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Advancements in Accident Tolerance Fuel: A New Horizon in Nuclear Safety

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A B S T R A C T

Accident Tolerant Fuels (ATFs) are a breakthrough in nuclear safety that can reduce the hazards of nuclear reactor accidents by preventing core meltdowns and withstanding extreme conditions. This paper provides a comprehensive overview of the development and current state of ATF technology, tracing its evolution and highlighting key technological milestones. We used different case studies to assess how ATFs work and perform in actual situations. Despite the promising capabilities of ATFs, they face difficulties in their development and deployment. We delve into the technical, regulatory, and economic hurdles that must be overcome to realize the full potential of ATFs. Looking ahead, we explore the prospects of ATFs, discussing potential advancements and their implications for the nuclear industry. The findings of this paper underscore the transformative role of ATFs in enhancing nuclear reactor safety and charting a new horizon in nuclear technology.

1. INTRODUCTION[*]

Accident Tolerant Fuels (ATFs) are a novel and remarkable innovation in nuclear power technology. They improve the ability of nuclear reactors to withstand nuclear-related accidents and greatly increase safety levels [1]. Beyond safety, ATFs also contribute to economic efficiency by potentially improving fuel management, extending fuel cycles, and reducing waste [2]. This dual benefit of enhanced safety and economic efficiency highlights the pivotal role of ATFs in the future of nuclear energy [3].

ATFs encompass a range of innovative technologies aimed at substantially improving nuclear power plant safety [4]. They are engineered to deliver superior performance during normal operation, transient conditions, and accident scenarios [5]. ATFs strive to enhance current nuclear fuel materials by introducing innovative materials that offer numerous benefits [6]. These include reducing hydrogen buildup—a common safety issue in nuclear reactors—and improving fission product retention [7], [8]. Moreover, these materials are structurally designed to resist radiation, corrosion, and high temperatures [9]. This amalgamation of safety and performance enhancements positions ATFs as a transformative force in the nuclear industry.

The role of ATFs in the nuclear industry is paramount. They possess the unique ability to

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endure the loss of active cooling in a reactor core for a significantly longer duration than current fuels [10]. This capability substantially augments the existing safety margin for nuclear plants. Additionally, ATFs enhance the performance of nuclear plants by providing longer-lasting fuel [11]. This not only empowers the current fleet of nuclear plants but also lays the groundwork for licensing fuels for advanced reactors. The overall goal for the development of ATF for reactors is to identify alternative fuel system technologies to further enhance the safety, competitiveness, and economics of commercial nuclear power [12]. Collectively, ATFs play an integral role in augmenting the safety, efficiency, and economic viability of the nuclear industry.

The development of ATFs is driven by the nuclear industry's pursuit of more robust and high-performing reactor fuels [13]. These fuels are engineered to exhibit superior performance during both normal and accident conditions, thereby enhancing the safety and reliability of nuclear power plants. The development of ATFs is not just a technological advancement, but a strategic initiative that could potentially unlock new opportunities [14], [15]. By enhancing safety, ATFs could significantly boost the competitiveness of commercial nuclear power plants. Therefore, the aggressive development of ATFs underscores the industry's commitment to safety, performance, and competitiveness.

2. HISTORICAL DEVELOPMENT OF ATF

Ever-increasing energy needs and the disaster at the Fukushima nuclear power plants have raised the demands for novel and creative solutions to the research challenges, including advanced fuels and cladding materials that withstand irradiation for long periods with improved accident tolerance [16]. This catastrophic event highlighted the urgent need for fuels capable of withstanding severe accident conditions. Consequently, the new ATF technologies, which have the potential to improve the safety of nuclear power plants by offering better performance in normal operations, transient conditions, and accident scenarios [17].

The catastrophic damage inflicted on the Fukushima Daiichi nuclear power plant, coupled with the escalating need for accident tolerance at Light Water Reactors (LWR), sparked intense discussions. These discussions were so impactful that they led to the initiation of the ATF Development Program by the US Department of Energy's Office of Nuclear Energy (DOE-NE) [18]. The research scope broadened to include not only the performance of these fuels under normal operating conditions but also their resilience under severe, beyond design basis accident conditions [6]. This paradigm shift in research direction signified a substantial stride towards the creation of safer and more reliable nuclear fuels, setting a new standard for nuclear safety in the post-Fukushima era [19].

The evolution of ATF development has been punctuated by several key milestones. A significant milestone was achieved in the summer of 2014 when testing of promising fuels and materials with enhanced accident-tolerant characteristics began in a U.S. nuclear test reactor [12]. This was the turning point from abstract studies to concrete tests, making ATFs more feasible. Another notable milestone was the formation of the Expert Group on ATFs for LWR (EGATFL) [20]. Facilitated by the Nuclear Energy Agency (NEA), this group convened leading experts in the field, fostering collaboration and expediting progress in ATF development. These milestones have been instrumental in shaping the trajectory of ATF research and development.

The advancement of ATFs has been characterized by several noteworthy technological breakthroughs. For instance, new types of ATFs such as U_3Si_2, UN, and UC have been developed [21], [22], [23], [24], [25]. These fuels, with a higher uranium density and thermal conductivity than traditional UO_2 fuel, offer significant performance and safety benefits. Alongside fuel composition, progress has also been made in cladding options. Materials such as Fe-Cr-Al and silicon carbide have been explored, with studies confirming that ferritic alloys exhibit superior response under severe conditions [26], [27]. These technological breakthroughs are pivotal in enhancing the safety and efficiency of nuclear reactors, underscoring the transformative potential of ATFs in the nuclear industry.

The current landscape of ATF development is characterized by the proactive initiatives of industry leaders such as Framatome, General Electric (GE), and Westinghouse [28], [29]. These pioneers are at the forefront of the aggressive development of new reactor fuels, pushing the innovation envelope within an accelerated timeframe. Their efforts are reinforced by the support from government entities and national labs, fostering a collaborative ecosystem for ATF development. Looking forward, these companies aspire to commercialize their fuels and deploy them in commercial reactors by 2025 [14]. This prospect not only highlights the rapid progress in ATF development but also signals a transformative shift in nuclear reactor technology soon.

3. CURRENT STATE OF ATF TECHNOLOGY

The development of ATFs encompasses three primary research and development strategies: fuel pellet, fuel cladding, and their interaction [28], [30]. Fuel pellets can be divided into three categories: improved UO_2 pellets, high-density fuels, and encapsulated fuels. Improved UO_2 pellets are achieved by doping UO_2 with oxides such as Cr_2O_3 and Al_2O_3-Cr_2O_3 [31], a strategy being pursued by the French Joint Programme (FJP) and Westinghouse [28]. Alternatively, the Korea Atomic Energy Research Institute (KAERI) is developing ceramic microcell UO_2 pellets [32]. Another approach is to enhance the thermal conductivity of UO_2 pellets by adding metallic or ceramic additives such as Mo, BeO, and other types of dopants [33], [34], [35]. High-density fuels are based on non-oxide fuels, such as uranium silicide (U-Si), uranium nitride (UN), uranium carbide (UC), and other uranium metals [2], [7], [25], [36], [37]. The most recognized encapsulated fuel is the tristructural isotropic (TRISO) fuel, which is also used for advanced reactors, such as high-temperature gas-cooled reactors (HTGRs) [38], [39]. For fuel cladding, there are three approaches: modifying the current zircaloy, coating zircaloy with elements such as Cr and Mo, and developing new cladding materials, such as FeAlCr, FeAlCr-ODS, and silicon carbide (SiC) composite [26], [27], [40]. Each of these approaches has its own strengths and weaknesses, depending on various factors, including knowledge, technology, and industrial perspectives.

ATFs possess a range of capabilities that significantly enhance the safety and efficiency of nuclear reactors. One of the key capabilities of ATFs is their ability to endure the loss of active cooling in a reactor core for a much longer duration than the current fuel [19]. This not only enhances the safety of nuclear plants but also improves the existing safety margin. In terms of performance, ATFs contribute to improved efficiency by offering fuel that stays critical for a longer time [6]. This leads to a reduction in operational and maintenance costs. Furthermore, ATFs leverage innovative materials that offer multiple benefits. These materials are designed to reduce hydrogen buildup and improve fission product retention, both of which are crucial for maintaining a controlled reaction [1], [2], [7], [41], [42], [43]. Additionally, these materials exhibit enhanced resistance to radiation, corrosion, and high temperatures, thereby improving the structural integrity of the fuel [4], [21], [26], [27], [33], [44], [45], [46]. These capabilities underscore the transformative potential of ATFs in the nuclear industry.

Despite their numerous advantages, ATFs do come with certain limitations. For instance, doped UO_2 fuels, while offering improved fission gas retention, are significantly influenced by preparation parameters, which can affect their grain size [47], [47], [48]. New fuel materials like UN and U_3Si_2, despite their increased density and superior thermal conductivity, require significant investment in research and development [49]. Chromium-coated claddings, while comparable in thermo-mechanical performance to Zircaloy-4 cladding, may have limited high-temperature performance due to the formation of a Cr-Zr liquid eutectic [50], [51], [52], [53]. FeCrAl alloys, despite their excellent oxidation resistance, are being developed to maintain this resistance while reducing their Cr content to minimize susceptibility to irradiation-assisted Cr-rich α’ formation [54], [55]. Lastly, the interaction between fuel and cladding materials, particularly the oxidation of zirconium in primary circuit water at around 300° C, can result in the formation of solid oxide on the metal’s surface [56], [57]. These limitations, while challenging, are areas of active research in the ongoing development of ATFs.

4. CASE STUDIES

Several companies are advancing and experimenting with ATFs to improve the safety and efficiency of nuclear reactors. Some of the key players in this field are Framatome, General Electric (GE), and Westinghouse, among others [28].

Framatome leads the ATF development, initiating the PROtect program to enhance the accident tolerance of fuel assemblies [58]. This initiative underscores Framatome’s commitment to advancing the industrialization and series production of these assemblies. A significant breakthrough in their research is the substitution of uranium dioxide with UN in fuel pellets, which markedly enhances their performance [49]. This pivotal work is being conducted in collaboration with the Idaho National Laboratory. In addition, Framatome is spearheading the development of SiC composite cladding materials, further cementing its position as a leader in ATF technology.

General Electric (GE) is making substantial advancements in the field of ATFs [59]. They have introduced an innovative ATF concept that incorporates a FeCrAl alloy and the currently used UO_2 fuel pellets [60]. This combination results in a fuel assembly that not only builds on the performance of existing LWR fuel assembly designs and infrastructure but also enhances their accident tolerance [29]. A testament to GE's efforts is its Iron Clad fuel design, which was developed under the Department of Energy's ATF program and is now primed for testing in a commercial nuclear reactor [48]. This marks a significant milestone in ATF development.

Westinghouse is making considerable progress in the development of several ATF concepts [29], [61]. They have received approval from the U.S. Nuclear Regulatory Commission (NRC) to utilize their Advanced Doped Pellet Technology (ADOPT™) fuel pellets in US PWRs [62]. The fuel, which is doped with small amounts of chromium and alumina, achieves greater burn-up and a 50% lower oxidation rate compared to conventional UO2 pellets. This significantly enhances the safety and reliability of PWRs and improves fuel cycle economics as well as extending the operational cycle length. In addition to the ADOPT fuel, Westinghouse is also developing SiC composite cladding materials [63]. This cladding, which consists of woven SiC fibers impregnated with additional SiC to form a rigid tube, offers increased maximum tolerable cladding temperature (up to 2000 °C), fuel cycle cost benefits, and higher corrosion resistance. This development is part of Westinghouse's commitment to enhancing the accident tolerance of conventional UO2 fuel pellets and improving nuclear plant safety and reliability.

These case studies underscore the innovations of the ATFs. The synergistic collaboration between industry and research institutions is propelling the development of safer and more economical nuclear power reactors and shaping the future landscape of nuclear energy. This collective endeavor is a testament to the power of scientific collaboration in driving technological advancements and setting new benchmarks in nuclear safety.

5. CHALLENGES IN ATF DEVELOPMENT

The development of ATFs is a complex process that encounters several technical challenges [64]. A primary obstacle is the data gaps for each of the cladding technologies, which can impede the understanding of the performance and safety characteristics of the cladding materials, making it challenging to predict their behavior under various operating conditions [65]. Additionally, the lengthy timeframe of testing and licensing process of fuel design to deployment poses another significant challenge. The process from initial design to final deployment of ATFs can span several years if not decades [14]. This extended timeframe can decelerate the pace of innovation and delay the implementation of ATFs. These challenges underscore the need for sustained research and development efforts in the field of ATFs.

The regulatory landscape for licensing nuclear fuel technology presents considerable challenges [66]. The existing process, which is both outdated and overly complex, is a major hurdle to the advancement of this crucial technology. The methods currently employed by the U.S. Nuclear Regulatory Commission were developed decades ago when computing capabilities were relatively limited [67]. Today, however, we have access to far more advanced computing power, and the role of modeling and simulation has become increasingly important. These tools can significantly accelerate the path from design and testing to commercial deployment. Therefore, a transformational shift in the licensing approach is needed to align with the current technological capabilities and to facilitate the development and deployment of innovative nuclear fuel technologies.

The economic challenges in the development and deployment of ATFs are multifaceted [4], [68]. A primary obstacle is the limited opportunity due to the existing fuel testing facilities and abundant R&D programs. These factors can create a bottleneck, slowing down the pace of innovation and making it difficult for new technologies to break through. Moreover, the economic viability of ATFs for the existing fleet is another significant challenge [69]. The cost of developing, testing, and deploying these new fuels can be substantial, and the economic benefits may not be immediately apparent. This can make it challenging to secure the necessary funding and investment for these projects. Furthermore, the regulatory and market conditions can also pose challenges. The process for licensing and approval of new nuclear fuel technologies can be lengthy and complex, which can further delay the deployment of ATFs. On the market side, the relatively low price of traditional nuclear fuels and the competition from other energy sources can also limit the economic attractiveness of ATFs. Therefore, addressing these economic challenges requires a comprehensive approach that includes technological innovation, regulatory reform, and market incentives. This could involve efforts to streamline the licensing process, increase funding for R&D, and create market conditions that favor the adoption of ATFs.

6. PROSPECTS

6.1. *Potential Future Advancements in ATFs*

The future of ATFs is brimming with promising advancements that aim to fortify the safety of nuclear reactors. One such advancement is the development and deployment of an enhanced Zr-based alloy or coated zircaloy for fuel cladding [64].

Moreover, the investigation of different cladding materials with enhanced accident tolerance is ongoing. For instance, SiC composite cladding has attracted attention due to its high temperature and corrosion resistance [27], [62], [63]. This material could significantly enhance safety margins during severe accidents.

Consideration is also being given to alternative fuels with enhanced accident tolerance and/or a higher uranium density. High-density fuels such as U_3Si_2 and UN are particularly promising due to their increased uranium densities and superior thermal properties compared to UO_2 [7], [21], [22], [23], [49], [70], [71], [72]. These fuels could bring significant economic benefits to ATF concepts.

Lastly, TRISO-type fuel represents another long-term concept for future advancements in ATFs. TRISO fuels are microencapsulated fuel forms that consist of a spherical kernel of fissile materials surrounded by two layers of pyro carbon and a SiC layer [39], [73]. Known for their robustness and ability to withstand extreme temperatures, they are potential game-changers in the field of nuclear fuels.

6.2. Impact on Nuclear Safety

ATFs have a significant impact on nuclear safety [2], [4], [28], [74]. They are engineered to withstand the loss of active cooling in a reactor core for a considerably longer duration than the existing fuel. This capability increases the safety margin for existing nuclear plants, thereby enhancing their overall safety profile.

ATFs also augment nuclear plant performance by providing fuel that stays critical for a longer period, leading to operational efficiencies and cost savings [4], [14], [19]. They are suitable for powering the current fleet of nuclear plants and are laying the groundwork for licensing fuels for advanced reactors.

Furthermore, ATFs may present opportunities to enhance the safety and competitiveness of commercial nuclear power plants. Enhanced accident tolerance is achieved by key features such as lower hydrogen production (due to cladding oxidation), better fission product containment under severe accident scenarios, diminished cladding response to high-temperature steam, and optimized fuel-cladding interaction for improved performance under extreme conditions [1], [2], [28], [41].

6.3. Revolutionizing the Industry

ATFs are set to transform the nuclear industry by enhancing the overall economics and performance of existing nuclear power reactors [6]. This novel technology is designed to withstand high temperatures in severe, beyond design basis accident situations, and could extend the refueling period from 1.5 years to 2 years or more and consume about 30% less fuel [19]. This decrease in fuel usage could reduce the number of fuel assemblies required to operate the reactor, resulting in less waste production and a substantial reduction in fuel costs over the reactor’s lifespan.

Leading companies such as Framatome, General Electric (GE), and Westinghouse are at the forefront of the aggressive development of these new reactor fuels. With support from government and national labs, these companies are on course to commercialize their fuels and deploy them in commercial reactors by 2025. This accelerated development and deployment of ATFs could signify a major milestone in the nuclear industry, contributing to safer and more efficient nuclear power generation.

7. CONCLUSION

ATFs are a novel class of nuclear fuels that can improve the safety and technology of nuclear reactors. They can withstand extreme conditions and prevent core meltdowns, reducing the dangers of nuclear accidents. They can also lower the cost of electricity generation and waste disposal, increasing the economic feasibility of nuclear power. However, ATFs face technical, regulatory, and economic barriers that need to be resolved to achieve their full potential. The future of ATFs is bright, with possible innovations and impacts that can revolutionize the nuclear industry. This paper shows how ATFs can change the game of nuclear reactor safety and open new horizons in nuclear technology.

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AUTHOR CONTRIBUTION

I Wayan Ngarayana conceived the idea and drafted the manuscript. Rusbani Kurniawan conducted the research and validated the data. Agus Nur Rachman and Eka Djatnika Nugraha contributed to data analysis and writing. Egnes Ekaranti and Ika Wahyu Setya Andani reviewed, edited, and revised the manuscript.

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