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# Nuclear Power Plants: Recent Advances Towards to Safety

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**Abstract**: The Fukushima Daiichi accident in 2011 significantly impacted the licensing process for nuclear power plants (NPPs) due to the necessity to mitigate the hydrogen generation from the reaction between water/steam and zirconium-based alloy cladding material. Small modular reactors (SMRs) have emerged as a safer alternative, incorporating passive safety systems and design simplifications to mitigate risks. SMRs also offer advantages such as modular construction, reduced costs, and the ability to generate electricity and heat for various applications. However, challenges remain, including public perception, high costs, and the risk of proliferation. To address these challenges, ongoing research and development efforts focus on combustible gas management, accident tolerant fuels (ATFs), and computational simulations to optimize SMR designs and ensure their safety and sustainability.

**Keywords:** Small Modular Reactors (SMRs), Combustible Gas Management, Accident Tolerant Fuels (ATFs), Safety Systems.

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# Usinas Nucleares: Avanços Recentes em Segurança

**Resumo**: O acidente de Fukushima Daiichi em 2011 impactou significativamente o processo de licenciamento de usinas nucleares (NPPs) devido à necessidade de mitigar a geração de hidrogênio a partir da reação entre água/vapor e o material de revestimento de liga à base de zircônio. Reatores Modulares de Pequeno Porte (SMRs) surgiram como uma alternativa mais segura, incorporando sistemas de segurança passivos e simplificações de projeto para mitigar os riscos. O SMR também oferece vantagens como construção modular, custos reduzidos e capacidade de gerar eletricidade e calor para várias aplicações. No entanto, permanecem desafios, incluindo a percepção pública, os altos custos e o risco de proliferação. Para enfrentar esses desafios, os esforços contínuos de pesquisa e desenvolvimento se concentram no gerenciamento de gases combustíveis, em combustíveis tolerantes a acidentes (ATFs) e simulações computacionais para otimizar os projetos de SMR e garantir sua segurança e sustentabilidade.

**Palavras-chave:** Reatores Modulares de Pequeno Porte (SMRs), gerenciamento de gases combustíveis, combustíveis tolerantes a acidentes (ATFs), sistemas de segurança.

## 1. INTRODUCTION

The licensing process for Nuclear Power Plants (NPPs) applied for the generation of electricity worldwide was deeply affected by the Fukushima Daiichi accident in 2011 [1], where the loss of cooling in the reactor core caused an exothermic reaction between water/steam and fuel rod cladding material (zirconium-based alloy), resulting in the generation of a significant amount of hydrogen ($H_2$). Because of this, public perception, high costs, and risks associated with the implementation of a NPP can be an obstacle to the expansion of the use of nuclear energy around the world.

In this sense, small modular reactors (SMRs) arise as a promising technology for nuclear power generation, with the potential to offer a clean, safe, and economical energy source. SMRs have technological advances compared to conventional NPPs such as: modular construction allowing factory manufacturing and efficient transportation, reducing costs and construction deadlines; incorporation of passive safety systems such as natural convection and emergency cooling systems to reduce the risk of accidents; application for electricity generation and heat to other processes, such as water desalination and $H_2$ production, increasing efficiency and versatility [2].

Some examples of safety systems in different SMR designs are presented in Table 1. However, one of the major challenges in SMR design is the combustible gas management, which is crucial for maintaining reactor safety under severe accident conditions, especially considering the small free volume inside the containment. During an accident, the reactor cooling system can be compromised, leading to an increase in heat production and internal pressure. SMRs present smaller internal volumes and may cause a more sudden climb of pressure; moreover they have a smaller surface area available to dissipate heat. If internal pressure increases a lot, there may be difficulties in maintaining the structural integrity of the reactor vessel. This can lead to a vessel rupture and consequent release of radioactive materials. Therefore, it is essential that SMRs are designed with adequate combustible gas management system to avoid this type of accident [1, 3, 4].

**Table 1:** Safety system of some SMR projects [5, 6, 7, 8].

| SMR Project | Developer | Passively Cooled Containment | Residual Heat Removal System | Passive Autocatalytic Recombiners (PARs) | Accident Tolerant Fuels (ATFs) |
|---|---|---|---|---|---|
| NuScale | NuScale Power (USA) | ✓ | ✓ | ✓ | ✓ |
| Rolls-Royce SMR | Rolls-Royce (UK) | ✓ | ✓ | ✓ | ✓ |
| Holtec SMR-160 | Holtec International (USA) | ✓ | ✓ | ✓ | ✓ |
| Westinghouse AP300 | Westinghouse Electric Company (USA) | ✓ | ✓ | ✓ | ✓ |
| B&W mPower | Babcock & Wilcox (B&W) (USA) | ✓ | ✓ | ✓ | -- |
| SMART | Korea Atomic Energy Research Institute (KAERI) (South Korea) | ✓ | ✓ | ✓ | -- |
| CAREM | Argentine National Atomic Energy Commission (CNEA) (Argentina) | ✓ | ✓ | ✓ | -- |

SMRs are designed to generate up to 300 MW of electricity. IAEA classifies SMRs that it has on record into six different types: land-based water-cooled SMRs; marine-based water-cooled SMRs; High-temperature Gas cooled SMRs; Fast Neutron Spectrum SMRs; Molten Salt SMRs, and Micro-sized SMRs [2].

A fundamental feature of SMRs is their improved safety, achieved mainly through passive safety systems and design simplifications [6]. Passive safety systems depend on natural phenomena such as natural convection and radiative heat transfer to ensure reactor safety in case of accidents [1].

SMRs are designed with enhanced safety systems and better reliability through simpler designs and a reduced number of components, which minimizes potential accident initiators. Key safety features include taller vessels to increase the volume of coolant and improve heat dissipation; reducing the power density of the core decreases the rate of heat generation and the risk of overheating; larger surface-to-volume ratio, improving heat transfer and helping the maintenance of a safe core temperature. In addition to these design characteristics, SMRs incorporate passive safety features that rely on natural phenomena like free convection, condensation, and evaporation to remove decay heat and prevent core damage in case of an accident or shutdown. These passive safety systems can provide cooling for up to 72 hours, and some designs even incorporate infinite heat sinks like air or water. Can be partially or fully immersed in underground water walls to increase resilience against pressure waves, such as those experienced during the Fukushima accident. These safety features contribute to reduce emergency planning zones and improve the overall safety of SMRs compared to traditional NPPs [2].

Modularity and systems integration are also important characteristics of SMRs. Modularity allows components to be manufactured, tested, and assembled off site, leading to faster and more cost-effective construction compared to conventional NPPs [6]. Systems integration, such as Integral PWR (IPWR) projects, involves placing the main components of the primary cooling system within the reactor pressure vessel, eliminating the need for large pipes and external components [9]. This not only reduces the cost and size of the plant, but also reduces the probability of accidents, such as Large Break Loss of Coolant Accident (LBLOCA) [10].

SMRs are suitable for a wide range of applications, including electricity generation, seawater desalination, $H_2$ production, and heat supply for industrial processes [9].

SMRs offer the deployment feasibility feature as standalone units or in assembly module setups, providing options for different power generation capacities and demands. [2, 6]. This adaptability makes them suitable to meet the energy needs of various users, from small communities to large industrial complexes.

SMRs are well-suited for polygeneration compared to large reactors (LRs). This is because SMRs can switch some of their modules for cogeneration purposes, allowing them to operate at full nominal power and maximum conversion efficiency. Polygeneration can address the limitation of nuclear energy as a base load supplier of electricity by providing additional revenue streams and maximizing the use of generated heat [2]. Examples of polygeneration applications in conjunction with SMRs include desalination, $H_2$ production, district heating systems to residential and industrial areas, hybrid systems with other renewable energy sources, such as solar and wind power, to create hybrid energy systems that offer flexibility and resilience in responding to fluctuating electricity demands.

Therefore, SMR designs offer a low-carbon energy source, contributing to the reduction of greenhouse gas emissions [10], and present advantages over conventional NPPs. Passive safety systems and modularity contribute to greater inherent safety and faster construction can reduce initial investment costs [6, 10]; moreover SMRs can be deployed in places where the construction of large reactors would not be feasible and power generation capacity can be gradually increased by adding more modules [6].

However, there are also challenges associated with SMRs implementation, as design development, licensing, public acceptance and spent nuclear fuel management [6,11,2]. Table 2 provides examples of such SMR projects.

On the other hand, there is a need to expand on studies related to the social issues surrounding SMR sand how they affect their feasibility [2].

Despite these challenges, SMRs continue to attract global interest as a promising option for clean and flexible power generation [10]. Ongoing research and development efforts aim to overcome existing challenges and make SMRs a fundamental component of the transition to a more sustainable energy future.

**Table 2:** Examples of SMR projects that propose to use spent or recycled fuel [5, 8, 12].

| SMR Project | Developer | Fuel | Status |
|---|---|---|---|
| NuScale VOYGR | NuScale Power | Recycled fuel; TRISO: Carbon and ceramic layers fuel particles designed to support high temperatures and retain fission products. | In development, commissioning expected for 2029 |
| BWRX-300 | GE Hitachi Nuclear Energy | Recycled fuel; MOX: Mixture of uranium and plutonium oxides from the reprocessing of used nuclear fuel. | In development, commissioning expected for 2028 |
| SEALER | University of Bristol (UK) | Spent fuel (LWR) | In development, conceptual design phase |

## 2. NUCLEAR POWER PLANT SAFETY SYSTEM

The 2011 Fukushima Daiichi accident [13] event had a deep impact on the international regulatory framework for NPP licensing. The main reason was the LOCA led to an exothermic reaction between water/steam and the fuel rod cladding material (zirconium-based alloy), resulting in a meaningful amount of $H_2$ gas generated. Ever since, the combustible gas management within containment systems and the development of materials with enhanced performance under accident scenarios have emerged as critical safety concerns in the licensing process for the deployment of new facilities.

The removal of excess heat generated in an accident is also proposed in several projects. Reactors designed for nuclear propulsion are notable for the enhanced safety features that they possess against tsunamis or earthquakes and their passive cooling systems that are superior to land-based systems. Configurations characterized by enhanced safety systems and better reliability are made through simpler designs and reduced number of components that consequently reduce the sources of accident initiators. Among these inherent design characteristics are the use of taller vessels, a larger coolant inventory, lower core power density, and a larger surface to volume ratio [2].

In this sense, aiming to improve the operational safety of nuclear reactors, many SMR projects have been proposed. A fundamental aspect of SMRs is increased safety lies in mitigating risks associated with potential fuel failures and combustible gas accumulation during accident scenarios. Several SMR designs are incorporating innovative approaches, such as combustible gas management systems and Accident Tolerant Fuels (ATFs), to address these challenges.

For example, the NuScale SMR design utilizes a combination of Passive Autocatalytic Recombiners (PARs) and a nitrogen inerting system to manage $H_2$ accumulation within the containment. These passive devices (PARs) catalytically recombine $H_2$ and oxygen ($O_2$), preventing the formation of explosive mixtures. This approach ensures effective control of combustible gas, minimizing the risk of explosions or fires even during postulated accidents. Additionally, NuScale is actively exploring the implementation of ATFs with higher temperature and oxidation resistance, further enhancing safety margins [5, 8].

Similarly, the Westinghouse AP300 SMR incorporates PARs as a core component of its safety strategy. Furthermore, AP300 project leverages advanced fuel coating materials with improved oxidation resistance and reduced $H_2$ generation potential, contributing to greater accident tolerance [5, 8].

Another notable example is the Rolls-Royce SMR, which employs a comprehensive approach to combustible gas management. This project integrates PARs with a dedicated $H_2$ removal system, ensuring effective control of combustible gas under various accident conditions. Rolls-Royce is also actively pursuing the development and qualification of ATFs with enhanced performance characteristics, further bolstering the reactor's safety profile [5, 8].

These examples highlight the proactive efforts of SMR developers to address safety concerns related to combustible gas management and fuel performance. By incorporating innovative technologies and advanced materials, these SMR projects aim to achieve even higher levels of safety and reliability compared to conventional NPPs.

## 2.1. Combustible Gas Management

Combustible gas, such as $H_2$, can be generated in a NPP during design basis and severe accidents. $H_2$ is generated from metal oxidation, especially in fuel systems using zirconium-based alloys as cladding material, as well as other materials, such as boron carbide and stainless steel within the reactor's internal pressure vessel. Additionally, water steam and $H_2$ can be generated in later phases of severe accidents due to the molten core-concrete interactions (MCCI) [13, 14]. The water steam generated may react with the remaining metals, such as the metallic structure of the concrete. Table 3 presents the primary reactions involved in $H_2$ generation.

**Table 3:** Primary reactions involved in $H_2$ generation.

| | | | |
|---|---|---|---|
| Metal-Water Reactions | Oxidation of Zirconium | $Zr(s) + 2H_2O(g) \rightarrow ZrO_2(s) + 2H_2(g)$ | Zirconium from the fuel cladding reacts with water vapor to produce zirconium dioxide and hydrogen gas. |
| | Oxidation of Steel | $3Fe(s) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 4H_2(g)$ | Iron and other metals in the reactor vessel and core support structures react with water vapor to form iron oxide and hydrogen gas. |
| Metal-Carbon Dioxide Reactions | Oxidation of Zirconium | $Zr(s) + CO_2(g) \rightarrow ZrO_2(s) + CO(g)$ | Zirconium can also react with carbon dioxide, producing zirconium dioxide and carbon monoxide. |
| | Oxidation of Steel | $Fe(s) + CO_2(g) \rightarrow FeO(s) + CO(g)$ | Iron and other metals can react with carbon dioxide to produce iron oxide and carbon monoxide. |
| Concrete Decomposition during MCCI | Dehydration | $Ca(OH)_2(s) \rightarrow CaO(s) + H_2O(g)$ | Calcium hydroxide in concrete to calcium oxide and water vapor. |
| | Decarbonation | $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$ | Calcium carbonate in concrete calcium oxide and carbon dioxide. |

The presence of combustible gas, particularly $H_2$, is recognized as a safety issue in water cooled reactors, as combustion processes may pose a threat to containment integrity, among other safety concerns [13].

To ensure the effectiveness of applied mitigation systems, their performance must be evaluated under a wide range of accident scenarios. Considering the Fukushima Daiichi accident [1], additional experimental and analytical needs have been identified to address issues associated with $H_2$ generation and fission products, along with the development of mitigation systems for use inside the NPP containment, using PARs and ventilation systems, which shall be investigated in an integrated and optimized approach [13].

To limit the concentration of combustible gas inside the containment, strategies usually adopted are based on: recombination of $H_2$ generated under accident conditions using PARs; deliberate and controlled ignition to consume flammable gas through combustion at low concentrations; forced ventilation of the containment atmosphere, ensuring the removal of the $H_2$ present in the gaseous mixture; inertization through the injection of inert gas (nitrogen); and mixing of the gas atmosphere to ensure homogenization, avoiding the local accumulation of flammable gas mixtures [13].

The combustible gas ($H_2$) management in NPPs can be implemented using one or a combination of previous approaches.

The Fukushima Daiichi NPP had multiple layers of safety designed to prevent accidents; however, it was overwhelmed by extreme events, including a 9.0-magnitude earthquake on the Richter scale. In the aftermath, extensive discussions were held, leading to the development of additional safety systems, such as the application of PARs. Table 4 provides a comparison of various safety methods applied to NPP, highlighting the pros and cons of each approach.

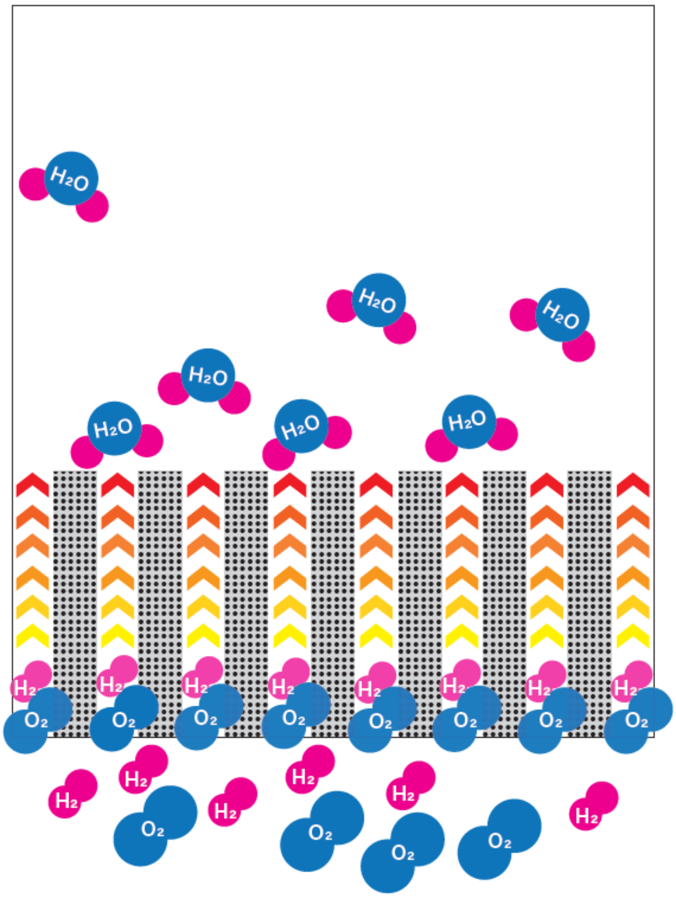
PARs, which have been developed and become commercially available in the last decade, are simple devices consisting of catalyst surfaces arranged in an open-end enclosure [15]. In the presence of $H_2$ and available $O_2$, a catalytic reaction occurs spontaneously on the surface of the catalyst. The heat from this reaction promotes a natural convection flow, which expels hot and humid hydrogen-laden air from the top of the device and allows fresh gas to enter from the bottom as showed in Figure 5.

**Table 4:** Comparison of safety methods applied to NPP.

| Safety methods | Pros | Cons |
|---|---|---|
| PARs (Passive Autocatalytic Recombiners) | Passive: No external power or operator action needed. | Limited capacity: Can be overwhelmed by high hydrogen generation rates. |
| | Reliable: Simple design with few moving parts. | Heat generation: Can contribute to containment heat loading. |
| | Continuous: Operate as long as hydrogen is present. | Catalyst poisoning: Certain substances can deactivate the catalyst. |
| Deliberate Ignition | Can handle high hydrogen concentrations. | Risk of detonation or deflagration, potential for equipment damage, requires careful control and timing. |
| Forced Ventilation | Removes hydrogen and other gas from containment. | May release radioactive materials to the environment, requires power and operability of ventilation systems. |
| Inerting (Nitrogen Injection) | Reduces oxygen concentration, preventing combustion. | Requires large quantities of nitrogen, can displace oxygen needed for workers, may affect other safety systems. |
| Mixing | Prevents local accumulation of hydrogen. | Relies on natural or forced convection, may not be effective in all situations. |

PARs do not require an external power supply or operator action; the use requires only appropriate positioning of PARs units within the containment considering the volume of containment and the required recombination efficiency. Performance analysis of PARs has shown that their performance is largely independent of their location within a particular compartment due to the very vigorous natural mixing process during operation. However, their performance is subject to mass transfer limitations and may not be sufficient for high $H_2$ release rates in small volumes, such as near the source of $H_2$ release [7].

**Figure 5:** Scheme of the circulation of gas in PARs.




PARs typically use platinum and/or palladium-based catalysts to oxidize (recombine) $H_2$ at low temperatures, across a wide range of $H_2/O_2$ concentration, and even under steam environment conditions [16].

Catalysts used in PARs must meet strict requirements, such as: high catalytic activity, ensure rapid recombination of $H_2$ and $O_2$, even at low $H_2$ concentrations [21]; poison resistance to substances present in the reactor environment, such as carbon monoxide (CO), carbon dioxide ($CO_2$), methane ($CH_4$) iodine compounds and water vapor, which can disable the catalyst's active sites [17, 18, 19]; thermal and mechanical stability at high temperatures and adverse conditions inside the containment environment; long service life, ideally throughout the life of the NPP [17].

Various types of catalysts and supports have been investigated for use in PARs. Platinum (Pt) and palladium (Pd) catalysts are the most common due to their high activity in recombining $H_2$ and $O_2$ [17, 20, 21]. Addition of ruthenium (Ru) or nickel (Ni), can improve poisoning and moisture resistances while reducing costs [17, 18]. Stainless steel supports offers a higher surface area and good thermal conductivity compared to ceramic supports but may be susceptible to corrosion [17, 18, 25]. Cordierite supports with high thermal and mechanical stability, low surface area and oxidative properties that can help with CO resistance [17]. Alumina and silica support with high surface area may be more susceptible to moisture deactivation [17, 19, 20].

Experimental studies with different catalysts and support have been carried out to evaluate the performance of PARs under realistic conditions. The use of metal foam coated with $Pt/Al_2O_3$ has shown high $H_2$ conversion rates, good thermal behavior, and reduced risk of unintentional ignition [21]. Pt-Ru bimetallic catalysts in stainless steel grid have shown high activity in the recombination of $H_2$ and $O_2$, even in the presence of $CO_2$, $CH_4$, relative humidity, and up to 400 ppm of CO [17]. Pt-Pd catalysts in stainless steel were effective in $H_2$ removal, but the cordierite-supported catalyst showed better performance in high $H_2$ concentrations and greater resistance to CO poisoning [17]. $Pd/Al_2O_3$ catalysts doped with alkaline metals (Li, Cs) increased the deactivation, with the most pronounce effect observed with Cs [22]. Deactivation of Pd, Pt, and Pd-Pt catalysts supported by alumina and silica is observed in present of water with the strongest deactivation observed in catalysts supported by alumina and for Pt compared to Pd [17].

Lalik et al. [25] identified that the recombination of $H_2$ and $O_2$ on Pd-based catalysts showed thermochemical oscillations and abnormally high thermal effects, exceeding the heat of water formation.

These studies demonstrate advances in PAR research and development, aiming to improve their performance, safety, and cost-effectiveness. Understanding deactivation mechanisms and more poison resistant catalysts is crucial for advancing PAR technology and consequently to ensure the safety of nuclear reactors, in particular SMRs.

## 2.2. Accident Tolerant Fuels

Under severe accident conditions, zirconium-based alloy cladding materials are rapidly heated due to nuclear decay heat, leading to rapid exothermic oxidation in a steam environment and the generation of large amounts of $H_2$ gas. Accident Tolerant Fuel (ATF) technology aims to enhance existing cladding materials by increasing their resistance to oxidation and reducing $H_2$ generation. Additionally, ATFs aim to improve mechanical strength to maintain the cooling geometry of the reactor core.

Several approaches and materials have been investigated for the development of ATFs, with the main focus on the cladding. Several studies with alternative materials are under assessment and one of the most promising candidates for ATF cladding is the zirconium-based alloy coated with chromium [24], which can increase tolerance of zirconium-based alloys and can be deployed without significant changes in existing fuel technology. Another promising candidate is iron-based alloy, named Iron-Chromium-Aluminum (FeCrAl) alloy, which can endure during 24 hours under high temperature (1,200$^{o}$C) [13, 23, 24]. Silicon carbide (SiC), which offers excellent oxidation resistance, a high melting temperature, and stable chemical properties, it is also a promising candidate [25].

Fuel pellet innovations are also being studied. Modifying the chemical composition of the standard $UO_2$ fuel by adding small amounts of other materials to improve its thermal conductivity, grain size, and fission gas retention. Uranium Silicide ($U_3Si_2$) fuel has a higher density of uranium and better thermal conductivity than $UO_2$, potentially allowing for higher power output or longer fuel cycles. Uranium Nitride (UN) offers higher uranium density and thermal conductivity, as well as a high melting point and low neutron absorption. Metallic fuels (e.g., Uranium-Zirconium alloys) offer significantly higher thermal conductivity compared to ceramic fuels and can potentially retain fission products more effectively. However, they may require higher enrichment levels [27, 28].

The Kairos Power KP-FHR reactor, a high-temperature fluoride-salt-cooled reactor, is designed to use TRISO fuel particles embedded in a graphite matrix. TRISO fuel is considered an Accident Tolerant Fuel (ATF) due to its robust multilayer design, which retains fission products even at extremely high temperatures. This feature significantly enhances reactor safety by preventing the release of radioactive material during accidents. Similarly, the Xe-100 reactor also uses TRISO fuel. The use of helium as a coolant and TRISO fuel contributes to the Xe-100's inherent safety characteristics. Furthermore, the Xe-100 employs High-Assay Low-Enriched Uranium (HALEU), enabling longer fuel cycles and reducing waste production. The Terra Power Natrium, a fast reactor cooled by sodium, is exploring the use of metal fuels. Metal fuels offer higher thermal conductivity and greater resistance to degradation under accident conditions compared to traditional oxide fuels. Additionally, metal fuels have the potential to improve reactor efficiency while reducing the volume of nuclear waste produced [5, 8]. Despite the advantages presented above, the implementation of ATFs faces significant challenges, including the need for extended research and development to ensure the compatibility of new materials with existing systems, as well as regulatory and licensing issues [25, 26]. However, the potential advantages in safety and performance justify continued investment in this area.

Computational simulations, such as those performed with the Froba-ATF code, play an important role in assessing ATF performance under normal and accident conditions [25]. These simulations allow the analysis of temperature distribution, mechanical behavior, and fission gas release, providing valuable design information aiming ATFs optimization.

The development of ATFs represents a crucial step in improving the safety and performance of nuclear reactors [25]. Continued research on advanced materials, such as metal alloys, ceramic materials and modified claddings, along with comprehensive computational simulations, will drive the next generation of nuclear fuels, making them more tolerant to accidents and contributing to a safer and more sustainable energy future.

## CONCLUSIONS

SMRs offer a promising avenue for nuclear energy production, especially in remote areas, due to their compact size and enhanced safety features. However, their implementation faces several key challenges. Technically, these include demonstrating effective combustible gas management and developing ATFs. From a regulatory standpoint, streamlining the licensing process and engaging with the public are crucial. Economically, SMRs need to prove their competitiveness through cost reduction and market development. Technologically, ensuring maturity, supply chain reliability, grid integration, and fuel supply are essential. Finally, robust safeguards, spent fuel management solutions, and public acceptance through open communication and education are necessary for the successful and safe deployment of SMRs as a sustainable, low-carbon energy source. Despite these challenges, international efforts are driving progress towards realizing the potential of SMRs in the energy transition.

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## CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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