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OVERVIEW OF WESTINGHOUSE LEAD ACCIDENT TOLERANT FUEL PROGRAM

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ABSTRACT

Westinghouse is commercializing two unique accident tolerant fuel (ATF) designs; silicon carbide (SiC) cladding with uranium silicide (U_3Si_2) fuel, and chromium-coated zirconium alloy cladding with U_3Si_2 fuel. Out-of-pile testing of the cladding alternatives has continued and samples have been irradiated at the Massachusetts Institute of Technology (MIT) Reactor and the Halden Project Reactor. Uranium silicide fuel is undergoing exposure in the Advanced Test Reactor and fuel pins have been removed and have undergone post irradiation examination at the Idaho National Laboratory. Out-of-reactor testing on U_3Si_2 fuel has revealed a need for additional oxidation protection and these programs are underway. A business case has been developed on the value of ATF for both fuel costs and operational savings which have indicated limited operational savings but significant fuel savings for 18 and 24 month cycles. In parallel, a licensing approach has been developed and is under discussion with the US Nuclear Regulatory Commission (NRC). This paper provides an update on these activities and a summary of results.

1. INTRODUCTION

The Westinghouse accident tolerant fuel (ATF) utilizes EnCore®* fuel consisting of SiC composites/SiC monoliths ceramic matrix composite (CMC) for cladding containing high density and thermal conductivity U_3Si_2 pellets [1] (Figure 1). The CMC from General Atomics consists of Hi-Nicalon-S SiC fibers infiltrated with SiC using chemical vapor infiltration (CVI) and an outer, hermetic layer of SiC deposited using chemical vapor deposition (CVD) [2]. The use of SiC cladding increases the fuel margin during loss of coolant accidents (LOCAs), eliminates departure from nucleate boiling (DNB) as a safety issue and provides added margin for beyond design basis accidents. The pellet option utilizes high density and high thermal conductivity U_3Si_2 pellets. Exposure of the U_3Si_2 pellets at linear heat generation rates of 39 kW/m to 49 kW/m at 20 MWd/kgU showed ~0% fission gas release and swelling [1].

Coated cladding will first be used in lead test rods (LTRs) in 2019 to first introduce U_3Si_2 into commercial reactors in preparation for the combination of SiC CMC cladding and U_3Si_2 pellets in lead test assemblies (LTAs) in 2022. The key properties of SiC cladding and U_3Si_2 fuel are presented in Table 1.

The immediate tasks are aimed at design and licensing with the required experimental backup to obtain Nuclear Regulatory Commission (NRC) approval for insertion of LTRs in 2019 and LTAs in 2022. These include:

- Deploy U_3Si_2 and enhanced UO_2 (ADOPT®* in Cr coated zirconium alloy cladding in LTRs by 2019;
- Deploy SiC and Cr coated rods with oxidation resistant U_3Si_2 and enhanced UO_2 fuels in LTAs by 2022;
- Continue licensing and manufacturing interactions aimed at implementation of regions in 2027.

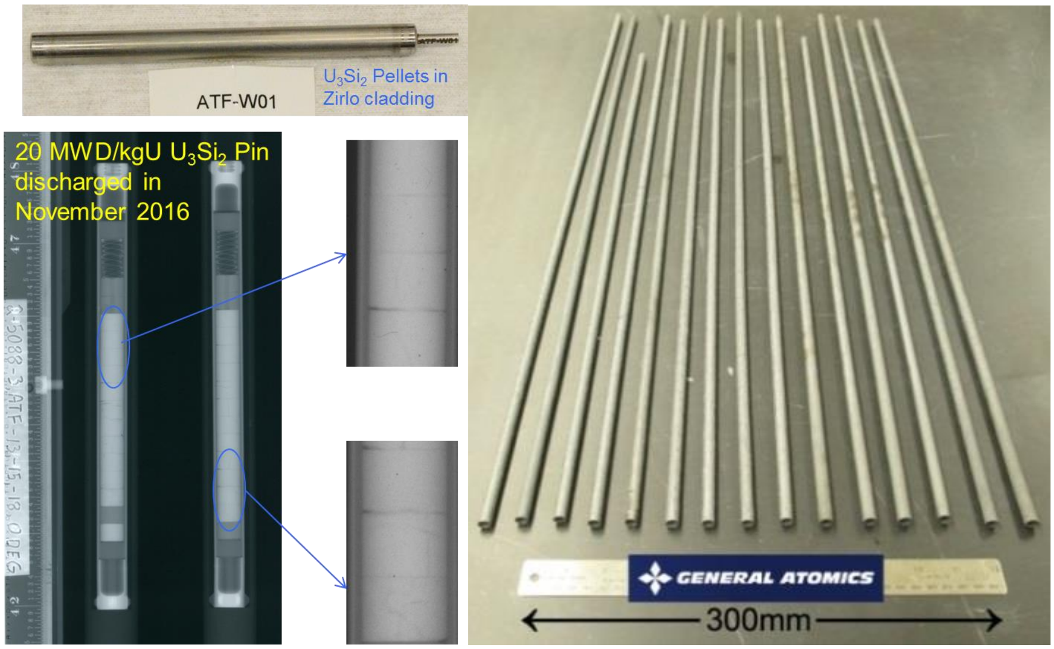


Fig 1. Left - Neutron radiographs from Idaho National Laboratory (INL) of 20 MWd/kgU U_3Si_2 Pins from ATR (Note the lack of pellet cracking and distortion.); Right – SiGA™* SiC/SiC Composite Cladding from General Atomics (GA)

*SiGA™ is a trademark of GA's SiC/SiC composite material.

Property	**SiC/SiC Cladding**	**U_3Si_2 Pellet**
Melting Point (°C)	SiC ~1900°C β to α transition; decomposition ~2000°C	1665°C
Thermal Conductivity (W/m/K), at 600°C	~4 to 12	15
Margin to Melt (°C) at 98 kW/m	Not applicable	885°C
Density (g/cm^3)	>2.58 for SiC composite	12.4 @94% theoretical density
Water/Steam Reactivity	SiC is Low at high temperatures <1850°C; moderate at 300°C water in reactor	Low up to 300°C
Thermal neutron cross section in millibarns	150 mb (estimated) for SiC	Si 171 mb

Tab 1: Key Properties of Westinghouse SiC/SiC Composite/U_3Si_2 and Coated Zr/U_3Si_2 Fuel System

2. LEAD TEST ROD PROGRAM

Two Westinghouse 17x17 OFA assemblies will contain up to 20 EnCore ATF rods with Cr coated Zr alloy and U_3Si_2 and enhanced ADOPT fuel in Exelon's Byron Unit 2 in Cycle 22. Shipping date is February, 2019. Coated tubes and U_3Si_2 and ADOPT pellets will be delivered to the Westinghouse Columbia Fuel Fabrication Facility for manufacture of the assemblies.

There is continuing development work with the University of Wisconsin-Madison and Westinghouse is now working with commercial vendors for scale-up to full-length rods. The U_3Si_2 fuel pellets are being fabricated at INL. Fuel rod and fuel assembly design is progressing and the manufacturing plan being refined. Meanwhile, the 10-CFR-70/50 licensing plan is being updated. A License amendment request has been submitted to the NRC.

3. TESTING PROGRAM

Westinghouse is executing a wide ranging test program to support U_3Si_2 pellets and SiC and Cr coated Zr claddings. High temperature oxidation tests are being conducted at the Westinghouse Churchill site on both SiC and Cr coated Zr cladding. This test facility (Figure 2) utilizes either direct or indirect heating to reach cladding temperatures up to 2000°C in a flowing steam environment.

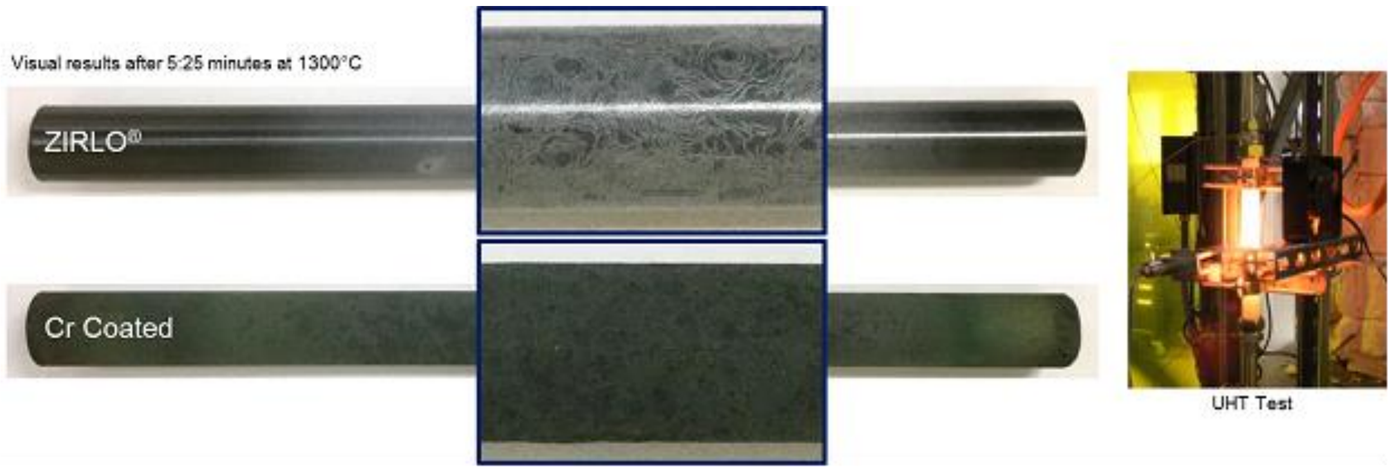
Cr coated cladding has been tested at up to 1500°C and SiC up to 1700°C [3]. The Cr coated Zr sample at 1300°C (Figure 2) showed no significant oxidation or weight change. The 1500°C sample showed evidence of surface melting due to the Cr-Zr eutectic that forms around 1333°C. However, there was no evidence of excessive oxidation. The 1600°C test showed no effect (Figure 2). The 1700°C test of SiC showed no evidence of excessive oxidation although some bubbles of solidified SiO_2 were found on the surface after the test. Higher temperature tests (up to between 1800°C at Churchill and about 1900°C at Karlsruhe Institute of Technology showed significant oxidation. These tests are being repeated in order to generate sufficient kinetic data to input into the on-going MAAP5 code (for beyond design basis accident core modeling) development and modeling effort at Fauske and Associates.

Autoclave tests on Cr coated Zr and SiC cladding are also continuing at Churchill. To date SiC corrosion rates of the best samples have been observed to be highest (up to 0.2 mg/dm^2/day) for the first exposure (10 days) and then level off at very low corrosion rates (0 to 0.03 mg/dm^2/day) afterward. Exposure times are up to >150 days.

Tests are continuing at the Massachusetts Institute of Technology reactor (MITR) on the Cr coated Zr and SiC cladding options [4]. These tests were run at PWR coolant conditions (B at 1000 to 1500 ppm, Li at 5 to 7 ppm, and H_2 at 40 to 50 cm^3/kg coolant). The results indicate minimal corrosion of the Cr coated Zr samples and minimal to moderate corrosion of the SiC, depending on the manufacturing conditions of the SiC and the manufacturer. The out of core but in the coolant loop samples corroded at levels about the same as the autoclaves (<0.015 mg/dm^2/day) with some samples showing loss in hermeticity, depending on the manufacturer. The in-core samples corroded at a significantly higher rate but with no loss of hermeticity. The high rate was due to spalling of some of the outer coating around the endplug joints. Extensive evaluation of two of the Cr coated Zr tubes will be carried out in June to September of 2018.

Oxidation testing of U_3Si_2 in flowing autoclaves in 360°C simulated PWR coolant (1000 ppm B, 4 ppm Li and 50 cm^3/kg coolant H_2) at 22 MPa and 500°C steam at 15.5 MPa was initiated at Westinghouse

Churchill [5]. Tests run on UO_2 pellets showed minimal corrosion rates while tests on U_3Si_2 pellets showed unacceptable corrosion rates and cladding tube bulging. Based on this work, the effort to develop corrosion resistant U_3Si_2 was accelerated. Currently efforts are being aimed at developing corrosion resistant coatings for pellets and for U_3Si_2 powder grains as well as additives aimed at generating a more corrosion resistant U_3Si_2 alloy.



	SiC 1600°C for 9 minutes; Heater rod failed
	SiC 1700°C for 7 minutes; Heater rod failed

Fig 2. High Temperature Testing in Steam at Churchill; Top – Cr coated Zr; Bottom – SiC.

Testing in the Advanced Test Reactor (ATR) at INL continued in the ATF-1 (U_3Si_2 in capsules) irradiation positions to continue to increase the burnup on the U_3Si_2 samples tests which were initiated in 2015 [6]. The next samples at ~40 MWd/kgU are due out in 2019. Samples for the ATF-2 irradiation tests were initiated. These tests utilized UO_2 pellets in Cr coated Zr rodlets. Expected start of ATF-2 irradiation testing is May 2018.

4. LICENSING PROGRAM

To get the EnCore licensed and loaded in region quantities by 2027, Westinghouse has initiated a program that looks to apply advanced modeling and testing technology to fully leverage the value of existing and available test data [7]. It is believed that this approach could help to compress the minimum time from initial testing to commercial delivery, while improving the quality of the data and resulting design models used to describe the fuel.

Westinghouse plans to apply atomic scale modeling technology, which utilizes first principles to determine physical properties of irradiated materials. In addition, Westinghouse has been engaged with DOE-sponsored development programs such as NEAMS (a DOE program focused on basic property prediction) and CASL (virtual reactor design), which can provide additional insights into new material behaviors and performance in advanced applications. Finally, commercial technology such as MedeA and Thermo-Calc software are being used by Westinghouse.

In addition, capabilities to gather real-time in-reactor test data to verify the atomic scale modeling is being developed. This includes:

- Pool-side data generation
    - Gamma emission tomography based on gamma-ray spectroscopy and tomographic reconstruction
    - Can be used for rod-wise characterization of nuclear fuel assemblies without dismantling the fuel (pellet swelling, pellet-cladding interaction, pellet cracking)
    - If a spectroscopic detection system is added, different gamma-ray emitting isotopes can be selected for analysis, enabling nondestructive fuel characterization with respect to a variety of fuel parameters (fission gas release)
- Wired or wireless transmission technology for measurements [8]
    - Centerline temperature
    - Fuel rod gas pressure
    - Swelling of fuel

Besides the time and cost benefits Westinghouse hopes to achieve with this approach, NRC will benefit due to increased confidence in predictability of performance since the performance models will have a theoretical rather than just an empirical basis. In addition, there should be reduced time and effort requirements due to the reduction in the number of submission-review-revision-submission cycles, and taking the review process off the critical path for commercialization.

Communications with the NRC Commissioners and coordination between the DOE, NRC and industry for licensing of ATF are in progress and continuing.

5. COLLABORATION EFFORTS

The fifth Collaboration for Advanced Research on Accident Tolerant Fuel (CARAT) annual meeting was held in Cranberry, Pennsylvania in October of 2018. Over 50 people attended in person and over 20 via webinar. This collaboration is aimed at obtaining world-wide technical support for the Westinghouse EnCore fuel program. Participants included government agencies, utility customers and licensees, universities and government laboratories. The next meeting will be held in Prague, Czech Republic from September 26 to 28, 2018.

Westinghouse is also participating in programs led by Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI) to define the safety benefits and potential operating savings that might accrue for the utilities that use ATF. This effort is coordinated with the effort to improve the modeling of beyond design basis accidents (BDBAs) in the MAAP5 and MELCOR codes. This is important because any ATF safety benefit or cost savings is dependent on how these models describe the changes in behavior of the reactor to these BDBAs. Since these models have not been tested as a whole, having a complete as possible picture of all the processes that could occur during a BDBA is imperative. What has been identified so far is that a minimal amount of cooling water is required to keep the core from melting in a BDBA. This effort is also being expanded to include design basis accidents.

6. FUTURE EFFORTS

The future efforts in the Westinghouse ATF program are aimed at supporting the technology development, design and analysis required to support LTRs and LTAs to be installed in U.S. commercial power plants in 2019 and 2022 respectively. Note that these are just the first of several rounds of LTRs and LTAs that will be inserted between 2018 and 2027. An additional effort is on developing an accelerated licensing approach in cooperation with the NRC for the ATF concept that will achieve region loading in commercial reactors by 2027 [9]. The first efforts will be to develop PIRTs for the EnCore fuel products. These efforts required test reactor work to continue in ATR, TREAT, MITR and hopefully Halden and other reactors before 2027. This test reactor work will be aimed at verifying the models generated using atomistic modeling.

Specific development activities include further work on SiC cladding to confirm corrosion approaches, performance in steam atmospheres above 1900°C, sealing and gas backfill development work performed by General Atomics and others. In addition, work on low cost manufacturing techniques for up to 4.3 meter rods will also continue [10]. Testing supporting the corrosion resistance and low cost manufacture of U_3Si_2 will also continue.

Finally, work with outside groups such as NEI and EPRI will continue to identify changes in operations and/or equipment to maximize the value of ATF in preserving plants, reducing costs and increasing safety of existing plants. To do this, increased emphasis will be placed on leveraging CASL and NEAMS to help ATF model development to support licensing and BDBA and DBA modeling.

7. SUMMARY

Westinghouse is developing a revolutionary fuel product, EnCore that will provide additional time and temperature margin for fuel during DBAs and BDBAs and to reduce operational and fuel costs. This effort is leveraging support from the USDOE, national laboratories, universities and groups around the world to make this happen on an accelerated schedule unmatched by any other fuel innovation since the change from stainless steel to zirconium cladding in the 1960's.

8. REFERENCES

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9. ACKNOWLEDGMENTS

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