Current Status and Necessity of Accident-Tolerant Fuels (ATFs)

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1. Introduction

During the 2011 Fukushima accident in Japan, hydrogen explosions occurred due to oxidation of zirconium-alloy cladding, underscoring the need for enhanced safety. Accident tolerant fuels (ATFs) are a set of new technologies with the potential to enhance nuclear power plant safety by offering improved performance during normal operation, transient conditions, and accident scenarios. In this study, we review domestic and international ATF developments, identify near-term deployment pathways, and evaluate the feasibility of long-term implementation.

2. Methods and Results

This section outlines the approaches adopted following the shift in nuclear fuel development. It focuses on fuels developed by KEPCO Nuclear Fuel (KNF), Westinghouse, and Framatome with summarizing R&D trends in major countries.

2.1 KNF

KNF has been developing Accident Tolerant Fuel (ATF) based on chromium-coated zirconium alloy claddings produced via Arc Ion Plating (AIP) and UO_2 pellets doped with lanthana–alumina–silica (LAS).

The AIP process forms a dense, adherent chromium layer on HANA-6 zirconium alloy cladding, significantly enhancing high-temperature steam oxidation resistance and reducing oxidation and hydrogen generation under accident conditions. It also reduces corrosion rates and hydrogen uptake during normal operation. Compared to conventional zirconium alloy cladding, the chromium-coated cladding developed by KNF enhances overall performance in corrosion, high-temperature oxidation, and high-temperature burst behavior.

LAS-doped UO_2 pellet (<0.1 wt% La_2O_3 + Al_2O_3 + SiO_2) retains the fundamental property of UO_2 while improving strain tolerance, reducing fission gas release, and lowering rod internal pressure about one-third comparing with standard UO_2. Also, LAS reduce creep rates causing mitigate pellet-cladding interaction. Compared with standard UO_2 pellet, LAS doping at KNF improved in most performance metrics, including grain size, commercial fabricability, and high-temperature deformation/strain.

After completing material development at 2022, KNF assessed the safety implication of ATF application as a lead test-rods (LTRs) and completed the Nuclear Safety and Security Commission (NSSC) review in 2023. In 2024, in-reactor testing began with prototype fuel rods. In 2025, lead test assembly (LTA) test was started.

In the long-term strategy, SiC-based cladding and metal–ceramic hybrid fuel pellets are considered as a primary candidate, and a TRISO–SiC composite is being developed in parallel which can insulate radionuclide releasing under severe-accident. This portfolio outlines a development plan aligned with domestic regulatory technology development (target: 2026) and a U.S. PWR-oriented regulatory readiness roadmap (target: 2027). The object is to enhance severe accident mitigation resistance and increase operational safety margins relative to conventional Zr–UO_2 fuel.

2.2 Westinghouse

Westinghouse has developed ATF system which called EnCore®. As a near-term candidate within this system, Westinghouse composes ZIRLO™ cladding with a chromium (Cr) coating with cold spray and ADOPT™ fuel pellets, i.e., UO_2 doped with Cr_2O_3 and Al_2O_3.

Cold-spray deposition accelerates Cr powder to supersonic velocity using a nitrogen or helium carrier gas and mechanically combines it onto the cladding's outer surface at relatively low temperatures. Then, this process changes substrate properties as minimal and achieves high throughput. The Cr coating enhances cladding integrity and coping time with increasing safety margins during design-basis accidents (such as loss-of-coolant accidents (LOCAs) and reactivity-initiated accidents (RIAs)) and even beyond-design-basis conditions exceeding 1200 °C by enhancing resistance to high-temperature oxidation and corrosion.

ADOPT™ apply additions which composed with chromium and aluminum oxides (Cr_2O_3 and Al_2O_3) to growing UO_2 grain size. This grain growth reduces pellet–cladding interaction (PCI) through pellet deformation at high temperatures and lowers fission-gas release rates. By enabling a modest increase in sintered density, ADOPT™ also allows greater U-235 loading.

These technologies have been assessed through research-reactor irradiations (e.g., ATR, MITR) and in-reactor performance evaluations via lead test rods (LTRs) at Byron-2 (2019) and Doel-4 (2020). The Vogtle-2 lead test assembly (LTA) received U.S. NRC approval in July 2023 for loading at 2025. From a licensing standpoint, the ADOPT topical report (ToR) was submitted in May 2020 and approved in November 2022. A topical report for the Cr-coated cladding is planned for submission around 2025. completing technology development will be at 2027.

For longer-term deployment, the pellet candidate has been shifted from the initial U_3Si_2 to UN. Comparing with UO_2, UN allows about a 40% higher U-235 density (roughly equivalent to a 7% increase in enrichment) and offers enhanced thermal properties. However, UN has a problem with rapid oxidation under steam condition, manufacturability and corrosion. Laboratory-scale studies invest on protecting oxidation by Cr or Ni sheet/foil liners. For cladding, a longer-term deployment is a SiC/SiCf ceramic-matrix composite (CMC) which keep researching with General Atomics (GA), which shows more than 100-fold higher oxidation resistance than zirconium at 1200 °C and retains a strength of ≥300 MPa at temperatures above 1500 °C. GA has fabricated a 1-m-long SiC-based fuel rod. Irradiation testing is underway in MITR and ATR, and commercial-reactor demonstrations are planned for the late 2020s.

2.3 Framatome

Framatome's PROtect™ Enhanced Accident Tolerant Fuel (E-ATF) program consist of developing near-term and long-term applicable ATF. Near-term ATF is chromium-coated M5™ cladding by the High Power Impulse Magnetron Sputtering (HiPIMS) and chromia-doped UO_2 fuel pellets, while longer-term development focuses on SiC-based cladding. The HiPIMS process has advantage of highly uniform and dense chromium layer, while it has a long deposition time and requires technology to increase efficiency. Accordingly, framatome has been developing technologies to reducing the coating process time and increase manufacturing efficiency, and has been developing commercial scale equipment for Cr-coated cladding since 2019.

Chromia-doped UO_2 fuel pellets have high density, promote grain growth to ≥40 μm, and improved high-temperature creep performance. These properties reduce fission-gas release and suppress pellet–cladding interaction. Chromia-doped UO_2 fuel pellets has been applied commercially in European BWRs. A topical report for PWR in USA received regulatory approval in October 2023. Between 2019 and 2023, lead test rods were irradiated at Vogtle, Gösgen, and ANO. Additionally, at Calvert Cliffs Unit 2, the world's first lead test assembly (176 rods) was loaded in November 2021 and subsequently completed two full operating cycle. Framatome plans to commercialize its 24 month, 3 batch operation in 2029 by using LEU+ and ATF to constellation, a US utility.

From a long-term ATF, Framatome and CEA are co-developing a sandwich type SiC-based cladding that incorporates an internal zirconium liner. This has the advantage of solving the problems of SiC cladding such as helium leak-tightness and end-cap welding. However, issues such as increased cladding wall thickness and reduced thermal conductivity require further development. Irradiation testing of sandwich type SiC-based cladding began in 2021, and commercialization target is the mid-2030s.

3. Conclusions

Among near-term candidates of ATF, the combination of chromium-coated cladding and doped UO_2 pellets are regarded as the most promising item. This combination gives most compatibility with existing reactors while providing measurable improvement and comparatively straightforward regulatory approval. Nevertheless, to enable commercialization of ATF concepts, it is essential to demonstrate, through integrated testing spanning normal operation, transients, and accident conditions, that the fuel provides measurable improvement in safety margins relative to current UO_2–Zr systems.

In the long term, innovative fuel systems that combine ATF with LEU+ are required to maximize safety performance while improving economic efficiency. Accordingly, ATF R&D should pursue practical near-term deployment to secure safety and performance. At the same time, it should advance toward next-generation fuels that increase economic efficiency and meet the broader requirements of future nuclear power plants.

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