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Exploring the Nuclear Fuel Cycle: Highlights and Innovations

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Abstract: The paper thoroughly covers the nuclear fuel cycle, a complex and vital process in energy generation through uranium fission. The cycle comprises various stages, from uranium extraction and processing to its use as fuel material in nuclear reactors. This work primarily aims to highlight the peculiarities and innovations of the nuclear fuel cycle in the Brazilian context, seeking to promote academic and commercial interest and drive research and investments in this strategic area. The research conducted to underpin this work was comprehensive, involving literature reviews, technical visits, and discussions with specialized professionals. The conclusion emphasizes the relevance of the nuclear fuel cycle and how this work intends to highlight its specificities, underscoring the importance of this cycle for Brazil as a source of clean and safe energy generation.

Keywords: nuclear fuel cycle, nuclear energy generation, uranium.

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Explorando o Ciclo do Combustível Nuclear: Destaques e Inovações

Resumo: O trabalho abrange minuciosamente o ciclo do combustível nuclear, um processo complexo e vital na geração de energia por meio da fissão do urânio. O ciclo compreende diversas etapas, desde a extração e processamento do urânio até sua utilização como material combustível em reatores nucleares. Este trabalho tem como objetivo principal destacar as peculiaridades e inovações do ciclo do combustível nuclear no contexto brasileiro, buscando fomentar o interesse acadêmico e comercial e impulsionar pesquisas e investimentos nessa área estratégica. A pesquisa realizada para embasar este trabalho foi abrangente, envolvendo revisões bibliográficas, visitas técnicas e debates com profissionais especializados. A conclusão enfatiza a relevância do ciclo do combustível nuclear e como este trabalho se propõe a destacar suas particularidades, ressaltando a importância desse ciclo para o Brasil como fonte de geração de energia limpa e segura.

Palavras-chave: ciclo do combustível nuclear, geração de energia nuclear, urânio.

1. INTRODUCTION

Considering the prerogative of decarbonization of the world's energy matrices, Brazil aims at its diversification, as well as the development of technologies and improvement of its various ranges of energy capture, which are more than 70% from renewable energies.

Based on such information, the nuclear sciences, especially the one focused on energy production, have been in the process of national promotion in recent years, aware that Brazil dominates the cycle of nuclear fuel from uranium, this document has as a key element the synthesis of the stages of the fuel and the evidence of peculiarities about it.

2. MATERIALS AND METHODS

This is a theoretical essay, supported by bibliographic research, brief and summary case study and summary cognition of aspects of Science, Technology, Innovation and Management (STI&G) in knowledge about the development of the market for energy production with nuclear sources. The study has a qualitative, exploratory bias, corroborating technical visits to INB facilities and information collected in scientific and commercial events in the nuclear area in Brazil, which is introductory to the object of research. Being limited to the Brazilian reality, especially observing the present and the last decade, it seeks to reflect on particular aspects of a strategic sector of production and consumption in relation to the uranium input. It is intended to contribute to the formulation of proposals for the establishment and institutionalization of forms of collaborative research in STI &G and enabling their interconnection with Defense, aiming at the development of teaching, research and, purposefully, new technologies of interest to the Nation. In order to contextualize the intention, aspects associated with nuclear exploration with a bias towards energy production are outlined.

3. DEVELOPMENT

3.1. Mining

Uranium mining in Brazil is a process that involves the extraction of minerals, in the specific case of uranium, open-pit mining is more common due to the surface outcropping of mineral compounds, such as autunite, carnotite, branerite and torbernite.

In Brazil, uranium mining activity is conducted by state-owned and private companies, under the regulation of the National Nuclear Energy Commission (CNEN). Uranium mining takes place in different types of deposits, and not all of the national territory has been prospected. According to information obtained by the Federal Government's website, only 30% of the territory was analyzed, identifying areas of interest for uranium mining, such as Pitinga/AM, Rio Cristalino/PA, Campos Belos or Rio Preto/TO, Santa Quitéria/CE, Espinheiras/PB, Caetité or Lagoa Real/BA, Amorinópolis/GO, Quadrátero Ferrífero/MG, Poços de Caldas/MG and Figueira/PR.

Indústrias Nucleares do Brasil (INB), a federal public company linked to the Ministry of Mines and Energy, is responsible for uranium production in the country. INB has three uranium mining units: the Uranium Concentrate Unit in Caetité, Bahia; the Uranium Processing Unit in Resende, Rio de Janeiro; and the Uranium Concentrate Unit in Lagoa Real, also in Bahia. In addition, there is Galvani, a private company that produces fertilizers, which together with INB makes up the Santa Quitéria consortium. This consortium has the commom objective of implementing a mining project in the state of Ceará.

Uranium mining presents a number of challenges and risks, such as soil and groundwater contamination, the emission of dust particles, the risk of accidents, the exposure of workers to radiation, and the generation of radioactive waste. For this reason, the activity is regulated by government agencies such as CNEN and requires the implementation of strict safety and environmental protection measures.

Some particularities of the uranium mined in the country in question come from sedimentary rock deposits, which cover different geological periods, mainly the Mesozoic period. These sedimentary rocks contain concentrations of uranium minerals in their formations, making them targets of these mining activities, in this context in particular the extraction of uranium is evidenced, which could be better diversified enabling the collection of other materials and minerals, which come from the same pits as uranium, that is, Given the reserves of Fluoride and other compounds present in these mineral deposits, there is thus a possibility of economic return and diversification in the activities and handling of compounds and tailings from uranium extraction processes.

The exploitation of these uranium deposits involves a series of steps. Initially, geological and geophysical studies are carried out to identify areas with potential for the presence of uranium minerals. This is followed by prospecting activities, which include collecting samples and conducting laboratory tests to determine the presence and amount of uranium in the rocks. After the identification of a promising area, the development phase of the mine begins, in which engineering work is carried out for the construction of the necessary facilities and infrastructure. This includes the opening of accesses, the creation of roads, and the construction of extraction wells. The uranium mining process in Brazil is divided into three main stages, which are respectively: drilling, blasting and loading. In the drilling stage, holes are drilled in the rock with a drilling rig in order to obtain sampling of the depth of the uranium reserves and the stability of the ground to provide the greatest safety and stability of the subsequent stage.

Then, in the blasting stage, explosives are placed in the holes and detonated to break the rock so that they are broken in order to reduce its size and weight, thus enabling the final stage of the mining process, which is loading, where the ore is removed from the mine and transported to the place designated for the beneficiation stage.

3.2. Benefit

After the uranium ore extraction stage, it is necessary to carry out beneficiation to separate the uranium from the impurities present in the raw ore. The beneficiation process is essential to obtain a high-quality uranium concentrate and meet the purity requirements required for its further use.

Due to the low concentration of uranium in the ore, usually around 0.1% to 0.2%, the beneficiation method used is the wet method. In this method, the ore undergoes a series of chemical and physical steps to separate the uranium from the impurities.

The wet beneficiation process begins with the crushing and grinding of the ore, turning it into a fine pulp. This is followed by acid leaching, in which the pulp is treated with sulfuric acid to dissolve the uranium present. Sulfuric acid reacts with uranium, forming a water-soluble compound, while impurities remain insoluble.

After leaching, the solvent extraction step takes place, in which the uranium is separated from the impurities by means of organic solvents. The solvent is mixed with the uranium-containing solution, and the uranium is transferred from the aqueous medium to the organic solvent due to the chemical affinity properties. This selective extraction allows for the efficient separation of uranium from impurities.

This is followed by the precipitation stage, in which the uranium is recovered from the organic solvent. Through controlled chemical reactions, uranium is precipitated as a solid compound, usually ammonium diuranate or sodium diuranate. This precipitate is separated from the solvent and subjected to drying and calcination processes to obtain a high-purity uranium concentrate.

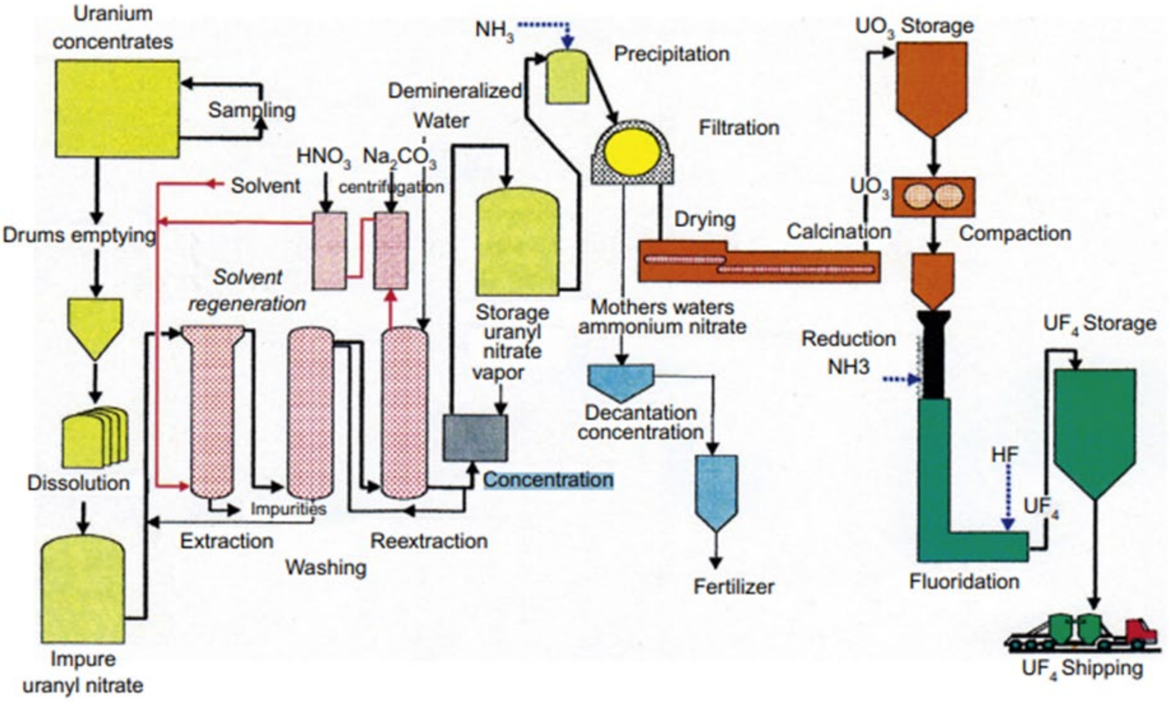
In contrast, the dry method of uranium beneficiation is used in some parts of the world, especially when the ore has a higher concentration of uranium. In this method, the ore is ground and sorted by size in an electromechanical mill. The separation of uranium from impurities is accomplished by physical processes such as flotation, in which uranium is collected in floating foam, or magnetic separation, in which uranium is separated by its magnetic properties.

It should be noted that both the wet and dry methods have their advantages and disadvantages, and the choice of processing method depends on the characteristics of the ore, the desired efficiency, and the specific economic and environmental conditions of each region.

The uranium beneficiation process in Brazil mainly involves the wet method, in which the ore is crushed, ground and subjected to leaching, solvent extraction and precipitation steps to obtain a high-purity uranium concentrate. Other countries may adopt the wet or dry method, depending on the characteristics of the ore and the available resources. Proper beneficiation is crucial to ensure the quality and purity of the uranium mined, contributing to the safety and efficiency of further applications of this important mineral resource.

In addition to Brazil, the wet method can be found in other countries such as Canada, France, Russia and China. The wet method can be seen in figure 1, where there is an example of the operation of the Comurhex company, which is located in France (OLIVER AND OZBERK, 2016).

Figure 1: Comurhex Wet Process



Source: OLIVER AND OZBERK, 2016.

In the dry process, there is no water involved in the main process, but the refining by distillation of the UF6 is carried out. This process can be found at the Honeywell plant in Metropolis, Illinois (OLIVER AND OZBERK, 2016). It is worth mentioning that this plant was built in 1958 and was deactivated in 2018 due to low demand. At the beginning of 2023, the Illinois plant restarted its production and, with that, it was once again the only national uranium conversion facility in the United States of America.

When it comes to environmental issues, Brazil follows special care so that there is no radiation contamination of any worker involved or the environment as a whole. To this end, Brazil has specific rules that are prepared and supervised by the National Nuclear Energy Commission (CNEN), NE-1.13: Mining Licensing and Uranium and/or Thorium Ore Processing Plants, is the rule that governs the licensing of processing plants (NACIONAL DE ENERGIA, 2006).

3.3. Isotropic enrichment

The ultracentrifugation of uranium is one of the parts of the uranium isotope enrichment process, from this method it is possible to note for which purpose the uranium will be used. Ultracentrifuges with traditional bearings suffer from both thermal and structural mechanical limitations. With this in mind, an equipment was developed that minimizes the contact of a structural rotating part, which suffers from these limitations mentioned above.

A peculiarity was the designation of such a system as magnetic bearings, where its application proved to have wide advantages over conventional bearings, namely: absence of lubrication; can reach high speeds; longer part life; high precision; operation diagnosis can be obtained online. There are certain disadvantages to its application, such as: higher manufacturing cost; requires skilled labor.

When working at a rotational speed of around 90,000 revolutions per minute, mechanical systems suffer from various wear and tear. Because of these high rotations, Brazil has chosen to constitute in its rotors, rotating cylinders of the machine, parts that levitate from magnetism. When actively controlled electromagnetic bearings are incorporated, the friction between the rotating and fixed parts of the equipment is subtracted. Commercial ultracentrifuges usually do not contain this electromagnetic part, and therefore have rotors that rotate on metal pin bearings.

One way to measure the power of an ultracentrifuge is from the value of separative work units (SWU) that this ultracentrifuge generates. SWU is a measurement factor that relates to the energy that is required to separate U-235 and U-238 for a defined level of enrichment. There are values of 3 SWU for equipment with less technological advancement, and values between 50 and 100 SWU for those with greater technological advancement. According to Erico Guizzo in an editorial called “How Brazil spun the Atom”, he wrote that it is believed that the Brazilian ultracentrifuge would have a capacity of around 10 SWU, but data like this are considered classified and cannot be confirmed until the International Atomic Energy Agency or the Brazilian government confirms such values.

When it comes to environmental issues, there is a work from 2014, in which a method was made to analyze the risk in nuclear isotope enrichment facilities. It was then shown that the area of greatest potential danger are the areas of product and tailings removal, where UF_6 is in a liquid state. Isolating the building that houses this area was a solution found for safety, it was observed that where UF_6 is underpressurized it can be considered a low-risk area and that leaks are abnormal events. Finally, it was noted that accidental releases into the atmosphere would only predominate the chemical toxic effect of UF_6 and there would be no major problems (OLIVEIRA NETO et al., 2014).

3.4. UF_6 conversion of UO_2 inserts

As already noted, uranium is a metal that can be found in rocks, soils, rivers, and seawater. The mining process that removes uranium from deposits and then is treated through a process of crushing and chemical separation, with two isotopes of uranium in a yellow cake sample, approximately 99.3% U-238 and 0.7% U-235 (COTTON, 2020). The conversion process includes some steps such as pre-treatment, heat treatment, reduction, hydrofluoridation, fluoridation and distillation according to the main production routes widely used around the globe. Chemically, after uranium mining and processing, uranium oxides are converted into uranium hexafluoride, so that it can be enriched and used for the manufacture of pellets and fuel elements, to be used in power plants for energy production or other destination of interest.

The particularity focuses on the reconversion stage, which is part of the process where uranium hexafluoride (UF_6) is transformed into uranium dioxide (UO_2). The reconversion process is the return of UF_6 gas to a solid state in the form of uranium dioxide powder (UO_2). UF_6, the only volatile uranium compound, sublimates at about 56.2 °C, despite its high molecular weight (INB, 2004). This property is combined with the relative chemical stability of UF_6. In addition, fluorine has only a single naturally stable isotope (19F) and there are only two isotopes of UF_6 and they differ in their molecular weight only due to the presence of ^{235}U and ^{238}U.

Some advantages are attributed such as being handled at reasonable temperatures and pressures and solubility in water. There are many ways to obtain UF_6 vapor, where various fluorine agents can be used in this synthesis, such as gaseous fluoride (F_2), liquid or gaseous halogen fluorides (ClF_3, BrF_3, BrF_6, IF_7, and others), metal fluorides (CoF_3), hydrogen fluoride (HF), carbides (UC_2), uranium oxides (UxOx) and others (RIELLA, 2020). These are some possibilities, they are the most common routes to obtain hexafluoride, being well disseminated and applied due to the ease of using the final UF_6 product due to its physicochemical properties.

While UF_6 is obtained, its processing for reconversion begins with the vaporization or expansion of the gas, being channeled with the addition of carbon dioxide and ammonia, and precipitated as ammonium tricarbonate and uranyl, TCAU. After this step, the TCAU is conducted to a rotary vacuum filter, then fed into a fluidized bed furnace where hydrogen gas and water vapor are added where it is stabilized (INB, 2004). After stabilization, inert nitrogen and air are added, when the system homogenizes it is possible to obtain the uranium dioxide powder that will be sent to the production of fuel pellets.

For the production process of the fuel pellets, it follows the production line, where the uranium dioxide powder is pressed in a rotary press and already assumes the shape of the fuel pellet as it is widely known, being able to change its dimensions according to the project. When it comes out of the rotary press, it has a molded physical appearance and a greenish color (known as green insert), then these inserts are taken to the sintering furnace to increase their density. After leaving the furnace, they are taken to the grinding machine, where the process of producing uranium dioxide pellets is completed. In this way, the processes are integrated and complement each other, giving shape to the reconversion and the products of interest.

When thinking about innovations, it is common knowledge that Brazil is moving beyond the complete mastery of the fuel cycle, since the processes and routes are known and already employed, even with certain operational difficulties, but because it is a sensitive area, little is known about the real operational potential for this sector.

3.5. Fuel element manufacturing

Fuel element manufacturing is a crucial and complex step in the life cycle of nuclear reactors, playing an essential role in the production of energy from nuclear fission. This process involves several intricate steps that aim to create a set of components capable of housing, controlling, and protecting the fissile material during reactor operation. The fuel element, also called the fuel assembly, begins its manufacturing cycle with the fuel pellets – or pellets. These small pellets are mainly composed of uranium dioxide (UO_2) or other fissile materials, and are responsible for triggering the nuclear fission reaction. The inserts must be highly stable, resistant to radiation, maintain their structural integrity at high temperatures, and be chemically stable. Generally, pellets are about 1 cm in diameter and 1 cm long. According to Glasstone and Sesonske (2008), in some cases, a thin coating of a material such as graphite or silicon carbide is applied to the surface of the fuel granules, so that it helps to prevent the release of radioactive gases during reactor operation.

A notable innovation in the area of nuclear fuel element manufacturing concerns the development of advanced fuel materials, in which uranium dioxide (UO_2) is mixed with refractory materials such as monocarbide uranium (UN) and uranium trisilicide (U_3Si_2). These materials improve fuel element efficiency, reduce the risk of fission product leakage, and provide economic and safety benefits, according to Goddard (2018). In addition, they have better thermal properties compared to traditional uranium dioxide (UO_2) fuel, resulting in more efficient and safer nuclear reactor operations. These pads are grouped into assemblies that form fuel rods, gathered into a single element. In pressurized water (PWR) reactors, specific positions in the fuel elements may contain burnable poisons instead of fuel pellets, or may require more holes for coolant to pass through, in accordance with power distribution constraints, while some positions are reserved for control rods.

In addition to fuel pellets, the fuel element may contain other components, such as spacers to maintain proper separation between fuel rods and moderators, such as water or graphite, that aid in controlling chemical reactions. There are several configurations of fuel elements, such as 15x15, 17x17 and 18x18, indicating the number of rods in each direction, with spacer plates or grids to provide support and prevent bulging of the rods. In the context of a typical 1100 MW PWR reactor, the core is composed of about 180 to 190 fuel elements (INB, 2022; LAMARSH AND BARATTA, 2019).

Subsequently, the pellets are inserted into long, thin tubes, made from zirconium, and then arranged on rods, commonly referred to as rods, approximately 4 meters long. These rods are filled with inert helium (He) gas, subjected to an appropriate pressure, and hermetically sealed.

After the fuel pellets are inserted, the coating – or cladding – is produced by acting as a barrier between the nuclear fuel and the coolant. The coating material, especially the zirconium alloy, must have specific characteristics, such as high strength, compatibility with nuclear fuel, and neutron transparency. The production process of zirconium plating involves reducing zirconium tetrachloride to obtain a high-purity alloy, followed by the manufacture of billets or plates. The coating undergoes annealing and is treated with an oxide layer to resist corrosion. Therefore, it is assembled with the fuel pellets to form fuel rods. A curious innovation studied by Was (2013) is Zircalloy, a metal alloy composed primarily of zirconium with small amounts of other elements such as tin, iron, chromium, and nickel, is often used due to its mechanical strength, low neutron capture section, and corrosion resistance. This material has a low thermal neutron capture cross-section, which means it minimally interferes with nuclear reactions. This characteristic allows for a more efficient flow of neutrons in the reactor, contributing to the maintenance of a controlled chain reaction. In addition, Zircalloy is highly resistant to corrosion and has excellent chemical stability in contact with nuclear fuel and fission products.

Thus, the assembly of the fuel elements proceeds with the pellets being loaded into the casing tubes and hermetically sealed undergoing extensive quality testing to ensure the integrity of the element. Some defects, such as fuel swelling, can occur due to the generation of fission products and neutron bombardment, but they are mitigated by appropriate designs, so controlling fuel swelling and densification is crucial to avoid problems. Generally speaking, fuel densification is more problematic in boiling water reactors (BWRs) than in pressurized water reactors (PWRs) due to core size (JERNKVIST et al., 2003; MURPHY et al., 2009).

Currently, there has been a significant advance in research into the application of advanced additive manufacturing techniques, such as 3D printing, to create complex components with precision and efficiency. This advancement enables more precise control of the geometry and quality of the fuel elements, resulting in optimized reactor performance. As discussed by Hofbeck (2018), the use of additive manufacturing in the production of fuel assembly components overcomes traditional limitations, making room for new designs that improve the efficiency of fuel assemblies. Betzler et al. (2019) highlights the various applications of advanced manufacturing, with a focus on additive manufacturing, within the scope of nuclear core design. A relevant aspect is the application of additive manufacturing to create complex coolant channel geometries, resulting in improvements in heat transfer properties and the reduction of material temperature peaks.

Proceeding with the process of this crucial step of the nuclear reactor fuel cycle are the fuel elements that are then arranged into specific patterns to optimize the reactor's performance and ensure its safe and efficient operation. In addition to fuel rods, control elements play a critical role in regulating the chain reaction by controlling reactor power.

These elements can be inserted or removed as needed, allowing for precise adjustment of the neutron flux and maintenance of a stable reaction. Spacer grids, end fittings, and guide tubes are important components for maintaining proper spacing and ensuring the reactor's structural support, heat transfer, and functionality. And finally, there is the installation of the fuel elements, a crucial step that requires precision and consideration of factors such as power distribution and reactivity control. The subsequent phase involves start-up and commissioning procedures to prepare the reactor for safe and reliable operation. Quality assurance and maintaining the integrity of fuel elements play a key role in this entire process.

3.6. Nuclear power generation

Nuclear energy is one of the most efficient and environmentally sustainable forms of power generation available today. Its production, as seen, involves a fuel cycle composed of a series of processes that enable the extraction, processing and use of uranium as fuel material in nuclear reactors. In addition, the cycle also encompasses the safe management of the resulting waste.

Nuclear fission of the uranium atom is the central technique used for generating electricity in nuclear power plants.

One of the biggest environmental advantages of electricity generation through nuclear power plants is their independence from the use of fossil fuels, which avoids the emission of gases responsible for global warming and other toxic substances. In addition, nuclear power plants occupy small areas compared to other forms of energy generation, allowing them to be installed close to consumer centers, and do not depend on weather conditions such as rain or wind to operate.

Effective protection measures for nuclear installations guarantee and minimise risks in the event of eventualities. Safety is ensured by redundant and independent systems. The reactor core is the most critical and protected region, with technologically advanced protection devices. The concept of defense-in-depth is applied, using successive physical barriers that control radiation. Uranium dioxide pellets have a molecular structure that retains most of the products generated in fission. The rods containing these inserts are sealed and manufactured with a special metal alloy. The reactor vessel acts as a watertight barrier. The radiological shielding allows safe access to the areas near the reactor. The special steel wrap, 3 centimeters thick, is designed to withstand the most serious accidents, and the concrete wrap, 70 centimeters thick, would contain any material in the event of failure of the other barriers.

The current innovation for the safe management of nuclear waste and the possibility of reusing these products, make up the next evolution to break the paradigms concerning the use of nuclear energy, with this in mind, Centena was created. This project aims to design, build and commission the Nuclear and Environmental Technology Center, the intention is for this program receive low and medium level radioactive waste, commonly called class 2.1 waste, where the half-life is less than 30 years. It is worth highlighting the importance of this program for Brazil, as the topic was highlighted at the International Nuclear Atlantic Conference (INAC) in the year of 2024, at this congress it was also mentioned that the project is in the final phase which consists of choosing the location where the program will be installed.

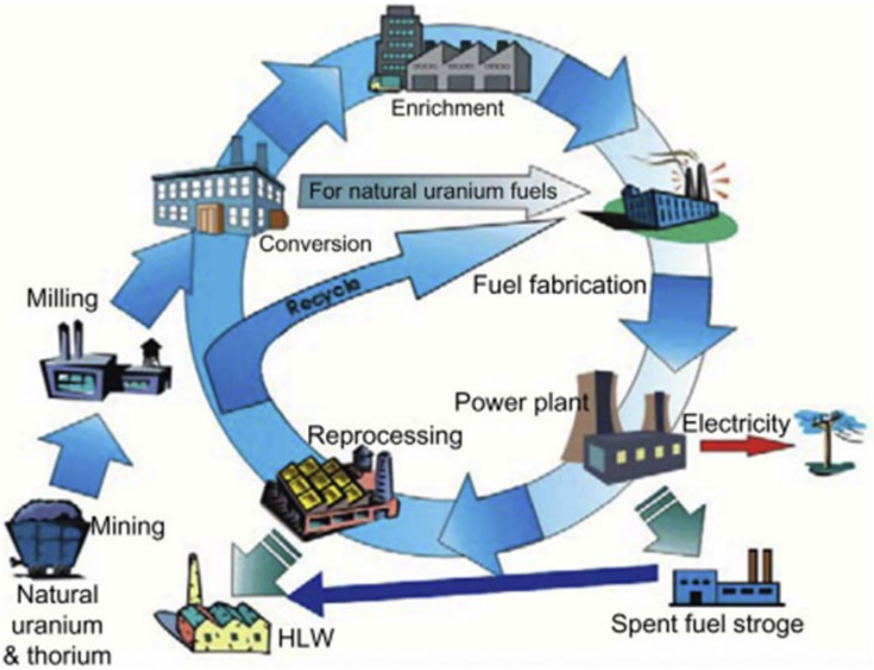
The generation of nuclear energy in Brazil has a great impact on the country's economy, in a study carried out by the Getúlio Vargas Foundation (FGV), it was shown that for every R$ 1 billion made in investment in the area of nuclear energy, there is an increase of R$ 3.1 billion in the country's production. The Gross Domestic Product (GDP) could be impacted with a value of around R$ 2 billion, and a large part of this value would be directly influencing the economy of the state of Rio de Janeiro. These figures show that nuclear energy has a great capacity to influence the country's economy and that an increase in the Brazilian generation of nuclear energy favors the country's economy, thus generating jobs and improving the quality of life of the population (FGV,2023).

Because of this impact that nuclear energy generates in the country, the Brazilian Association for the Development of Nuclear Activities (ABDAN) has been doing a job of informing the Brazilian population about what nuclear energy is and how it can impact the lives of each Brazilian citizen. Through events such as the Nuclear Energy Summit 2024 and the Nuclear Cast Podcast, the association seeks to educate Brazilian society by demonstrating that nuclear energy has more benefits than harms, and that events such as the Chernobyl and Fukushima accidents are events with a low probability of happening and, with this, it tries to reduce the population's fear of this type of energy generation.

3.7. Fuel cycle worldwide

When it comes to the fuel cycle, it is possible to observe in figure 2 a schematic of this cycle, where in this figure it covers the open cycle and the closed cycle.

Figure 2: Fuel cycle schematic



Source: OJOVAN et.al, 2019

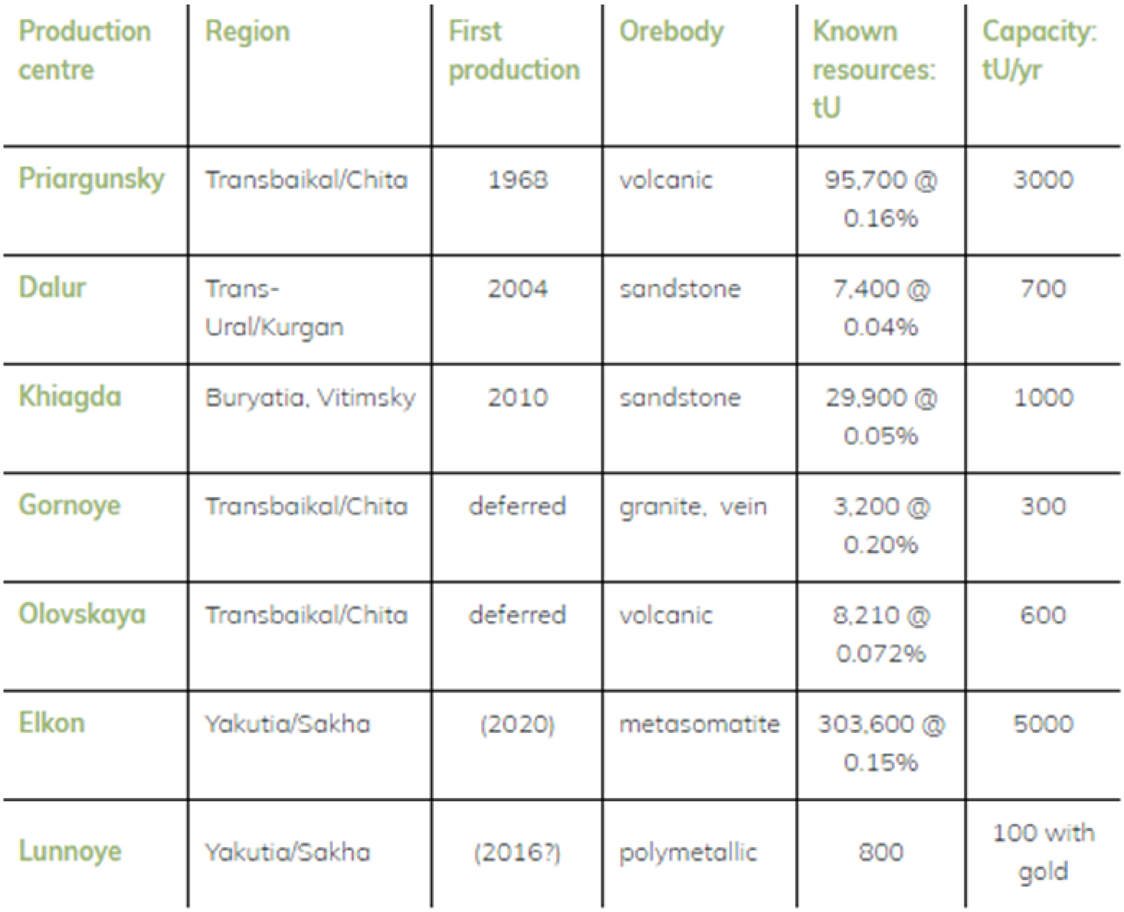
An open cycle is considered to be one in which nuclear fuel is used only once and, after its use, this fuel is temporarily discarded to a storage site. It is a closed cycle when there is a recycling of the fuel that has been spent, with this there is a reprocessing of uranium and plutonium, having to be carried out in a sealed environment and with protective barriers, due to the manufacture of mixed oxide of uranium and plutonium (OJOVAN et al., 2019).

When it comes to the fuel cycle worldwide, there are a total of 13 countries that have uranium enrichment facilities, Brazil being one of them. It is worth mentioning that each country has different production capacities (INB, 2021). With the completion of the Uranium Hexafluoride Plant (USEXA), Brazil will be part of a select world group, where it should join nuclear potentials such as the United States and Russia, thus dominating the complete fuel cycle.

The so-called group that dominates the complete fuel cycle, where the country does everything from mining to the final product, is not made up of many countries. It can be observed that powers such as Japan are not part of this select group, since this country does not have uranium reserves, so other countries such as Australia, Canada and Kazakhstan are examples of nations that meet its need for use. Japan adopts the closed cycle fuel policy, this can be noticed since 1956, when Japan adopted a policy of maximizing the use of uranium, so the country can extract between 25 and 30% of extra energy from recycled fuels. Like uranium mining, the reprocessing of Japanese fuel is also not carried out in Japan, in general, reprocessing is carried out in European lands (WORLD NUCLEAR ASSOCIATION, 2021). As a demonstration of Japan's recycling cooperation among the countries of the European community, the Japan Federation of Electric Power Companies (FEPC) has signed a joint work agreement with the French company Orano, where they are conducting research and developing the reprocessing of mixed oxide fuel (MOX) that has already been used by Japan (WORLD NUCLEAR NEWS, 2023).

Russia is an important country that dominates the complete fuel cycle, its uranium mining is in the order of thousands of tons per year. According to figure 3, the size of the Russian mining capacity can be seen.

Figure 3: Russian uranium mining



Production centre	Region	First production	Orebody	Known resources: tU	Capacity: tU/yr
Priargunsky	Transbaikal/Chita	1968	volcanic	95,700 @ 0.16%	3000
Dalur	Trans-Ural/Kurgan	2004	sandstone	7,400 @ 0.04%	700
Khiagda	Buryatia, Vitimsky	2010	sandstone	29,900 @ 0.05%	1000
Gornoye	Transbaikal/Chita	deferred	granite, vein	3,200 @ 0.20%	300
Olovskaya	Transbaikal/Chita	deferred	volcanic	8,210 @ 0.072%	600
Elkon	Yakutia/Sakha	(2020)	metasomatite	303,600 @ 0.15%	5000
Lunnoye	Yakutia/Sakha	(2016?)	polymetallic	800	100 with gold

Source: https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle

It is known that most of the facilities that are currently part of the Russian fuel cycle were originally created for another purpose, so some locations have closed access, making it impossible to know their exact location (WORLD NUCLEAR ASSOCIATION, 2022).

As is well known, after mining, other processes must be carried out so that the fuel can be used. When it comes to uranium conversion, by the year 2020 Russia held 40% of the total uranium conversion infrastructure, and 46% of the total uranium enrichment capacity, these data are relative to the world. This demonstrates the enormous capacity of this country to dominate the fuel cycle (CLIFFORD, 2022). The Russian generation capacity is such that even the United States of America buys Russian enriched uranium. In 2023, Russia supplied

24% of all enriched uranium that the U.S. used it, thus becoming the second largest supplier of the product to the Americans, behind only other American producers. This supply situation ended in May 2024, when the U.S. government imposed a ban on the import of enriched uranium (FOLHA DE S.P., 2024).

When it comes to uranium mining, the U.S. has about 1% of the world's total, which makes it 15th in the world when it comes to known uranium resources in a given category. This amount makes the U.S. somewhat dependent on uranium imports from other countries. In 2023, the Nuclear Fuel Security Act was approved by the subcommittee on energy, climate, and network security. This document aims to expand U.S. nuclear fuel-related programs, thereby boosting the entire fuel cycle chain and domestic uranium conversion. When it comes to conversion, the United States has only one conversion plant, which in 2017 declared that it would stop its production due to low demand, but in April 2021 there was an announcement that in 2023 there would be a restart of work on this plant, this restart would take place after updating the manufacturing plant. Also in 2023, it was announced that a new mineral processing facility will be built and that it will start operating in 2026, thus increasing uranium production. Unlike Japan, the U.S. chose to follow the open cycle of nuclear fuel (WORLD NUCLEAR ASSOCIATION, 2023).

China has a policy of obtaining its uranium supplies based on: one third domestic uranium, one third coming from foreign mines, which China exploits through its domestic companies, and finally, the last third comes from the open market. As this nation is dependent on other countries, it has an agreement with France that is called 'agreement 123', and since 1985 it has had an agreement with the USA, this agreement was renewed in 2015. When it comes to conversion, the veracity of the information regarding the Chinese capacity is uncertain, the numbers obtained show an increase in the Chinese conversion capability. In addition, it is noted that if China's expansion plans come to fruition, this nation will reach a total conversion capacity of around 31,000 tU/year. China plans to increase the capacity for reprocessing and recycling nuclear fuel, it is expected that in 2025 it will start operating a fuel reprocessing plant, this plant has a capacity of 800 tons of used fuel per year, this plant will make use of the Purex process, so it is noted that China is part of the group of countries that has a closed cycle policy for nuclear fuel (WORLD NUCLEAR ASSOCIATION, 2024).

3.8. Regulatory and policy structures in Brazil

In the federal constitution of 1988 of Brazil, it is described about nuclear activity, where it is mentioned that the federal government has exclusive competence on this subject. In addition, it is also stated that the national nuclear activity will be used only for peaceful purposes. Regarding the regulatory framework, CNEN is responsible for inspecting and regulating the nuclear sector in Brazil, but this responsibility is expected to be transferred to the National Nuclear Energy Authority (ANSN), with this CNEN should only have research, development and organization activities, thus leaving aside regulation. It is worth mentioning that when it comes to embarked nuclear plants, this inspection, regulation, and licensing authority is transferred to the Brazilian Navy Command (ANSN, 2021).

Brazil is having significant evolutions in terms of regulatory structure and, for this, in 2022, the Brazilian Company of Participations in Nuclear and Binational Energy (ENBPar) was created, which aims to give INB a greater degree of budgetary and financial autonomy, and facilitate partnerships with the private sector.

Brazil follows the international guidelines for the correct regulation of the nuclear sector, it is worth mentioning that the International Atomic Energy Agency (IAEA) itself cites that the country has acted to strengthen technical cooperation activities, with a greater appeal to the so-called developing countries. In addition, the country has been supporting the Preparatory Commission of the future Organization for the Comprehensive Prohibition of Nuclear Tests, a subject that, as previously stated, the country has in its constitution the proper prohibition (AGENCIA SENADO, 2023).

In June 2024, the IAEA carried out a long-term operational safety review at one of the Brazilian nuclear power plants, the purpose of which was to review the Safety Aspects of Long-Term Operation (SALTO), which was requested by the company that operates the plant. This visit was conducted by people from different countries, and at the end the team praised the Brazilian operation team. This visit and the positive feedback from the agency are yet another demonstration that Brazil follows all international standards, and that its practices are in accordance with what is requested by the agency (IAEA, 2024).

4. CONCLUSIONS

The manufacture of the nuclear fuel element is constantly evolving. It is driven by innovations – many of them disruptive – some of which are considered curiosities, and which aim to improve the performance, efficiency and comprehensive safety of nuclear reactors. The use of advanced materials, additive printing techniques, and unconventional geometries is redefining the way fuel elements are designed and constructed. These innovations not only promote the sustainability of nuclear power, but also contribute to mitigating risks associated with operating reactors and maximizing energy efficiency. As the nuclear industry advances, fuel element manufacturing continues to play an essential role in the quest for safer, more reliable, and more efficient energy production.

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CONFLICT OF INTEREST

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