNCT. Historically, it has been used reactor-based neutron sources. However, the use of accelerator-driven neutron sources is currently being studied [15,27,28,29]. One of the main advantages of using these devices is the possibility of being constructed near a hospital.

3. NEUTRON PRODUCTION TECHNIQUES

A traditional form of neutron production for matter investigation applications is the use of research reactors. Although they are much smaller and less complex than other types of reactors, such as those used for energy production, for example, they are still expensive equipment from the point of view of construction, maintenance, environmental licensing, operation, and safety. Besides, research reactors occupy a lot of space and require highly specialized workers. According to the IAEA - International Atomic Energy Agency, in 2012, there were 382 research reactors around the world and only 27 in developing countries [4]. Four of them are in Brazil. The prospect at that time was of little equipment under construction and a lot of equipment expected to be decommissioned in the not-too-distant future, that is, an indication that the availability of reactors for analytical techniques with neutrons could be in decline. Data updated also by the IAEA, show that in September 2020, only 220 research reactors were in operational condition. Considering that two-thirds of these reactors are more than 40 years old, they are reaching the end of their useful life. Then, countries have to decide whether to build new reactors or seek new technologies for their needs currently met by existing reactors [26].

Isotopic sources produce neutron fluxes using radioisotopes in two ways: as a byproduct of spontaneous fission of atomic nuclei or by activation of nuclei of light elements. The only commercially available type of source that produces neutrons by spontaneous fission uses the radionuclide ^{252}Cf. This radioisotope is synthesized in nuclear reactors and has a half-life of 2.645 years, decaying by alpha emission and spontaneous fission. It produces neutrons at a rate of 2.314×10^6 $n.s^{-1}$ μg^{-1}, with an average energy of 2.1 MeV [30]. On the other hand, the neutron production process by nuclei activation is based on the (α, n) and (γ,n) type reactions. A light element, usually beryllium, is bombarded with gamma radiation or alpha particles, and the subsequent reaction causes neutron emission [5].

In isotopic sources, the neutron flux is much smaller than that produced in reactors. To obtain high fluxes, large amounts of radioactive material are required, which increases the danger of handling and imposes the use of an elaborate system of safety barriers [4]. In addition, the half-life of these materials is short, which implies constant replacement. The cost of the material is high and has risen over time, and restrictions on the acquisition of this type of sensitive material are strict due to the risk of diversion for criminal use.

Neutrons can also be produced in particle accelerators. These are devices that make it possible to accelerate an electrically charged particle (an ion) through its interaction with an electric field, which generally varies from tens of keV to the MeV range. The energy given to the particle translates into an increase in its speed so that it can be "thrown" against a "target". The most common method of doing so is through nuclear fusion of low atomic number nuclei (light nuclei). In particle accelerators called neutron generators - NG, deuterium (^2H) nuclei are accelerated by a potential between 100 and 500 kV, against a target where deuterium or tritium atoms are present, causing a nuclear fusion reaction as shown in Equation 1 (deuterium/deuterium generator - DD generator) or Equation 2 (deuterium/tritium - DT generator).

$$ {}_{1}^{2}\mathrm{H}+{}_{1}^{2}\mathrm{H}\rightarrow{}_{2}^{3}\mathrm{He}+{}_{0}^{1}\mathrm{n}+3,266\ \mathrm{MeV}\quad(\text{neutron energy}\sim 2,4\ \mathrm{MeV}) \tag{1}$$

$$ {}_{1}^{2}\mathrm{H}+{}_{1}^{3}\mathrm{H}\rightarrow{}_{2}^{4}\mathrm{He}+{}_{0}^{1}\mathrm{n}+17,586\ \mathrm{MeV}\quad(\text{neutron energy}\sim 14,1\ \mathrm{MeV}) \tag{2}$$

These reactions are exothermic and do not conserve mass, so the difference in mass is converted into energy. The energy used to accelerate deuterium nuclei is relatively low when compared to the energy released in the reaction [4]. After the collision, the helium nucleus and the neutron are ejected at high speed and share the energy released in the reaction. The efficiency of using tritium (more energetic neutron and more intense flux) is greater than that of deuterium. However, as tritium is radioactive, deuterium is a more interesting choice considering the safety of the operation.

4. NG TECHNOLOGIES

Considering the construction technology, the typical NG equipment can be divided into three groups: vacuum neutron generators (Figure 3), sealed neutron generators (Figure 4), and the Inertial Electrostatic Confinement type (Figure 5), or NG-IEC [26,30]. Vacuum NG use a vacuum generation system, usually with two pumps, one for initial vacuum and a second for high vacuum. These devices generate high neutron fluxes, dissipate much more power and have much larger volumes than sealed NG. Both operate under high vacuum (about 10^{-6} mTorr). However, the sealed NG is compact and uses the vacuum generation system only during the construction of the generator, after which, to preserve the vacuum, it is sealed. Furthermore, in compact NG, due to the relatively low power, a cooling system is generally unnecessary. The absence of these two systems allows the construction of equipment with much-reduced dimensions. In IEC-type NG, the vacuum is produced in a similar way to NG under vacuum. There are still other models of NG that do not fit this classification, being of less common use or still in research, such as Neutristor, a kind of ultra-compact NG (1.54 cm wide by 3.175 cm long and 0.3 cm thick) built as a solid-state electronic component [31].

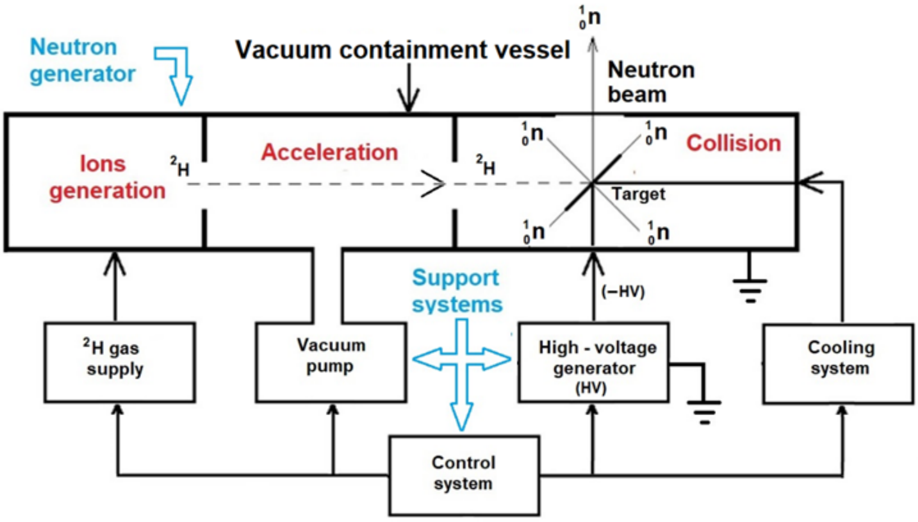
In general, the structure of NG is analyzed considering the following three distinct processes [3,4,21,32,33,34,35]:

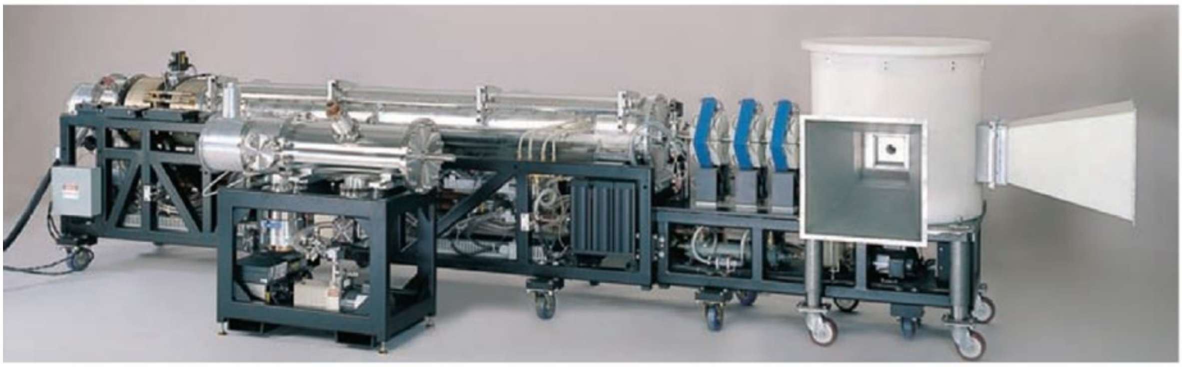
• Production of Ions - It aims to create a large amount of ^{2}H ions per unit of volume, under relatively low pressure in a confined region;

• Acceleration and extraction of ions - An electric field of tens to hundreds of kV removes the positive deuterium ions from the chamber and accelerates and focused them on the target, which is negatively polarized;

• Collision with the target - In the focus region there is a target, usually titanium containing adsorbed deuterium or tritium, against which the ions will collide. The collision will cause the fusion of the ions with the nuclei of the deuterium or tritium atoms of the target, producing neutrons and alpha particles according to Equations 1 and 2. The NG-IEC has a simpler configuration and does not need a metallic target. In this device, a metallic grid negatively polarized attracts the positive deuterium ions to converge towards the center of the device where they merge and generate neutrons.

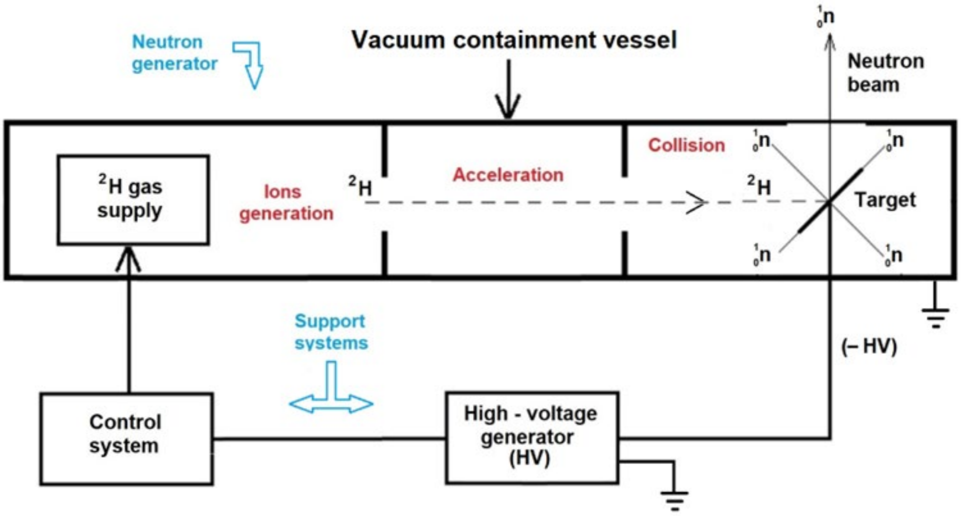
Figure 3: Vacuum neutron generators - Conceptual design and photo.





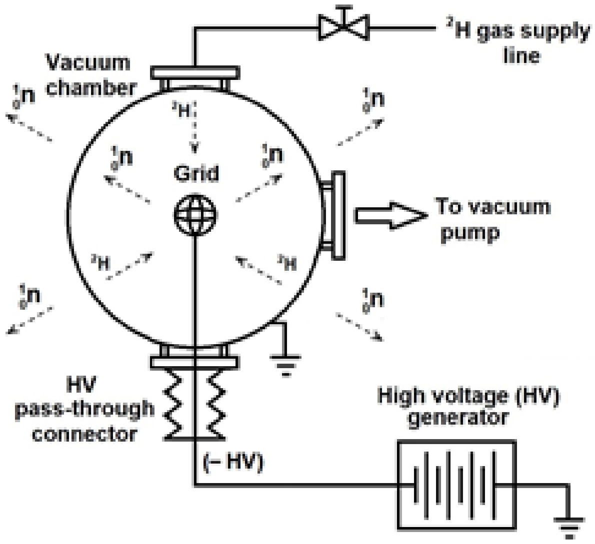
Source : Conceptual design by authors, photo adapted from (Chichester, 2012).

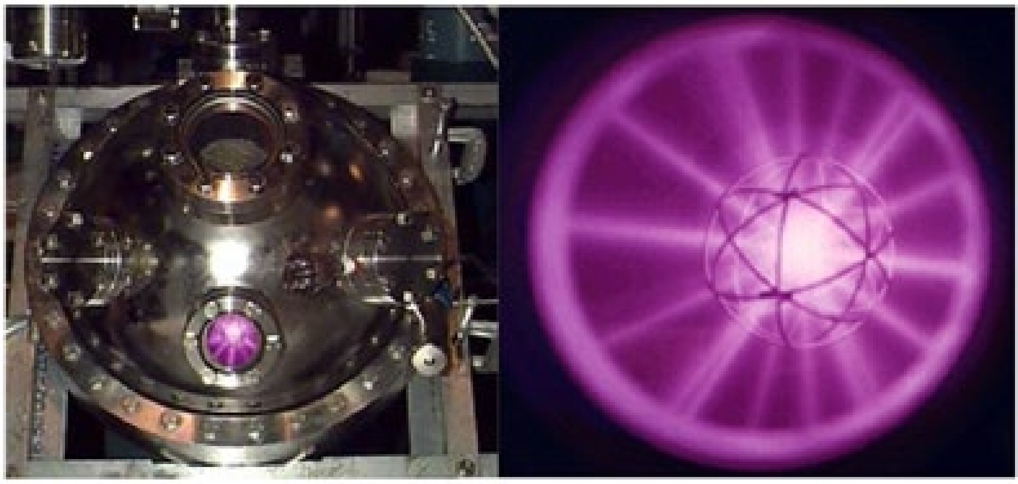
Figure 4: Compact neutron generators - Conceptual design and photo.



Source : Conceptual design by authors, photo adapted from (Chichester, 2012).

Figure 5: IEC neutron generators - Conceptual design and photo.





Source : Adapted from (Miley and Murali, 2014).

5. NG APPLICATIONS IN BRAZIL

5.1. Authorized installations

Currently in Brazil, the application of neutron generators is practically restricted to industry, mainly in cement and sinter production and in a few applications in mining, well profiling, and research. The CNEN (Brazilian Nuclear Energy Commission) website does not separately list the installations that operate neutron generators. However, through an informal consultation with that commission, in July 2024, where listed of 16 users in the industrial area authorized to operate in analytical techniques with neutron radiation. Eight of these operated only isotopic sources and eight others operated isotopic sources and neutron generators. It is interesting to note that as all facilities operate radioisotope sources and half of them also operate neutron generators, it can be assumed that these last facilities are migrating from source technology to generator technology. In particular, there is a cement company that has been operating with two NG, one since 2019 and the second since 2023. It is important to mention that there are currently 93 cement factories and about 67 sinter industries in operation in Brazil [36, 37]. In 2021, there were 59 coal industries and 609 metallic mineral extraction industries [38]. If, conservatively, 10 % of these industrial plants use analytical techniques with neutron sources, there could be enormous potential for increased use of NG.

The practice of profiling wells is a common technique in Brazil carried out by specialized suppliers who sell this service to companies that drill wells mainly oil ones. Differently from what happens with the use of neutron radiation in the industrial area, CNEN separately informs the facilities authorized to operate in the practice of well logging, which is generally carried out with isotopic sources of AmBe. With the increase in well logging operations, due to the discovery and exploration of new oil and gas fields, CNEN recently published a standard with the Safety and Radiological Protection Requirements for Well Logging [39]. Currently, there are 12 authorized installations. Assuming that each of these facilities has more than one source, it can be deduced that there is room for future replacement of these sources by neutron generators. In this area, great potential for the use of NG can be seen, given that there are, currently, 281 oil and gas-producing areas in Brazil [40].

In the research area, there is an authorized facility, which uses two DT neutron generators and several neutron emitting sources of AmBe, in the Institute of Advanced Studies (IEAV), a unit of the Brazilian Air Force (FAB) [41]. The National Metrology

Laboratory of Ionizing Radiation (LNMRI) of the Institute of Radiation Protection and Dosimetry (IRD) is another authorized facility that has isotopic neutron sources such as AmBe, PuBe, and ^{252}Cf. LNMRI/IRD is an institute of the Brazilian Nuclear Energy Commission (CNEN), and it was designated the National Laboratory for Metrology of Ionizing Radiation by the Brazilian Institute of Metrology, Standardization and Industrial Quality (INMETRO). It calibrates neutron sources, calibrates individual and area monitors in neutron beams, and irradiates individual monitors and samples, in addition to developing R&D and training in neutron radiation metrology [42].

Two new neutron metrology laboratories were recently constructed. The Neutron Calibration Laboratory (LCN) of the Nuclear and Energy Research Institute (IPEN), which is also an institute of the CNEN [43]. And, a private lab, named Metrobras Neutron Detectors Calibration Laboratory (LCDNM), constructed in collaboration with the LNMRI/IRD [44]. The three neutron metrology laboratories, mainly the LNMRI, must plan to adapt their calibration facilities to produce a neutron field that simulates the energy spectrum found in various workplaces, using a NG [7].

There is also room for NG application in the surveillance of goods and baggage in ports, airports, and borders. Currently, 66 installations are authorized for Baggage and Container Inspection. These licensee industries do not use neutron sources.

5.2. Costs of acquisition of neutron generators

Table 2 provides information regarding the acquisition costs of different models of neutron generator equipment from traditional manufacturers. All values are based on July 2019 and refer only to equipment and do not include operator training, customer installation, and optional items. The values are for equipment placed at the factory and must be added expenses with transport, insurance, taxes, and installation. In a first assessment, the added value is around 30 % to 60 % of the equipment value, depending on the tax classification.

The neutron generators usually have a delivery time between 6 to 8 months, depending on the model. It must also be considered that neutron generators are subject to strict export controls by the governments of the countries where they are manufactured.

Table 2 : Costs of acquisition of neutron generators.

Production $n.s^{-1}$ / type	Cost	Country of origin	Production $n.s^{-1}$ / type	Cost	Country of origin
1 x 10^8 / DD	108k USD	USA	1 x 10^{10} / DD[a]	237k USD	USA
1 x 10^9 / DD	158k USD	USA	2 x 10^7 / DT	90k USD	USA
4 x 10^9 / DD	210k USD	USA	1,6 10^8 / DT[b]	90k EURO	France
1 x 10^{10} / DD	257k USD	USA	1,6 10^6 / DD[b]	95k EURO	France
1 x 10^9 / DD[a]	163k USD	USA	1,6 10^8 / DT[c]	38k EURO	France
2 x 10^{10} / DD[a]	310k USD	USA	1,6 10^6 / DD[c]	43k EURO	France

Observation:
a) This NG model has a moderator device for the production of thermal neutron;
b) In this model is possible to replace the NG at the end of its useful life;
c) Modules for substitution in NG indicated in b) at the end of their useful life, estimated at:
2000 work hours producing 1.6×10^8 $n.s^{-1}$ with DT tube or 1.6×10^6 $n.s^{-1}$ with DD tube;
3200 work hours producing 1.0×10^8 $n.s^{-1}$ with DT tube or 1.0×10^6 $n.s^{-1}$ with DD tube;
6400 work hours producing 5.0×10^7 $n.s^{-1}$ with DT tube or 5.0×10^5 $n.s^{-1}$ with DD tube;

Source: Quotation obtained from manufacturers.

5.3. Brief description of the neutron generator licensing process in Brazil

Brazilian standard CNEN 6.02 treats licensing radioactive installations that use sealed sources, non-sealed sources, equipment that generates ionizing radiation, and radioactive installations for producing radioisotopes. Industries that use sealed neutron sources are normally classified as group 3C radiation installations. When neutron generators are used, installations are normally classified as group 7C.

In the authorization process, an analysis of the design plans of the installation and documentation, such as radioprotection plan, calibration certificates, etc., is carried out to verify that everything is in accordance with the specific regulatory standards. This will allow the importation of the equipment, if necessary. Then, once the generator is installed in the laboratory and before starting to operate, a CNEN team performs an inspection in the place during which, in addition to checking all the security systems and all the documentation, a radiometric survey of neutrons and photons is performed. It is necessary to demonstrate that the levels of radiation in the regions occupied by the operators and scientists doing their experiments, and the areas occupied by the public, are acceptable and that, in all its stages, the operation is safe.

As an example, the Institute of Advanced Studies (IEAV) mentioned above was authorized by the Brazil Regulatory Agency (CNEN) to operate the two NG in 2018, being the radiation levels measured at the occupied areas all compatible with the natural background.

6. FINAL REMARKS

Compared to nuclear reactors and isotopic sources, neutron generators have both advantages and disadvantages:

Advantages [4,35]:

• The neutron emission can be turned on and off immediately at any time because the energy source is an electric current. Therefore, they are safer than isotopic sources and nuclear reactors that do not have this possibility;

• The neutron emission can be pulsed at a controllable frequency, which is essential for certain analysis techniques. This is a characteristic only possible to obtain using neutron generators;

• The generated neutron fluxes, in general, have fluence adequate to the analysis techniques. To obtain intense beams, isotopic generators manipulate sources with high activities;

• The DD type neutron generator, which uses deuterium in the target, is safe when considering the handling of radioactive materials;

• Can be built in a variety of shapes and can be compact and sealed, allowing safe use in the field;

• Handling the generator is simpler than the reactor and the isotope sources;

• Considering the useful life, which depends on the amount of deuterium or tritium, the cost is infinitely less than that of the nuclear reactor, and competitive with respect to isotopic sources. In addition, depending on the constructive characteristics, it is possible to open the equipment and replace the used gas on the sealed NG or the target in the vacuum NG, extending its useful life.

Disadvantages [8]:

• Isotopic sources are completely reliable, as they do not stop delivering neutrons, whereas accelerators that produce neutrons are complex devices that can fail due to internal causes (e.g. component failure, loss of vacuum or wear of the target material) or external (e.g. lack of electrical power, vibration, mechanical shock, excessive heat);

• Neutron generators are considerably larger than isotopic sources. A portable generator that produces approximately 10^8 $n.s^{-1}$ has dimensions of 15 cm x 25 cm x 60 cm and weighs 12 kg, excluding the notebook that controls the system. A ^{252}Cf source that would produce the same neutron intensity would have dimensions smaller than 2 cm^3;

• As neutron generators are electro-electronic drive equipment, in addition to the accelerator itself that generates the neutrons, they demand a series of support systems;

• The operating life expectancy of compact neutron generators is in the order of a few thousand operating hours before maintenance and/or replacement of worn parts is required. For high fluence generators interventions that are even more regular are required. Over time, there is usually a drop in neutron production in the generators. Isotopic sources, in contrast, can operate for years before they need to be replaced.

Although neutron generators have disadvantages, especially when compared with isotopic sources, their comparative advantages are much greater, and, in addition, commercially produced generators have become increasingly efficient and cheap, which justifies the growth of their use in last years. With the increasing difficulties of obtaining neutrons in nuclear reactors and isotopic sources, the use of neutron generators - NG, has experienced a significant growth.

Based on the experience of the co-authors of this article, who have worked at CNEN, in the area of licensing of industrial installations that use neutron sources, in Brazil, for more than 15 years, there has been a significant increase in the utilization of NG to replace ^{252}Cf sources in the mineral and cement industry. However, there is room for an increase in NG utilization, not only in the mineral and cement industry but also, in the surveillance industry and scientific research.

Despite the growing use of NG in the world and Brazil, it is important to emphasize that there are few manufacturers of this type of equipment. Currently, there is none in Brazil. Although the cost of acquisition, installation, and operation is high, the benefits of the process seem to recommend, either the use of neutron radiation in general (sources and generators) or the eventual replacement of isotopic sources by neutron generators.

A more comprehensive survey must be carried out, involving technical visits to facilities that use sealed neutron sources and/or neutron generators, followed by analyses of the import processes, to provide a better overview of the applications of these sources in Brazil. However, the panorama presented in this work is important to provide the country's scientific and industrial community with an overview of the NG's construction technologies and applications of neutron sources/generators in industry and research, aiming to encourage the growth of these applications and the production of neutron generators by the Brazilian industry.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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