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NUCLEAR REACTORS: FUNDAMENTALS, APPLICATIONS, AND ADVANCES

REATORES NUCLEARES: FUNDAMENTOS, APLICAÇÕES E AVANÇOS

REACTORES NUCLEARES: FUNDAMENTOS, APLICACIONES Y AVANCES

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ABSTRACT
This work aims to present a comprehensive review of nuclear reactors, covering everything from the fundamentals of atomic structure and the principles of nuclear fission to the most recent technological advances in the field. Initially, the components and types of reactors are explored, highlighting the PWR, BWR, GCR, AGR, HTGCR, HWR, and FBR models, emphasizing their operational characteristics, applications, and energy implications. The study also addresses third- and fourth-generation reactors, small modular reactors (SMRs), and nuclear fusion projects, highlighting advances in safety, energy efficiency, and sustainability. Nuclear fusion is presented as a promising alternative for the future of the global energy matrix, although it is still in the experimental phase. It is concluded that, despite historical challenges and associated risks, nuclear energy remains a strategic option for energy diversification and climate change mitigation, provided it is accompanied by rigorous safety standards, investments in research, and transparent dialogue with society.

KEYWORDS: Nuclear energy. Nuclear reactors. Power generation. Nuclear fusion. Nuclear safety.

RESUMO
Este trabalho tem como objetivo apresentar uma revisão abrangente sobre os reatores nucleares, abordando desde os fundamentos da estrutura atômica e os princípios da fissão nuclear até os avanços tecnológicos mais recentes na área. Inicialmente, são explorados os componentes e tipos de reatores, com destaque para os modelos PWR, BWR, GCR, AGR, HTGCR, HWR e FBR, evidenciando suas características operacionais, aplicações e implicações energéticas. O estudo também aborda os reatores de terceira e quarta geração, os pequenos reatores modulares (SMRs) e os projetos de fusão nuclear, destacando os avanços em segurança, eficiência energética e sustentabilidade. A fusão nuclear é apresentada como uma alternativa promissora para o futuro da matriz energética global, embora ainda esteja em fase experimental. Conclui-se que, apesar dos desafios históricos e dos riscos associados, a energia nuclear permanece como uma opção estratégica para a diversificação energética e a mitigação das mudanças climáticas, desde que acompanhada por rigorosos padrões de segurança, investimentos em pesquisa e diálogo transparente com a sociedade.

PALAVRAS-CHAVE: Energia nuclear. Reatores nucleares. Geração de energia. Fusão nuclear, segurança nuclear.

RESUMEN
Este trabajo busca presentar una revisión exhaustiva de los reactores nucleares, abarcando desde los fundamentos de la estructura atómica y los principios de la fisión nuclear hasta los avances tecnológicos más recientes en este campo. Inicialmente, se exploran los componentes y tipos de reactores, destacando los modelos PWR, BWR, GCR, AGR, HTGCR, HWR y FBR, haciendo hincapié en sus características operativas, aplicaciones e implicaciones energéticas. El estudio

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también aborda los reactores de tercera y cuarta generación, los reactores modulares pequeños (SMR) y los proyectos de fusión nuclear, destacando los avances en seguridad, eficiencia energética y sostenibilidad. La fusión nuclear se presenta como una alternativa prometedora para el futuro de la matriz energética mundial, aunque aún se encuentra en fase experimental. Se concluye que, a pesar de los desafíos históricos y los riesgos asociados, la energía nuclear sigue siendo una opción estratégica para la diversificación energética y la mitigación del cambio climático, siempre que se acompañe de rigurosos estándares de seguridad, inversión en investigación y un diálogo transparente con la sociedad.

PALABRAS CLAVE: Energía nuclear. Reactores nucleares. Generación de energía. Fusión nuclear. Seguridad nuclear.

1. INTRODUCTION

The growing demand for sustainable and high-efficiency energy sources has driven the development of technologies capable of meeting global energy needs with a lower environmental impact. In this context, nuclear energy stands out as a strategic alternative, offering high energy density and low greenhouse gas emissions. However, its use also raises complex issues related to safety, radioactive waste management, and public acceptance.

This study aims to provide a comprehensive analysis of nuclear reactors, encompassing the fundamentals of atomic structure and the principles of nuclear fission, as well as the various reactor types, their applications, and the most recent technological advancements. The investigation examines the key operational characteristics, advantages, and limitations of the main nuclear reactor designs, namely:

- PWR: Pressurized Water Reactor.
- BWR: Boiling Water Reactor.
- GCR: Gas-Cooled Reactor.
- AGR: Advanced Gas-cooled Reactor.
- HTGCR: High-Temperature Gas-Cooled Reactor.
- HWR: Heavy Water Reactor.
- FBR: Fast Breeder Reactor.

The study also examines modern third- and fourth-generation reactors, small modular reactors (SMRs), and nuclear fusion projects, which represent the future of nuclear energy. These technologies aim to overcome the historical challenges of the field by delivering enhanced safety, efficiency, and sustainability.

Throughout this research, the goal is not only to understand the technical aspects of nuclear energy but also to reflect on its role within the global energy matrix and the prospects for a safer and more responsible use of this powerful energy source.

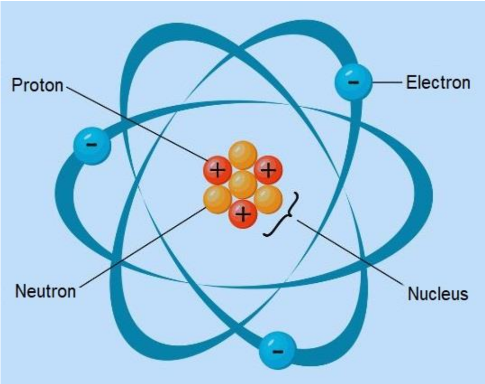
The education and training of professionals who are both aware and prepared to address the challenges and opportunities associated with nuclear energy are essential to ensure its ethical and sustainable development.

2. ATOMIC STRUCTURE

To understand how a nuclear reactor works, it is first necessary to understand how matter itself functions, that is, atoms and their properties. The atom is the fundamental particle that composes matter. Its structure can be divided into two parts: a positively charged nucleus, composed of protons and neutrons, where the proton carries a positive charge and the neutron has no electric charge. The other part is the electron cloud, the peripheral region where electrons are located; these electrons move around the nucleus and carry a negative charge [1].

Five models of atomic structure have been proposed. Like the one shown in Fig. 1, known as the “solar system” model, there were others, such as Dalton’s “billiard ball” model (1897), Thomson’s “plum pudding” model (1897), Bohr’s fixed-shell model (1913), and Schrödinger’s quantum model (1926).

Figure 1. Rutherford’s atomic model, 1911



Source: https://brasilescola.uol.com.br/o-que-e/quimica/o-que-e-atomo.htm

Every atom is identified by its atomic number, which corresponds to the number of protons in its nucleus. The mass of electrons is negligible when considering atomic mass, as it is approximately 1,836 times smaller than the mass of protons and neutrons, which are the particles that determine the atomic mass [1].

3. WHAT IS A NUCLEAR REACTOR?

The nuclear reactor is responsible for the production and control of the release of energy resulting from the division (fission) of certain atoms [2]. Fig. 2 shows the nuclear reactor room at Leningrad.

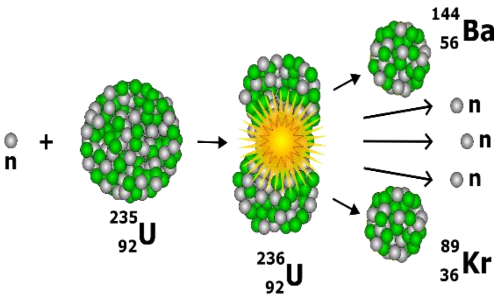
Figure 2. Reactor hall of one of the RBMK units

Source: https://pt.wikipedia.org/wiki/Usina_Nuclear_de_Leningrado

Nuclear fission is the process in which the nucleus of an atom splits into two or more smaller nuclei, with possible emission of particles and release of energy. These particles may include neutrons, alpha particles, electrons, positrons, neutrinos, and gamma rays [3]. Fission occurs when the nucleus is bombarded with neutrons. The fact that two or more neutrons are released in each fission event is essential for the occurrence of this type of chain reaction, in which each produced neutron can induce a new fission [4].

This discovery was made by Otto Hahn, Lise Meitner, and Fritz Strassmann in 1938, after they continued the work of the Italian physicist Enrico Fermi, who initiated such experiments a few years after the discovery of the neutron in 1932 by the English physicist James Chadwick [5]. Fig. 3 illustrates an example of a fission reaction.

Figure 3. Example of nuclear fission



Source: https://www.professordequimica.com.br/imagens/conteudo/fissao-nuclear.png

Natural uranium (Fig. 4) is a radioactive element found in nature. It is a dense metal composed mainly of the isotopes U-238 (~99.3%) and U-235 (~0.7%), along with trace amounts of U-234.

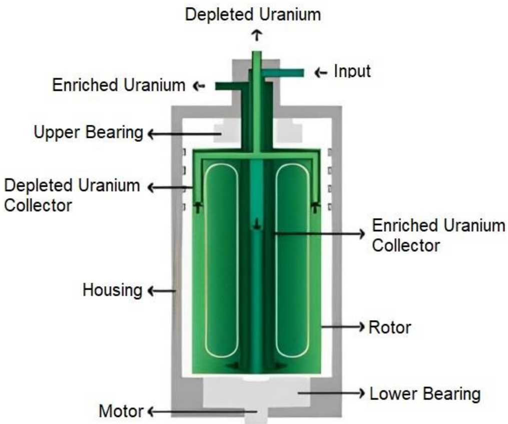
Figure 4. Natural uranium

Source: https://i0.wp.com/energiainteligenteufjf.com.br/wp-content/uploads/2025/06/image-19.png?w=321&ssl=1

Uranium-235 is widely used in the fission process because it is an atom with a heavy nucleus and is therefore more unstable. This element is an isotope of uranium-238, which is not fissile. The separation of these isotopes is carried out in ultracentrifuges (Fig. 5). In this equipment, uranium hexafluoride gas (UF_6) is subjected to extremely high rotational speeds, separating the lighter isotopes (uranium-235) from the heavier ones (uranium-238), increasing the concentration to up to 5% [6].

This process is called “enrichment”. After the mineral extraction stage, the material is crushed and chemically processed until a yellow powder known as “yellowcake” (U_3O_8) is obtained.

Figure 5. Rotating centrifuge



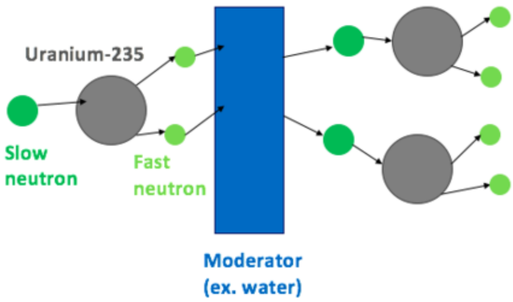
Source: https://i0.wp.com/energiainteligenteufjf.com.br/wp-content/uploads/2025/07/imagem_2025-07-01_233455948.jpg?resize=1024%2C821&ssl=1

In the most common methods, such as gas centrifugation, yellowcake is chemically converted into uranium hexafluoride (UF_6), a gas that can be easily separated due to the mass difference between isotopes. In this equipment, uranium hexafluoride gas (UF_6) is subjected to extremely high rotational speeds, generating a centrifugal force that separates the lighter isotopes (uranium-235) from the heavier ones (uranium-238) [6].

The lighter U-235 remains closer to the center, while the heavier U-238 moves toward the outer edges of the rotor. The gas enriched in U-235 is collected at the top, whereas the depleted gas (rich in U-238) is withdrawn from the bottom. The centrifuge operates supported by bearings and driven by a motor, and it is enclosed within a casing that ensures stability and protection during operation. This is currently the most effective and most widely used method worldwide for uranium enrichment.

An essential component of nuclear reactors is the moderator. The moderator functions to reduce the speed of neutrons, converting them into so-called "thermal neutrons" (Fig. 6). In this way, it becomes easier to produce new fission events. Materials commonly used as moderators include light water (H_2O), heavy water (D_2O), graphite, and beryllium [7].

Figure 6. Neutron moderator



Source: https://energyeducation.ca/encyclopedia/Neutron_moderator

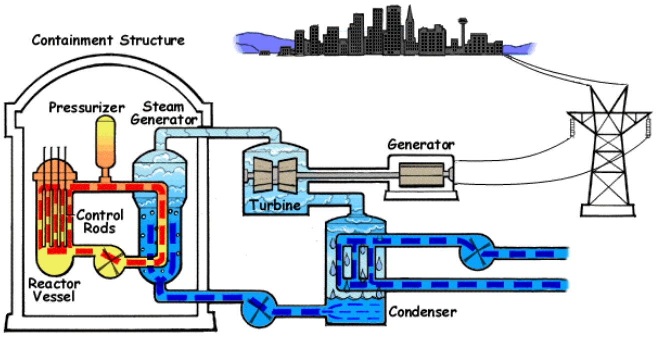
A nuclear reactor also requires a "coolant." The coolant is a fluid responsible for removing the heat generated by fission in the reactor core and transporting it out of the core, usually to a steam generator or directly to a turbine. The requirements for a nuclear coolant are: (a) low neutron absorption, in order to reduce thermal energy without decreasing reactor power; (b) resistance to high radiation doses; (c) high specific heat capacity; and (d) low operating pressure at high temperatures. The most commonly used coolants are light water (H_2O), heavy water (D_2O), carbon dioxide (CO_2), helium, and molten salts. [7]

4. TYPES OF REACTORS

4.1. Pressurized Water Reactor (PWR)

The Pressurized Water Reactor (PWR) is a thermal reactor in which thermal neutrons are the most effective. It is the most widely used type of nuclear reactor in the world [8]. PWR reactors were developed primarily by France, Germany, Japan, and the United States, Fig. 7.

Figure 7. Pressurized Water Reactor (PWR) model



Source: https://pt.energia-nuclear.net/usinas-nucleares/reator-nuclear/tipos/reator-de-agua-fervente

In this type of reactor, light water (H_2O) is used both as a moderator and as a coolant. The water is maintained at high pressure (about 150 atmospheres), preventing it from boiling even at temperatures close to 300 ºC [9]. The PWR operates with two separate hydraulic circuits. In the first, water circulates through the core, absorbs the heat from nuclear fission, and carries it to the steam generator. At this stage, the heat is transferred to the second circuit, where the water is converted into steam and drives the turbine that generates electricity [10]. In Brazil, the reactors at the Angra 1 and Angra 2 nuclear power plants are of the PWR type, Fig. 8.

Figure 8. Area where the turbines and the generator of Angra 2 are located

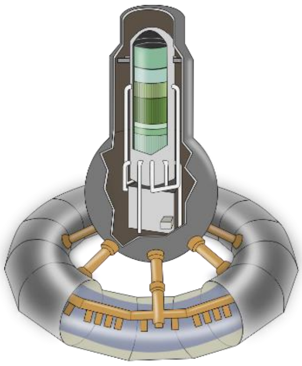
Source: https://www.gazetadopovo.com.br/energia/angra-2-como-funciona-maior-usina-nuclear-pais/

4.2. Boiling Water Reactor (BWR)

The Boiling Water Reactor (BWR) is one of the main technologies used in the generation of electric power through nuclear reactions, Fig. 9. It is widely used commercially, alongside the Pressurized Water Reactor (PWR), with which it shares prominence in nuclear thermoelectric power generation [11].

The BWR uses fuel rods containing enriched uranium dioxide (UO_2) as fuel. Water serves both as a moderator and as a coolant, slowing down neutrons and removing heat from the core, thereby simplifying the operational cycle.

Figura 9. Boiling Water Reactor (BWR) model



Source:
https://commons.wikimedia.org/wiki/File:Nuclear_BWR_Boiling_Water_Reactor_Mark_1.svg

During operation, the water boils inside the reactor vessel, generating steam directly above the core. The generated steam is sent directly to the turbines, without the need for a secondary steam generator. The steam drives the turbines, which in turn power electrical generators. After passing through the turbines, the steam is condensed and redirected back to the reactor [11]. BWR-type reactors were developed primarily in the United States, Sweden, and the Federal Republic of Germany [12].

4.3. Gas-Cooled Reactor (GCR)

The uranium-gas-graphite reactor uses natural uranium in metallic form as fuel, Fig. 10. The fuel is inserted into tubes made of a magnesium alloy known as Magnox. Graphite is used as the neutron moderator. The thermal coolant is a gas, specifically carbon dioxide (CO_2). The United Kingdom and France were the developers of this reactor model [13].

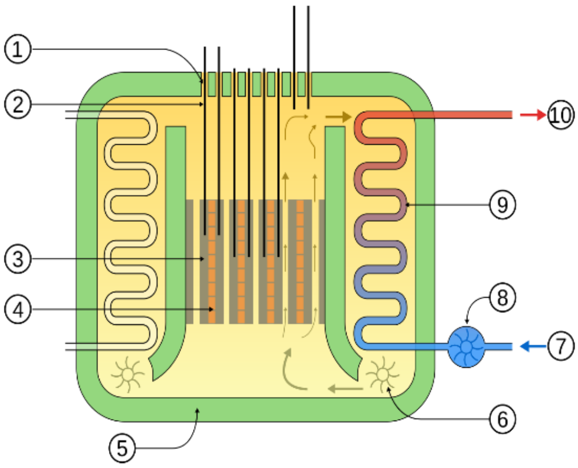
Figure 10. External view of the Saint-Laurent nuclear power plant in France

Source: https://pt.energia-nuclear.net/acidentes-nucleares/acidente-nuclear-saint-laurent-des-eaux-franca

4.4. Advanced Gas-cooled Reactor (AGR)

The Advanced Gas-cooled Reactor (AGR) represents an improved version of graphite-moderated gas-cooled reactors (GCRs), with its development concentrated primarily in the United Kingdom, Fig. 11. This reactor uses slightly enriched uranium dioxide as fuel, with a U-235 content between 2.5% and 3.5%, enabling more efficient fuel utilization compared to reactors that employ natural uranium [13]. Graphite acts as the moderator, slowing down fast neutrons, while carbon dioxide (CO_2), serving as a high-pressure coolant, removes the heat generated by fission and transfers it to steam generators located outside the core [11].

Figure 11. Simplified schematic of the Advanced Gas-cooled Reactor (AGR). 1: Fuel loading tubes; 2: Control rods; 3: Graphite moderator; 4: Fuel assembly; 5: Concrete pressure vessel/radiation shield; 6: Gas circulator; 7: Water; 8: Water circulator; 9: Heat exchanger; 10: Steam



Source: https://commons.wikimedia.org/wiki/File:AGR_reactor_schematic.svg

Compared with contemporary PWR and BWR reactors, the AGR stands out for achieving higher thermal efficiency, close to 41%, due to operation at elevated temperatures. However, its structural and operational complexity is greater, which poses challenges for construction and maintenance. Currently, these reactors are being gradually decommissioned in the United Kingdom [13].

4.5. High-Temperature Gas-Cooled Reactor (HTGCR)

The High-Temperature Gas-Cooled Reactor (HTGCR) is a new evolution of gas-cooled nuclear reactors (Fig. 12). The differences relative to the Advanced Gas-cooled Reactor (AGR) are mainly threefold: (1) helium is replaced by carbon dioxide as the coolant, (2) ceramic fuel is used instead of metallic fuel, and (3) the operating gas temperatures are much higher.

Figure 12. Shidaowan power plant with a fourth-generation HTGCR reactor

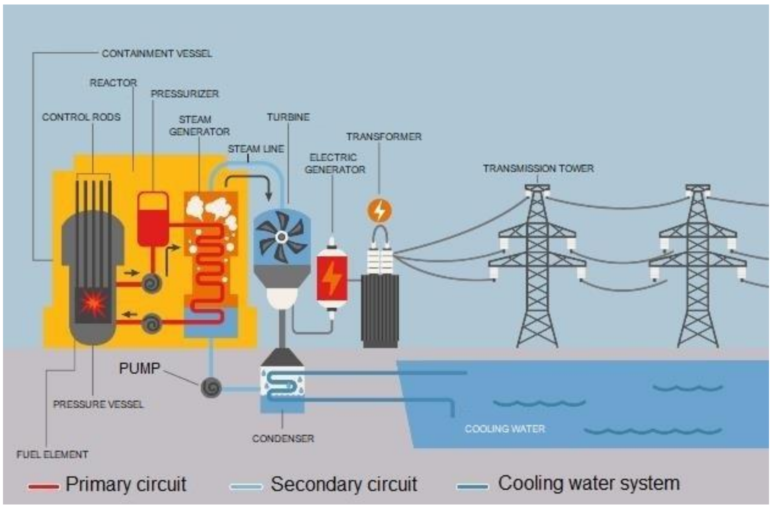
Source: https://noticiabrasil.net.br/20231206/china-anuncia-inicio-de-operacao-do-1-reator-nuclear-de-4-geracao-do-mundo-fotos-31874264.html

4.6. Heavy Water Reactor (HWR)

Nuclear reactors that use heavy water as a moderator, known as Heavy Water Reactors (HWRs), Fig. 13, operate with natural uranium as fuel, eliminating the enrichment process normally required in other technologies, such as PWR reactors, thereby reducing operational costs [14].

The main reason for this capability is that heavy water (D_2O) has a low neutron absorption cross section, making it more effective than ordinary water (H_2O) in moderating neutrons. This allows a sufficient number of neutrons to remain available to sustain the chain reaction even with unenriched uranium [11].

Figure 13. Schematic of an HWR nuclear reactor, highlighting the primary and secondary circuits and the cooling system



Source: https://cbie.com.br/energia-nuclear/

Despite these advantages, the use of heavy water poses technical and economic challenges. Its production is costly, and during reactor operation, D_2O can absorb neutrons and form tritium, a radioactive isotope that requires specific control and purification systems. In addition, because these reactors operate with natural uranium, they can generate significant amounts of plutonium, which raises concerns regarding nuclear proliferation [15].

For all these reasons, HWRs represent a strategic alternative for countries that choose to avoid dependence on uranium enrichment technologies, such as Canada, India, and Argentina. Heavy water nuclear reactors are a type of nuclear reactor developed primarily in Canada [13].

4.7. Fast Breeder Reactor (FBR)

The main characteristic of Fast Breeder Reactors (FBRs) is that they do not use a neutron moderator and, therefore, most nuclear fissions are produced by fast neutrons (Fig. 14). The core of this type of nuclear reactor consists of a fissile zone surrounded by a fertile zone in which natural uranium is converted into plutonium. The uranium-233–thorium fuel cycle can also be used. The coolant is liquid sodium, and steam is produced in heat exchangers [13].

These reactors are considered one of the keys to fourth-generation nuclear energy due to their potential to reduce inventories of long-lived radioactive waste by reusing minor actinides as fuel. Countries such as France, Russia, Japan, and India are investing in the development of FBRs as a strategic alternative for the future of the nuclear sector [16].

Figure 14. Internal view of an FBR-type nuclear power plant, highlighting the main generator (in orange) and the complex system of piping that carries steam from the turbines, which are essential for the conversion of thermal energy into electrical energy

Source: https://u-238.com.ar/reactor-ruso-bn-800-premiado-la-mejor-central-nuclear-2016/

5. OTHER FORMS OF REACTOR CLASSIFICATION

Nuclear reactors can be classified according to different criteria. One such criterion is their intended purpose. In this context, the following purposes can be distinguished: (1) Civil: electricity generation, nuclear medicine, industrial applications, etc.; (2) Military: development of military weapons or use as propulsion systems for war vehicles (submarines, ships, etc.); and (3) Research: used to develop nuclear energy technologies in various fields, both civilian and military [12].

Nuclear reactors can also be classified according to the type of fuel: they may use natural uranium, enriched uranium, or mixed oxides of uranium and plutonium. According to neutron speed, they are divided into thermal (slow neutrons) and fast reactors. Based on the type of moderator, they may use light water, heavy water, or graphite. Regarding the coolant, the most common are water, gas (helium or CO_2), molten salts, air, or liquid metals, some of which may also act as moderators. Finally, reactors are classified by the type of nuclear reaction: fission (currently the only type in operation) or fusion (experimental) [12].

6. WHAT ARE NUCLEAR REACTORS USED FOR?

Nuclear reactors are primarily used for the generation of electricity. In these systems, the heat produced by nuclear fission is used to heat water and generate steam, which drives turbines coupled to electrical generators [16]. They also play an essential role in the production of radioisotopes, which are widely used in nuclear medicine. Key examples include technetium-99m, used in imaging examinations; iodine-131, applied in the treatment of thyroid diseases; and cobalt-60, used for the sterilization of medical instruments [17].

In the defense and transportation sectors, nuclear reactors are used as energy sources for submarines and aircraft carriers, allowing them to operate for long periods without the need for refueling, thanks to their high autonomy [18].

Some reactors have also been employed in desalination projects, providing the heat required to convert seawater into potable water, which is particularly useful in regions with freshwater scarcity [19].

Finally, there are research and development initiatives aimed at the use of nuclear reactors in space missions, with the goal of ensuring a reliable power source for spacecraft and probes in environments where solar energy is not viable [20].

7. MODERN REACTORS, PROTOTYPES, AND FUSION REACTORS

7.1. Generation III and Generation III+ Reactors

Third-generation reactors (Generation III) are an evolution of second-generation reactors (Generation II), incorporating improvements in design, fuel technology, thermal efficiency, safety, and standardization, Fig. 15. They are designed to be safer, more efficient, and more reliable [21-23].

Its main distinguishing feature is the passive safety systems, which do not require active control or electrical power in the event of an accident, relying on natural phenomena such as gravity to maintain safety. They also have a longer service life, approximately 60 years [21,22].

Advanced third-generation reactors (Generation III+) are an evolutionary development of Generation III, offering even more significant improvements in safety. They enhance passive safety systems and often include core catchers to contain and cool molten material in the event of a core meltdown. They are expected to achieve higher fuel burnup, further reducing fuel consumption and waste production [21,22].

Figure 15. Chinese third-generation reactor

Source: https://clickpetroleoegas.com.br/primeiro-reator-nuclear-de-3a-geracao-da-china-tem-capacidade-impressionante-e-pode-abastecer-milhoes-de-residencias/

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Westinghouse's AP1000 reactors, the European Pressurized Reactor (EPR), and Russia's VVER-1200 are examples of advanced third-generation reactors (Generation III+). More specifically, the AP1000 is a Gen III+ design based on the AP600, but with increased output power. The European Pressurized Reactor (EPR) is a Gen III+ design that is an evolutionary descendant of the Framatome N4 and Siemens Power Generation Division KONVOI reactors. The VVER-1200/392M (AES-2006 type) is another example of a Gen III+ reactor design. [22]

7.2. Small Modular Reactors (SMRs)

Small Modular Reactors (SMRs) are advanced nuclear reactors designed for serial construction, emerging as a promising alternative to meet the demand for low-carbon electricity while overcoming challenges such as safety and the high cost of conventional nuclear power plants [24].

SMRs are small-scale nuclear reactors with a generation capacity of up to 300 megawatts electric (MWe)[1] per unit, which is considerably lower than traditional plants [25]. The International Atomic Energy Agency defines "small" as below 300 MWe and "medium" as up to 700 MWe.

The main advantages of SMRs include low initial cost and rapid construction. These reactors require fewer financial resources and have a significantly shorter time to commercial operation due to factory production and transportation to the deployment site, enabling a faster and more cost-effective construction process. The economies of scale from serial production are expected to further reduce unit costs. [24]

SMRs offer excellent modularity and flexibility. The modular design allows the installation of multiple units to increase capacity incrementally [25]. They employ more passive safety systems that rely on natural phenomena (such as convection and gravity) to shut down systems without human intervention or external power. Many SMRs can operate for 3 to 7 years without refueling, and some for up to 30 years [26].

Microreactors (a subset of SMRs, up to 10 MWe) are ideal for replacing diesel generators in rural communities and can provide power to areas with low demand or limited grid capacity [25].

CAREM, developed by Argentina as the first reactor with a fully national design, stands out as a benchmark in the new generation of nuclear power plants (Fig. 16). It is an innovative version of pressurized water reactors (PWR), a technology that accounts for about three-quarters of the reactors operating worldwide. The first unit, under construction by CNEA (Argentina's National Atomic Energy Commission), will have a capacity of 32 MW, enough to supply around 120,000 inhabitants, serving as a prototype for future higher-power versions. Its simplified modular design ensures shorter construction schedules, reduced costs, and standardization in the manufacturing of

[1] MWe é a abreviação de "Megawatts elétricos", e é uma unidade que mede a potência de saída elétrica de uma usina de energia ou a capacidade de geração de eletricidade de um sistema, sendo a letra "e" uma especificação de que o valor se refere à eletricidade gerada e não à energia térmica ou outra forma de energia produzida. Um MWe representa um milhão de Watts de potência elétrica.

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key components, which can be produced in factories and transported to the installation site. Furthermore, the possibility of adding new modules in the future allows for gradual expansion of electrical output and greater flexibility in investment [27].

Figure 16. Reator CAREM em construção, na Argentina

Source: https://www.argentina.gob.ar/cnea

The NuScale Power Module is an integral pressurized water reactor (PWR) with 77 MWe per unit. It was the first SMR to receive design approval from the U.S. Nuclear Regulatory Commission (NRC) in 2020. The Carbon-Free Power Project, at the Idaho National Laboratory, plans to deploy the first unit by 2029 [28].

Canada has shown interest in the development of SMRs, with the Canadian Nuclear Safety Commission (CNSC) conducting design reviews, while Canadian Nuclear Laboratories (CNL) plans to install a new reactor at Chalk River by 2026 [26].

Figure 17. NuScale Power Module

Source: https://www.businesswire.com/news/home/20200829005009/pt

Russia stands out as a pioneer in this field with the KLT-40S, the first floating SMR, and the Akademik Lomonosov plant (Fig. 18), which has been operating two 35 MWe reactors since 2020, considered the world's first commercial floating nuclear power plant. In addition, the state-owned company Rosatom plans the land-based RITM-200N reactor in Yakutia, scheduled for completion in 2028 [24,26].

Figure 18. Akademik Lomonosov Floating Nuclear Power Plant

Source: https://www.naval.com.br/blog/2018/04/30/russia-lanca-primeira-usina-nuclear-flutuante/

7.3. Generation IV Reactors

The Generation IV International Forum (GIF) is an international initiative aimed at developing the next generation of nuclear technology, focusing on overcoming disadvantages and enhancing the functionalities of existing plants. GIF was conceived and launched by the U.S. Department of Energy (DOE) in 2000, with its formal charter established in mid-2001. The forum is an international collective that brings together governments from 13 countries that consider nuclear energy crucial and vital for the future [29].

The founding members of GIF are Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, the United Kingdom, and the United States. Subsequently, Switzerland, China, Russia, Australia, and the European Union (through the Euratom research and training program) joined the group. The main objective of GIF is the sharing of research and development, rather than the direct construction of reactors. After approximately two years of deliberation and the review of about one hundred concepts, the forum announced the selection of six reactor technologies at the end of 2002, which represent the future shape of nuclear energy [29].

The Generation IV systems were selected for promoting advances in sustainability, economics, safety, reliability, and resistance to nuclear weapons proliferation [29]. Generation IV reactor concepts must incorporate all the features of Generation III+ reactors, as well as advanced actinide management [30].

Generation IV reactors are designed to be significantly safer than current nuclear power plants [18]. A central goal is for the design to be "inherently safe," meaning that severe accidents are not possible [31]. In extreme situations, such as the complete loss of cooling power, these reactors are conceived to prevent core meltdown, which could cause explosions [32]. The design of this type of reactor aims to minimize the risk of releasing radioactive material into the external environment [31].

Generation IV aims to be much more efficient in fuel utilization than current facilities [31]. The greater efficiency results from operating these reactors at much higher temperatures, ranging from 510ºC to 1000ºC, compared to current reactors that operate below 330ºC [29]. Such elevated temperatures allow for the conversion of a larger amount of heat into electrical energy [32]. Four of the six technologies selected by GIF are suitable for thermochemical hydrogen production due to their high operating temperature [29].

The reactors are designed for the destruction of long-lived radioelements created during operation [31]. Generation IV systems use a closed fuel cycle to maximize resource utilization while minimizing high-level waste [29]. The higher burnup efficiency, enabled by elevated temperatures, allows for better use of nuclear material and, consequently, the production of a smaller amount of waste [32]. These systems aim for complete recycling of actinides [30].

Preventing the diversion of materials for weapons proliferation is one of the fundamental criteria for selecting these technologies [29]. The fuel cycle is specifically designed so that uranium and plutonium are never separated or "diverted," remaining mixed with other elements [31]. By avoiding this separation, the system makes the creation of nuclear weapons more difficult, thereby increasing security [18]. Furthermore, fast-neutron reactor designs are not conventional fast breeders, as plutonium production occurs in the core, maintaining a high proportion of plutonium isotopes other than Pu-239 [29].

The six technologies selected by the Generation IV International Forum represent the future of nuclear energy, focusing on advancements in safety, sustainability, and efficiency [29]. In general, Gen IV systems include the complete recycling of actinides and the capability to operate at high temperatures, which enables the economical production of hydrogen and the utilization of heat for other processes [30]. These six technologies are described in more detail below.

1) Sodium-Cooled Fast Reactor (SFR): The SFR uses liquid sodium as a coolant. This type of reactor operates with fast neutrons and allows for a high power density at low pressure. The coolant temperature ranges between 500ºC and 550ºC. The SFR employs depleted uranium and MOX fuel in a closed fuel cycle. MOX fuel (an acronym for Mixed Oxide) is a nuclear fuel made from a mixture of plutonium oxide and uranium oxide. It is used as an alternative to enriched uranium fuel and serves to recycle plutonium and uranium recovered from spent nuclear fuel. The use of MOX helps reduce the amount of high-level waste and the consumption of natural uranium. [29,30]

2) Lead-Cooled Fast Reactor (LFR): The LFR is a fast-neutron reactor cooled by liquid lead or lead-bismuth. Cooling occurs at low pressure (typically atmospheric) through natural convection. The LFR is flexible and can use fuel matrices of depleted uranium or thorium, and it is capable of burning actinides from light-water reactor fuel. Although 550ºC is easily achievable, the target is 800ºC to enable thermochemical hydrogen production. The LFR is designed in various sizes, including a “battery” model of 20–180 MWe, which can operate for 15 to 20 years without refueling [29,30].

3) High-Temperature Gas-Cooled Reactor (HTGR): The HTGR (or VHTR, Very High Temperature Reactor) uses helium as a coolant. Operating at very high temperatures, typically between 900ºC and 1000ºC, it is suitable for thermochemical hydrogen production. The Shidaowan reactor in China, the first Generation IV reactor to begin commercial operations, is an example of this innovation, using helium instead of water. The fuel consists of uranium dioxide in TRISO[2] particles [29,31,32].

4) Molten Salt Reactor (MSR): There are two main variants of the MSR [30]. One is the Molten Salt Fast Reactor (MSFR), in which the fissile material (uranium fluoride) is dissolved in circulating fluoride salt. It operates with fast neutrons and features a closed fuel cycle. The other is the Advanced High-Temperature Reactor (AHTR/FHR), which uses molten salts as a coolant but employs solid fuel composed of UO_2 particles in prismatic blocks, similar to the VHTR. Both variants operate at low pressure and high temperatures, ranging from 700ºC to 1000ºC, making them suitable for hydrogen production [29].

5) **Gas-Cooled Fast Reactor (GFR):** The GFR is a fast-neutron reactor that uses helium as a coolant. It is a high-temperature unit (typically 850ºC), suitable for both power generation and thermochemical hydrogen production. The GFR is the only Generation IV design with no prior operational experience, and its greatest challenge lies in fuel development due to the high power density required [29].

6) **Supercritical Water-Cooled Reactor (SCWR):** The SCWR is cooled by water and operates at very high pressure, above the thermodynamic critical point of water (374ºC, 22 MPa). Supercritical water (approximately 25 MPa and 510ºC to 625ºC) is used to drive the turbine directly, eliminating the secondary steam system. This feature results in a thermal efficiency roughly one-third higher than that of current light-water reactors. The SCWR can operate with either thermal or fast neutrons [29,30].

Generation IV reactors were designed to be inherently safe, meaning that even in the event of a complete loss of cooling power, they prevent core meltdown (which can lead to explosions) without the need for human intervention or active safety systems [31].

China marked a transition from experimental to practical [32] by commissioning the first Generation IV nuclear reactor, redefining innovation and safety in the nuclear industry. The Shidaowan reactor, cooled by helium (HTGCR), increases its efficiency in electricity generation because high temperatures allow more heat to be converted into electrical energy. Its design can also be applied to ships that can operate for up to seven years without refueling [18].

[2] TRISO Particles (TRi-Structural Isotropic) are the most robust form of nuclear fuel, consisting of a uranium kernel (UO_2 or UCO) coated with multiple layers of carbon and ceramic. These layers act as a self-contained system to retain fission products, withstand extreme temperatures (without melting), and enable safer and more efficient reactors, particularly High-Temperature Gas-Cooled Reactors (HTGRs).

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The new generation aims for sustainability, being far more efficient in fuel utilization. Uranium-238, an abundant isotope, makes current uranium reserves sufficient to operate reactors for several thousand years [31]. In terms of non-proliferation, the fuel cycle is designed so that uranium and plutonium are never separated (diverted) [31]. While China is advancing rapidly, the rest of the world seems to be stumbling. Geopolitically, China's success could lead to a significant increase in its influence in strategic regions such as Africa, Latin America, and Southeast Asia, creating technological dependencies [32].

8. EXPERIMENTAL REACTORS AND CHALLENGES OF CONTROLLED FUSION

Humanity has long attempted to reproduce this process on Earth in a controlled manner, aiming to obtain an energy source that is clean, powerful, and virtually inexhaustible. The process consists of the coalescence of the nuclei of two light atoms, such as hydrogen isotopes, to form a larger and more stable nucleus. Energy is released through the conversion of mass into energy. This type of reaction is considered the most rational option for the future of global energy due to its remarkable efficiency in converting mass into energy. In terms of power, a fusion reaction is about one hundred times more powerful than a fission reaction [35].

The fusion reaction between deuterium and tritium, known as D-T, is the most likely candidate for the first generation of terrestrial reactors. In this process, 17.6 MeV of energy is released, with 3.5 MeV carried by the alpha particle and 14.1 MeV by the neutron. The choice of this reaction is due to its relatively low ignition temperature. Deuterium is abundant in water, whereas tritium is radioactive and scarce, requiring artificial production inside the reactor through the irradiation of a fertile lithium blanket with neutrons generated by the D-T reaction itself. For controlled thermonuclear fusion to occur, three conditions must be simultaneously satisfied: temperature, density, and confinement time [35].

The reactants must reach extremely high velocities to overcome the strong electrostatic repulsion between their nuclei, known as the Coulomb barrier. Heating to extremely high temperatures ionizes the gas, transforming it into plasma, the fourth state of matter. Plasma is an ionized medium that exhibits collective behavior [35]. The ion temperature required to overcome the electrostatic barrier is about 100 million degrees Celsius. The minimum temperature for fusion energy production to exceed radiation losses is 3 keV. No material can come into direct physical contact with plasma at these temperatures, as the walls would melt and the plasma would cool down [35]. In this context, two main approaches stand out:

1) Magnetic Confinement (Slow Fusion): Uses intense magnetic fields to confine the plasma. Charged particles are contained by the Lorentz force, moving along helical trajectories around the magnetic field lines. This method is characterized by low plasma density and a long confinement time [35].

2) Inertial Confinement (Fast Fusion): Achieved through the micro-implosion of a small deuterium pellet (microsphere) driven by powerful laser sources or ion beams. Confinement is maintained by the inertia of the fuel during the very short duration of the micro-explosion. This approach requires extremely high plasma density and a very short confinement time [35].

For the plasma to reach ignition (where the energy gain becomes self-sustaining), the triple product (which includes density, temperature, and confinement time) must exceed a minimum value established by the Lawson criterion [36]. The Lawson criterion defines the conditions required for a fusion reaction to produce more energy than is consumed to sustain the plasma. Ignition is achieved when the energy released by the fusion reactions themselves is sufficient to maintain the plasma temperature, making the process self-sustaining. For the deuterium-tritium (D-T) reaction, the most promising for current fusion reactors, the minimum value of the triple product $(n \times \tau \times T)$ is approximately $5 \times 10^{21}\,\mathrm{m^{-3}.s.keV}$ or higher [37]. The triple product $(n\tau T)$ is the combination of three critical parameters for nuclear fusion [38]:

- **Density (n):** Refers to the number of particles per unit volume in the plasma. A higher density increases the probability of collisions and fusion reactions.
- **Energy Confinement Time (τ):** Is the duration over which the plasma remains hot and confined. The longer this time, the more fusion reactions can occur.
- **Temperature (T):** Refers to the kinetic energy of the particles, which must be high enough to overcome electrostatic repulsion and allow the nuclei to fuse.

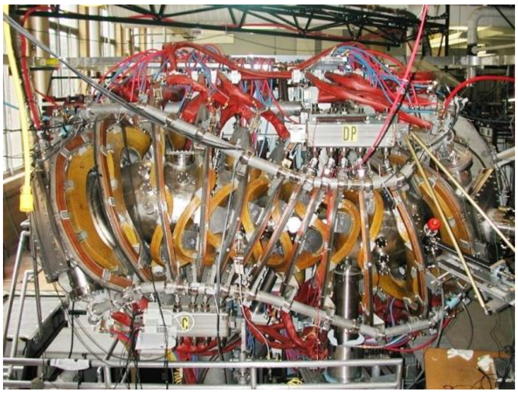
The one-dimensional (1D) analysis, which includes radial density and temperature profiles, suggests that more peaked profiles require a lower Lawson product for ignition than flatter profiles [36].

Tokamaks and stellarators, shown in Figs. 19 and 20, are the two main toroidal devices used for magnetic confinement. In both cases, confinement requires the generation of a helical magnetic field, which is the combination of a toroidal field and a poloidal field. A toroidal field is a magnetic field whose field lines form a closed ring with no radial component, while a poloidal field is a magnetic field that circulates around the cross section of the plasma, perpendicular to the main direction of the torus.

Figure 19. Tokamak at the Max Planck Institute for Plasma Physics

Source: https://euro-fusion.org/eurofusion-news/boronize-your-tokamak/

Figure 20. Stellarator at the University of Wisconsin-Madison



Source: https://en.wikipedia.org/wiki/Helically_Symmetric_Experiment

The tokamak generates the poloidal field through an electric current induced in the plasma itself. The tokamak operates in a pulsed regime because it relies on a transformer to induce the plasma current for a limited time [35]. The term “tokamak” is a Russian acronym for “toroidal chamber with magnetic coils”.

The current induced in the plasma also contributes to ohmic heating, although this mechanism becomes ineffective at temperatures above 1 keV. JET (Joint European Torus) is the largest tokamak currently in operation, and ITER is the first experimental reactor designed to demonstrate the feasibility of fusion [34].

The stellarator (proposed in 1952) generates the entire confining magnetic field solely through external coils [33]. It employs non-planar, laterally twisted coils to produce the poloidal component of the field, a concept known as multi-helicity stellarators. Its main advantage is the ability to operate in a steady-state (continuous) regime, as it does not rely on an inductive plasma current [35]. However, it has significantly greater design and construction complexity than the tokamak, which constitutes a disadvantage. [35]

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Controlled nuclear fusion is a long-term scientific and technological goal and is considered by many to be a potentially unlimited, low-carbon energy source [39]. The path toward realizing this energy is outlined by international collaborative projects such as ITER (International Thermonuclear Experimental Reactor) and EAST (Experimental Advanced Superconducting Tokamak), which are described below. [40]

The EAST (Experimental Advanced Superconducting Tokamak) is one of China's National Mega-Projects for Scientific Research, approved in 1998 [41]. It is conducted by the Institute of Plasma Physics of the Chinese Academy of Sciences, located in the city of Hefei. Its primary mission is to investigate the physics and technologies of advanced steady-state tokamak operation [42].

EAST was the first fully superconducting tokamak in operation to feature a non-circular (elongated) plasma cross section [42]. The device is 11 meters tall and 8 meters in diameter, with an approximate weight of 400 tons. Both the toroidal and poloidal magnetic fields are provided by superconducting magnet systems. This design ensures the capability to confine, shape, and control the plasma over long pulses or even in steady-state operation [41]. The EAST project established the technological foundation for future fully superconducting tokamak reactors. Advances achieved by EAST have paved the way for ITER [25]. In December 2021, EAST achieved the longest steady-state high-temperature plasma operation in history, sustaining the pulse for 1056 seconds (17.6 minutes) [42].

Chinese scientists succeeded in maintaining a high-temperature plasma for 411 seconds, with the central electron temperature exceeding 20 million degrees Celsius [42]. A recent study published in 2023 demonstrated that EAST achieved a tokamak operating mode that improves energy confinement, or long-term plasma retention, while simultaneously preventing the accumulation of impurities [25].

ITER (International Thermonuclear Experimental Reactor) is an international collaboration involving China, the European Union (host), India, Japan, South Korea, Russia, and the United States [43]. The project aims to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes [39]. ITER is a large conventional tokamak currently under construction in Cadarache, France. The device was designed with a major radius of 6.2 meters and a plasma volume of 830 m^3. Its structure is massive, weighing approximately 23,000 tons, and the core of the machine is housed within a cryostat measuring 29 meters in diameter and 29 meters in height [40]. The magnet system includes 18 toroidal field magnets, 6 poloidal field coils, and a central solenoid 13 meters tall and weighing about 1,000 tons [25,40].

ITER seeks to operate in a burning plasma regime in which energy is generated predominantly by the fusion reactions themselves [39]. The goal is to produce 500 MW of fusion power [40], with the objective of demonstrating scientific energy gain [25]. This means that the plasma must produce ten times more fusion energy than the auxiliary power required to heat it [44].

The baseline deuterium-tritium (D-T) scenario requires a plasma current of 15 MA and a toroidal magnetic field of 5.3 tesla [40].

ITER aims to sustain a burning plasma for periods of 300 to 500 seconds, with long-pulse (non-inductive) scenarios targeting operation for up to 3000 seconds [25]. The project will also test the integrated technologies, materials, and physical regimes required for the commercial production of fusion-based electricity [40]. ITER is currently under construction, and its schedule has faced multiple challenges. The organization anticipates that full operation with a burning plasma will occur in 2039, a later date than previously projected. The delay and cost increases are partly linked to technical complexity and to the decision to change the first-wall material from beryllium to tungsten [43].

The production of commercially viable fusion energy requires overcoming formidable challenges related to confinement, radiation, and materials [25]. The plasma must be confined at temperatures above 100 million degrees Celsius [25,39], and plasma confinement is never perfect, since turbulence can transport heat and particles toward the edge of the reactor, resulting in energy losses [25].

The Plasma Control System (PCS) must manage specific instabilities. It must also integrate disruption prevention and mitigation schemes, since disruptions are sudden interruptions of the plasma discharge and the plasma carries a large amount of magnetic and thermal energy [40]. Control of burning plasmas in ITER is more complex because the plasma is dominated by heating from alpha particles produced by fusion, making auxiliary heating power less effective as a control actuator compared to present-day tokamaks [40].

The presence of impurities and the management of excessive heat are also significant challenges [25]. Impurities that penetrate the hot plasma core lead to a loss of fusion power due to radiative cooling and fuel dilution. Helium, the product of the D-T reaction, must also be removed [39]. Heat and impurities are diverted and removed by the divertor, a component that is subjected to extremely high heat loads. ITER requires the divertor to withstand heat fluxes on the order of 20 MW/m^2 [44]. Simulations indicate that ultra-high-temperature plasma (exceeding 1 billion degrees) may cause greater damage to the reactor wall than previously anticipated, requiring improvements in plasma isolation techniques, possibly through the use of more powerful pulsed magnetic fields [39].

Finding suitable materials capable of withstanding the hostile environment of a fusion reactor is a fundamental challenge [25]. The D-T reaction releases high-energy neutrons (14.03 MeV) that bombard the reactor's first wall. This bombardment causes radiation damage by displacing atoms, leading to swelling and degradation of the material's mechanical properties [25,39]. Plasma-facing components (PFCs) must have a high melting point, resilience to neutron bombardment, and a low tendency to absorb tritium. Tritium absorption is the reason why carbon-based materials are avoided

[25]. ITER's plans include the use of beryllium for the first wall (although there are plans to switch to tungsten) and tungsten for the divertor. Tungsten is the material anticipated for the first wall of the future DEMO reactor. At present, there are no facilities capable of realistically and comprehensively simulating fusion neutron flux conditions to test these materials [25].

9. CONCLUSION

This study enabled a comprehensive understanding of the evolution and complexity of nuclear technology, from the fundamental principles of atomic structure to the most advanced energy generation systems. Initially, the operation of nuclear reactors was addressed, highlighting their essential components, such as moderators, coolants, and control systems, as well as the different existing typologies, each with specific characteristics regarding safety, efficiency, and application.

The technological advances introduced in third- and fourth-generation reactors, as well as in small modular reactors and nuclear fusion projects, indicate a promising path for the production of clean and sustainable energy. These innovations aim for greater efficiency, reduced radioactive waste, and inherently safe systems capable of minimizing risks even under extreme conditions. Nuclear fusion, although still in the experimental stage, represents a long-term prospect for meeting global energy demand with minimal environmental impact.

It is concluded that nuclear energy, despite historical challenges and legitimate concerns, remains a strategic alternative for diversifying the energy matrix and mitigating carbon emissions. The future of nuclear technology will depend on the ability to balance benefits and risks, investing in research, safety, and transparent communication with society. Thus, understanding the physical principles, the lessons learned from accidents, and technological trends is essential for training professionals who are aware and prepared to work in this constantly evolving field.

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