

WESTINGHOUSE ENCORE® ACCIDENT TOLERANT FUEL AND HIGH ENERGY FUEL STATUS AND COMMERCIALIZATION

JORIE L. WALTERS
Westinghouse Electric Company
Columbia, South Carolina, United States
Email: walte2jl@westinghouse.com

INTRODUCTION: Following the Fukushima Daiichi powerplant accident in March 2011 which resulted from an offshore tsunami, the U.S. Department of Energy (DOE) launched a program to investigate enhancing the accident tolerance of light water reactors (LWRs). The program mandated a focus on the development of accident tolerant fuel (ATF) that when compared to traditional UO_2 and zirconium-alloy fuel systems could tolerate a loss of active cooling in the reactor core for a considerably longer time period while maintaining or improving the fuel performance during normal operation, operational transients, or accidents [1]. Aside from the safety enhancements offered by ATF concepts, there is an economic driver for implementation as the new fuel concepts could increase fuel flexibility through power uprates and reaching higher burnups [2].

To support improved operating and safety margins while also enabling longer cycles, Westinghouse is commercializing a near-term high energy **EnCore** ATF product comprising chromium (Cr) coated zirconium-alloy fuel cladding with doped UO_2 (Advanced DOPed Pellet Technology – **ADOPT™**) fuel pellets with greater than 5% ^{235}U by the late 2020s. Post-irradiation examination (PIE) results of commercially irradiated Cr-coated lead test rods (LTR) have demonstrated enhanced performance with minimal oxidation and crud adherence to high burnups near 75 GWd/kgU. A Spring 2025 lead test assembly insertion with these new products included **ADOPT** pellets with greater than 5% ^{235}U fuel pellets. Licensing topical reports for high energy fuel (HEF) technologies and associated codes and methods are underway and to support future customer deliveries, manufacturing implementation of increased enrichment **ADOPT** fuel pellets and Cr coated fuel cladding are in-progress at multiple Westinghouse fabrication facilities.

1. ATF AND HIGH ENERGY FUEL TECHNOLOGIES AND BENEFITS

Increased electricity demand, the potential for zero-carbon new capacity installation and emission credits and other carbon-reduction initiatives are incentivizing nuclear power utilities to focus on increasing generation capability. Thus, utilities are striving for maximum electricity generation and reduced operating costs while enhancing safety. The Westinghouse HEF Program, which includes **EnCore** ATF technologies, combines near-term and future advancements of fuel cladding, pellets, and structural features to achieve these goals along with higher enriched ($>5\%$ ^{235}U) fuel pellets [3], FIG. 1.



FIG. 1. The Westinghouse High Energy Fuel and Accident Tolerant Fuel Program.

Existing fuel advancements include **AXIOM**[®] zirconium-alloy cladding and **PRIME**[™] structural features. **AXIOM** is a fully licensed, proven cladding which offers improved corrosion resistance, lower hydrogen pickup, and enhanced dimensional stability for higher duty use compared to other zirconium alloys. The **PRIME** skeleton offers improved corrosion resistance and lower grid growth through material optimizations, lowers assembly pressure drop, and provides more robust debris protection through bottom nozzle design enhancements [3].

Westinghouse **EnCore** Cr coated fuel cladding refers to a thin, dense, and adherent cold sprayed coating applied to the outer diameter of existing zirconium-alloy fuel cladding. The Cr coated cladding significantly reduces corrosion, hydrogen pickup, and cladding wear during normal operation compared to traditional zirconium-alloy fuel cladding materials. The coating provides enhanced safety during transient or accident scenarios by significantly reducing high temperature oxidation and improving rupture performance during a loss-of-coolant accident (LOCA) [5][6]. **EnCore** Cr coated fuel rod cladding has been irradiated in multiple commercial pressurized water reactor (PWR) nuclear power plants, reaching high burnup near 75 GWd/kgU. Poolside examinations as well as destructive PIE in hot cell confirmed full coating adhesion and protection of the zirconium-alloy substrate [7][8].

Westinghouse has decades of boiling water reactor (BWR) operating experience with **ADOPT** doped UO₂ fuel pellets and recent insertion in two PWR reactors supports product implementation in the PWR market. Added dopants include chromia (Cr₂O₃) and alumina (Al₂O₃) which result in a larger grain size compared to standard UO₂ and pellets improve thermal stability, increase uranium density, and improve oxidation resistance for increased pellet safety and operational margins [3]. Future ATF fuel cladding and pellet concepts for further operational enhancements are still in the research stage and include a silicon carbide (SiC) fuel cladding that will further increase the peak cladding temperature while preventing cladding rupture, and uranium nitride pellets (UN) which significantly increases thermal conductivity and density compared to standard UO₂ [9].

2. COMMERCIALIZATION AND LICENSING

While **ADOPT** pellet fabrication technology is well established, production line capability is being added to Westinghouse Columbia Fuel Fabrication Facility in Columbia, SC, USA. Additionally, to support needs for operational flexibility through longer cycles and high burnups, construction of a new deconversion facility to manufacture **ADOPT** and UO₂ fuels with greater than 5% ²³⁵U is underway with projected operability in 2028.

Westinghouse began developing coated cladding materials in 2012 with development efforts increasing after the Fukushima Daiichi event. Since then, collaborations with universities, national laboratories, and external suppliers have led to the development and testing of Cr coatings resulting in an optimized, scaled Cr coated fuel cladding to support LTR insertions. Testing of early development coatings aided in confirmation of performance and refinement of coating specifications [10]. Transitioning from laboratory-scale to full-scale development resulted in the need to adapt existing manufacturing techniques to process and inspect new cladding materials. Lessons learned from development and LTR programs are critical to support future product commercialization. Westinghouse has designed and is manufacturing equipment to produce and inspect Cr coated zirconium-alloy fuel cladding with the manufacturing line supporting initial production demands and projected operability in 2026.

Aside from manufacturing commercialization of ATF HEF technologies, product licensing is also a critical part of new product development to support customer adoption. Significant progress has been made in licensing **EnCore** HEF technologies and Westinghouse codes and methods to support fuel management strategies that require exceeding the current ²³⁵U enrichment limit of 5% and burnups up to 75 GWd/kgU to enable high burnup and 24-month cycles. Several topical reports are already approved for use including **ADOPT** fuel pellets, reports for increased fuel pellet enrichment and incremental burnup extension, and the Westinghouse **PARAGON2**[™] two-dimensional fuel energy transport code for commercial nuclear fuel modeling of ²³⁵U enrichments up to 10%. In addition, the Westinghouse Traveller fuel assembly shipping container package has been approved for ²³⁵U enrichments exceeding

5%. The topical report for **EnCore** Chromium Coated Cladding was submitted for review in 2025. Topical reports under development include extension for high burnups up to 75 GWd/kgU as well as fuel rod design and safety analysis methodology reports to support ATF and HEF technologies. The remaining topical reports are planned for submittal in 2025 and 2026.

3. CONCLUSIONS

In conclusion, tomorrow's needs include 24-month cycles with higher enrichment and higher burnup utilizing advanced fuel technologies to further improve fuel cycle costs as well as safety and operational margins. Westinghouse HEF Program combines both currently available and future advanced fuel technologies to support these critical nuclear industry drivers in a multi-phased approach for PWRs. Recent advancements include **ADOPT** fuel pellets which feature higher uranium density and safety benefits and Cr coated cladding which offers a reduced corrosion rate and hydrogen pickup, reduced high temperature oxidation, improved fretting resistance and improved LOCA rupture behavior. Lessons learned from early development and LTR programs have enabled product optimization for implementation into fuel fabrication facilities for further commercialization. Various concurrent licensing topical reports further support ATF technologies and extended fuel operability.

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