INCORPORATING ATF AND ADVANCED FEATURES IN THE ROBUST FUEL ASSEMBLY (RFA) DESIGN

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Westinghouse and ENUSA are commercializing two unique EnCore®* accident tolerant fuel (ATF) designs; SiGA™* silicon carbide (SiC) cladding with uranium nitride (UN) fuel, and chromium-coated zirconium alloy cladding with ADOPT™* and UN fuels. In Europe, these new products will be incorporated in the highly reliable RFA design. The initial product offering will be chromium-coated zirconium alloy cladding with ADOPT fuel followed by UN (and/or >5% enriched ADOPT fuel in the USA). Additional features such as improved debris removal are also being incorporated. While increased accident tolerance is the technical focus of this product, it is understood that the economic benefits must outweigh the additional costs of implementation. Economic benefits are enabled by incorporating advanced debris failure protection, by the use of failure resistant materials and by increasing the U235 density to enable longer fuel cycles or a dramatic reduction in the reload size resulting in lower overall plant operating costs.

INTRODUCTION

The 17x17 Robust Fuel Assembly supplied by Westinghouse and ENUSA started its irradiation as early as 1998 in PWR nuclear power plants around the world. Over the years, RFA has been improved and, today, the Spanish reactors loading this fuel have remained leak free during the last five years and, overall, European reactors loading this fuel have remained leak free during the last year.

Extensive on-site and hot cell fuel exams have demonstrated its excellent performance up to burnups as high as 70 MWd/kgU fuel assembly average. However, as new technologies become available, Westinghouse is developing new components, such as advanced filters, to be incorporated into the RFA design to cope with the residual debris failures that still are observed in the world fleet of nuclear power plants.

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In support of industry initiatives as a result of the Fukushima accident, Westinghouse and ENUSA embarked on a dramatic expansion of the accident tolerant fuel (ATF) program that had been ongoing in Westinghouse since 2004. From the beginning, enhanced economics as well as enhanced accident tolerance has been the goal. One example of this synergistic effect is the use of chromium (Cr) coated zirconium alloy cladding. The Cr coating dramatically reduces oxidation of the base zirconium (Zr) cladding during normal operation thereby allowing higher burnups by reducing the embrittlement due to hydride formation. In addition, the harder Cr coating along with the incorporation advanced debris filters will increase the resistance of the fuel to debris and grid to rod fretting failures which can eliminate the operating and availability costs due to fuel failures.

ROBUST FUEL ASSEMBLY

The 17x17 Robust Fuel Assembly design, see Figure 1 for the current design, solved the performance issues observed at the end of the 1990s such as grid-to-rod fretting failures and provided excellent fuel assembly dimensional stability, eliminating control rod insertion issues and restrictions during core loading/unloading. This high fuel assembly (F/A) dimensional

INCORPORANDO ATF Y CARACTERÍSTICAS AVANZADAS EN EL DISEÑO DE COMBUSTIBLE ROBUSTO (RFA)

Westinghouse y Enusa comercializan dos diseños EnCore® de combustible tolerante a accidente (ATF) únicos; el SiGA™* con vaina de carburo de silicio (SiC) y combustible de nitruro de uranio (UN), y la vaina recubierta de cromo con combustibles ADOPT™ y UN. En Europa, estos nuevos productos serán incorporados en el altamente probado y fiable diseño RFA. El producto inicial ofrecido será el de vaina recubierta de cromo con pastilla ADOPT seguido con UN (y/o con pastilla ADOPT con > 5% de enriquecimiento en EE.UU.). Además se incorporan características adicionales para mejorar sus propiedades anti-debrís. Aunque el aumento de la tolerancia a accidentes es el foco técnico por el que se desarrollan estas tecnologías, se reconocen en ellas los beneficios económicos que compensan el coste adicional asociado la implementación. Estos beneficios económicos son posibles gracias a la incorporación de protecciones avanzadas contra el fallo por debris, mediante el uso de materiales resistente a fallo y por el incremento de densidad en U235 que permitirá ciclos más largos y reducción del tamaño de la recarga, lo que repercute en una reducción de los costes de operación de la planta.

stability was further improved by incorporating the tube-in-tube design that eliminates the dashpot zone in the guide tube, and by increasing the rotational stiffness of the grid to guide thimble tube joint by double bulging.

In addition to these two key improvements, the RFA structural grid and intermediate flow mixer (IFMs) grids also improved the thermal performance and reduced the crud loading and hot spots. The improved thermal performance and the incorporation of higher corrosion resistant claddings such as ZIRLO and, today, Optimized ZIRLO are the elements that have allowed the plants to improve the fuel utilization in the today´s higher fuel duty. Consistently healthy fuel examinations and surveillance of the critical fuel performance parameters over many years have demonstrated the excellent performance and the reliability of the RFA fuel achieving burnups as high as 70 MWd/kgU F/A average [6].

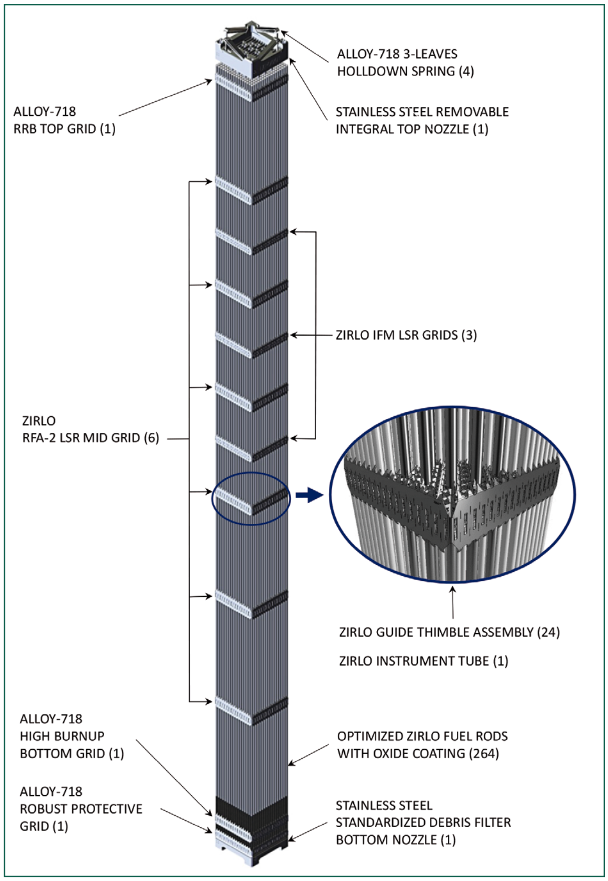

Figure 1. Robust Fuel Assembly design.

IMPROVED DEBRIS FILTERING FOR INCREASED FUEL RELIABILITY

RFA design currently has three debris protection features for PWR fuel: the standardized debris filter bottom nozzle (SDFBN), the protective grid, and oxide coated cladding over the bottom 150 mm of each fuel rod.

While the use of very hard Cr coatings on the Zr cladding can significantly improve the resistance of fuel to failures related to debris and grid to rod fretting, modifications in the design of the debris filter bottom nozzle are also being incorporated [5]. Two debris filter designs are being developed. One design, made with conventional manufacturing (CM), eliminates a key leakage path in the nozzle skirt region. This new design, shown in Figure 2, provides filtering of the flow through the skirt region by lowering the skirt and adding small flow holes to minimize the size of debris that can escape through the skirt region. The new CM skirt meets interface criteria by avoiding interference with bolts on the lower core plate by adding a pocket to the bottom center of the skirt and providing bypass cooling flow to the baffle-barrel region when the nozzle is in a peripheral core location. This new CM DFBN has the same pressure drop as the current DFBN, as demonstrated by full-scale hydraulic testing. Comprehensive, full-scale debris filter testing has proven that the new skirt design is effective at preventing debris from escaping through the skirt region.

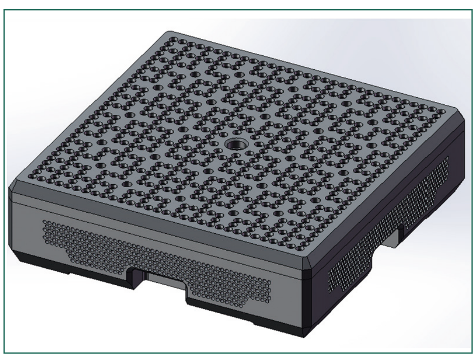

Figure 2. New Conventionally Manufactured DFBN (skirt hole pattern shown is not the final pattern).

The second design (Figure 3) utilizes additive manufacturing (AM) to dramatically improve the debris filtering capability through the top flow plate of the DFBN, which is the main flow path of coolant into the fuel assembly. A much stronger material (Alloy 718) is used as the nozzle material to minimize the thickness of the required structural members. This creates pressure drop margin that can be used by complex debris filtering features (a double layer of an internal spire mesh in this case, shown in Figure 3) to reduce the debris size that can get through the top flow plate by a factor of >10. Westinghouse has developed the AM process to print the entire AM DFBN, and this process was used to make nozzles for structural, hydraulic and debris testing. Full-scale debris filter testing has shown that the debris filtering efficiency of the DFBN improves from 65% in the current design to 95% in this new AM design based on the standard debris package used in Westinghouse PWR debris filter testing. Development of the AM design is nearing completion and will be ready for lead assembly introduction in 2020.

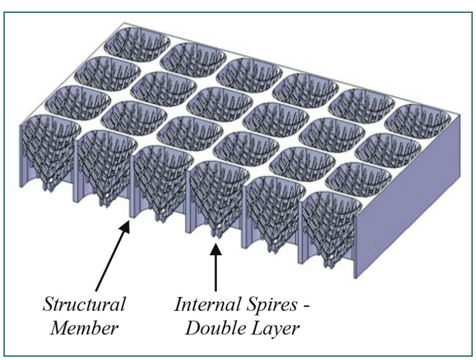

Figure 3. Top Flow Plate of the New AM DFBN (Skirt design will be similar to the CM DFBN).

ADVANCED TECHNOLOGY FUEL

As the largest supplier of nuclear fuel and fuel components globally, Westinghouse has developed a world-class network of research, design and manufacturing partners. Leveraging the breadth and depth of its resources, combined with U.S. Department of Energy (DOE) and utility support, Westinghouse is collaborating with respected industry partners to deliver its revolutionary new accident tolerant fuel design, EnCore® Fuel, to the market on an aggressive, accelerated schedule. Spain found the opportunity to engage in the development of ATF fuel by means of a Frame Cooperation Agreement (FCA) signed in 2018 by Enusa Industrias Avanzadas (ENUSA) and Westinghouse Electric Company. Details of the EnCore Fuel Program were previously published in Nuclear España early this year [7].

From the beginning, enhanced accident tolerance as well as enhanced economics have been the goals. In many instances, achieving enhanced accident tolerance either enables or provides significant opportunities for operational cost benefits. One example of this synergistic effect is the use of Cr coated zirconium alloy cladding. The Cr coating dramatically reduces oxidation of the base Zr cladding during normal operation thereby allowing higher burnups by reducing the embrittlement due to hydride formation. In addition, the harder Cr coating along with the incorporation of advanced debris filters will increase the resistance of the fuel to debris and grid to rod fretting failures which can eliminate operating and availability costs due to fuel failures.

The use of ADOPT fuel has the potential of reducing the fission gas release and fuel fragmentation at high burnup as well as fuel loss following the unlikely failure of the fuel cladding. Increased pellet performance allows the use of >5% U235 enrichments to achieve increased fuel burnups. An alternate approach to >5% U235 enrichment is the use of UN fuel. UN fuel provides a 5x to 10x increase in the thermal conductivity while also reducing fission gas release, fuel swelling and providing significant temperature reductions during departure from nucleate boiling (DNB) events that can allow increased plant maneuverability and power increases due to significant reduction in the likelihood of fuel failures.

The increased resistance of the Cr coated cladding to ballooning and burst synergistically increases the plant maneuverability benefits afforded by UN. Higher burnups afforded by either >5% U235 or UN will reduce the operating costs associated with handling and disposal of spent fuel.

Testing to support EnCore accident tolerant fuel design and licensing

The immediate tasks are aimed at design and licensing with the required experimental backup to obtain U.S. Nuclear Regulatory Commission (NRC) approval for insertion of Lead Test Assemblies (LTAs) by 2022 of Cr coated Zr with ADOPT UO_2 and regions in 2023. Data to support licensing is being generated by running tests out-of-reactor, test reactors (Massachusetts Institute Technology Test Reactor -MITR-, Idaho National Laboratory Advanced Test Reactor-ATR- and Idaho National Laboratory Transient Reactor Test -TREAT-) and in commercial reactors from lead test rods (LTRs). Cr coated rods were manufactured (Figure 4) and used in LTRs (Figure 5) which were loaded into the Byron Unit 2 reactor in April 2019. They consisted of Cr coated rods with ADOPT (Cr_2O_3+Al_2O_3 doped UO_2) pellets and Zr cladding with uranium silicide (U_3Si_2) pellets. Additional LTRs are expected in 2020 at Döel in Belgium (Cr coated cladding) and new LTRs or LTAs are expected to operate in Spain in late 2020 or early 2021. SiC and Cr coated Zr claddings will be used with ADOPT pellets in the Advanced Test Reactor in early 2020 and with Mo pellets in BR-2 as part of the Il Trovatore program at the end of 2019.

Tests are continuing at the Massachusetts Institute of Technology reactor (MITR) on the Cr coated Zr and SiC cladding options as well as the in-rod sensor that is being developed by Westinghouse to support the ATF testing and licensing process [1]. These tests are being run at pressurized water reactor (PWR) coolant conditions. 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 in-core sensor

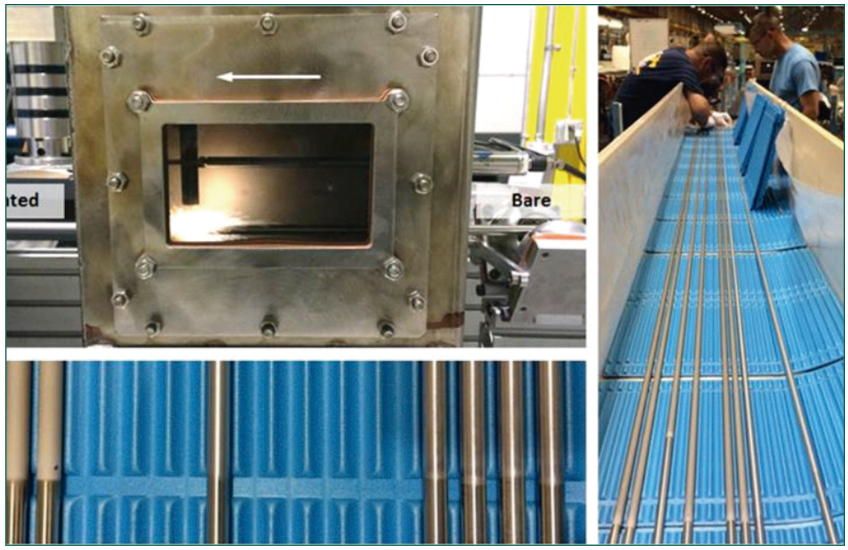

Figure 4. Rods being cold spray coated.

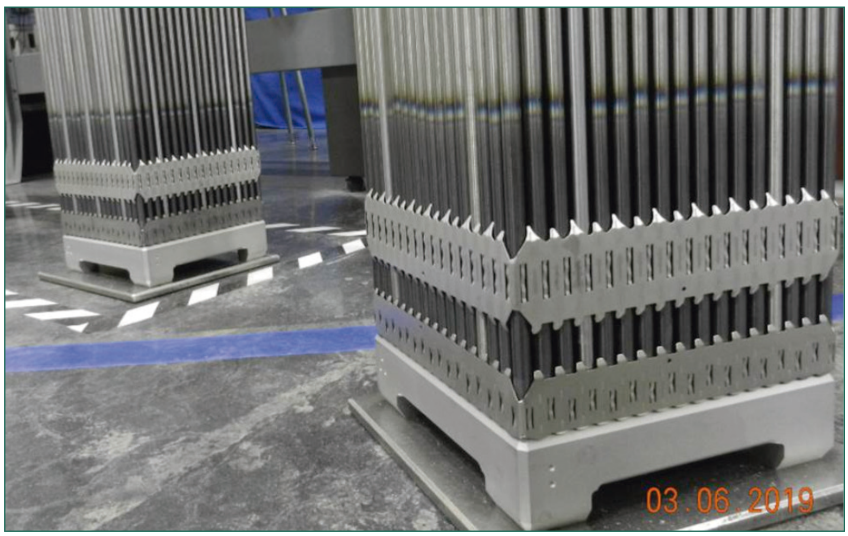

Figure 5. Byron Unit 2 assemblies with EnCore fuel loaded.

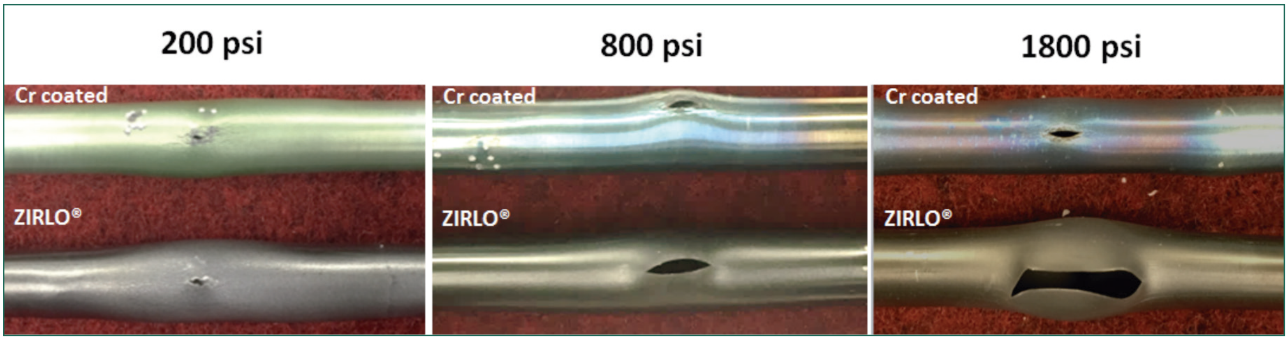

Figure 6. Burst hole-size comparisons of coated (top) and uncoated (bottom) cladding at various pressures.

tests are proceeding well with the sensor responding proportionally to temperature changes as measured by an in-core thermocouple.

Rodlets for the ATF-2 irradiation tests starting in January 2020 at ATR have been constructed using ADOPT pellets in Cr coated cladding. Rodlets utilizing ADOPT pellets in SiC cladding are being fabricated for insertion in the mid-2020 timeframe.

Mechanical tests of Cr coated Zr showed slight improvements in ultimate tensile and yield strength under 0.2% strain, along with significant improvement (reduction) in elongation. These property improvements result in a significant reduction in the area of burst holes during temperature excursions (Figure 6). This, combined with the much lower hydrogen pickup due to the significant reduction in Zr corrosion during normal operation, provides significant safety benefits[2].

Previous oxidation testing of U_3Si_2 pellets in flowing autoclaves in 360°C simulated PWR coolant showed unacceptable corrosion rates and cladding tube bulging[3]. Westinghouse then considered testing of UN pellets at the same conditions and found that the UN did not bulge the zirconium tube nor did the UN totally dissolve. Based on this work, the current effort to develop corrosion resistant U_3Si_2 has been modified to develop UN. Currently efforts are being aimed at developing corrosion resistant coatings for pellets and for UN powder grains, as well as additives aimed at generating a more corrosion resistant UN pellet.

There is continuing development work with the University of Wisconsin-Madison and at Westinghouse (Figure 7) to evaluate new coatings as well as advanced coating application and finishing methods. Fuel rod and fuel assembly design and optimization is continuing.

High temperature oxidation tests continue at the Westinghouse-Churchill site on both SiC and Cr coated Zr cladding. Tests are also being conducted at Karlsruhe Institute of Technology (KIT)[3]. This testing program indicates that Cr coated cladding has a much-reduced oxidation rate below the 1333°C eutectic point. The overall hydrogen production rate is still much reduced over that of uncoated Zr. The corrosion rate data from these tests is being used to generate revised models for the MAAP5 code (for beyond design basis accident core modeling) at Fauske and Associates.

Figure 7. Cold spray test apparatus at Westinghouse.

EnCore accident tolerant fuel collaboration with other institutions

The sixth and seventh Collaboration for Advanced Research on Accident Tolerant Fuel (CARAT) meetings were held at the Czech Technical University in Prague in September of 2018 and at Cambridge University in March of 2019 respectively. 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.

Westinghouse has also continued participation 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 be accrued for the utilities that use ATF. This effort is coordinated with the effort to improve the modeling of the MAAP 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 beyond design basis accidents (BDBAs). Since these models have not been tested, 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.

Licensing efforts

In the U.S., commercialization of EnCore fuel is proceeding in two phases. The first phase leading to regions (a reload quantity of fuel) of Cr coated Zr cladding with ADOPT pellets in 2023 is requiring topical submittals to the NRC in 2019 and 2020. These topicals are supported by LTRs and test reactor test programs at MITR, ATR and others. Future LTAs and transient tests in TREAT will follow. A non-testing activity that was completed was the Phenomena Identification and Ranking Table (PIRT) analysis of the Cr coated Zr. Parallel PIRT analyses were carried out by both Westinghouse and the NRC in 2019. The recent addition of >5% U235 enrichments to ADOPT has extended the scope of these activities since they affect the whole fuel cycle and not just the fuel vendors and power plants. However, it is recognized that the relationship between ATF claddings and >5% enrichments is symbiotic. The Cr coated Zr cladding enables the higher burnups that the >5% enrichment enables, which in turn enables the higher cost of the Cr coated Zr cladding (along with accident tolerant benefits) to be economically justified. Therefore, adding a >5% enrichment program funded by the Department of Energy (DOE) and industry to the current ATF program will be beneficial to both. Commercialization of Cr coated cladding with UN fuel will require an additional topical report on UN fuel.

Westinghouse advanced modeling and testing technology programs have made significant progress in supporting licensing in an effort to decrease the time and cost of licensing the various ATF products. Atomic scale modeling technology, which utilizes first principles to determine physical properties of irradiated materials, is being applied to UN. In addition, Westinghouse remains engaged with the DOE-sponsored Nuclear Energy Advanced Modeling & Simulation (NEAMS) and Consortium for Advanced Simulation of Light Water Reactors (CASL) programs to provide additional insights into new material behaviors and performance in advanced applications.

Westinghouse in-rod sensing capability has significantly advanced with the testing of the sensors at MITR [4]. While this capability was not employed in the current round of LTRs and test reactor activities, future applications in 2020 and 2021 are envisioned to gather real-time in-reactor test data to verify the atomic scale modeling that has been developed.

SUMMARY

Westinghouse and ENUSA are developing a revolutionary fuel product, EnCore fuel, for the European market that will provide additional time and temperature margin for fuel during DBAs and BDBAs and reduce overall operational costs. Additional features are also being added to the DFNB to reduce the chance of debris attack on the fuel rods which, in combination with the use of much harder Cr coating, are expected to dramatically reduce fretting and debris failures from the already miniscule levels achieved along the years by the highly reliable Robust Fuel Assembly design.

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