ENHANCED ACCIDENT TOLERANT FUEL (EATF) FOR BOILING WATER REACTORS AND GNF3 FUEL DESIGN INTRODUCTION

This article describes the results of Global Nuclear Fuel (GNF) efforts towards implementation of a cladding that provides enhanced accident tolerance as compared to current cladding. IronClad is an iron-chromium-aluminum (FeCrAl) ferritic alloy. ARMOR is a proprietary coating applied on the surface of existing Zirconium alloy fuel cladding named for its Abrasion Resistant, More Oxidation Resistant characteristics.
This article also gives a brief description of the latest bundle design, GNF3, which is an advanced mechanical design based on 10x10 fuel lattice. The GNF3 fuel design is a natural evolution of GNF2 that was motivated by GNF's pursuit of continuous improvement.

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INTRODUCTION

As part of the continuous effort to improve fuel safety and performance, GNF has been involved in technology development in areas such as Enhanced Accident Tolerant Fuel (EATF).

Since 2012 GNF has been engaged in the development of the iron-chromium-aluminum (FeCrAl) ferritic alloy concept as a robust, mid-term replacement for highly optimized zirconium-based cladding, together with the US Department of Energy (DOE) in an effort led by General Electric (GE) Global Research Center (GRC) with partners from the national laboratories and universities.

In parallel to the DOE sponsored effort, GNF has been working directly with utility partners to develop a coated Zircaloy concept that addresses improved debris fret resistance, as well as providing Enhanced Accident Tolerance via oxidation resistance to high temperature steam. GNF's proprietary coating is named ARMOR, which stands for, and is based on, the Abrasion Resistant, More Oxidation Resistant characteristics of the coating as compared with uncoated Zircaloy cladding.

The GNF3 product line is based on innovative evolutionary design changes to the historical 10x10 lattice design. GNF3 aims to substantially improve fuel cycle economics, enhance operational flexibility, and provide industry excellence in fuel reliability. GNF3's updated mechanical design, optimized fuel rod neutronics and core design techniques are just some of the first-of-its-kind engineering concepts deployed with this product line.

GNF ENUSA Nuclear Fuel S.A. (GENUSA) is a Spanish company based in Madrid, jointly owned by GNF and ENUSA to market and sell nuclear fuel and related services to the European Boiling Water Reactor plants. Since 1996, ENUSA has manufactured fuel sold by GENUSA to operators of boiling water reactors across Europe with GNF technology. Therefore, GENUSA is working on different opportunities to introduce and market these improved products within Europe.

IRONCLAD

IronClad is an iron-chromium-aluminum (FeCrAl) fuel cladding alloy, developed under US Department of Energy (DOE) Accident Tolerant Fuel (ATF) program. Ferritic alloys are desirable for its resistance to stress corrosion cracking from the coolant side, high thermal conductivity and low coefficient of thermal expansion. Ferritic steels also exhibit higher strength than current zirconium alloys at reactor temperatures, allowing for thinner tube wall thickness, to minimize the neutron absorption. The alloys contain sufficient chromium to remain passive under normal operation conditions and contain sufficient aluminum to develop a protective alumina external layer under severe accident conditions of high temperature steam.

The focus is on the three alloys (Table 1).

COMBUSTIBLE CON TOLERANCIA MEJORADA A LOS ACCIDENTES PARA REACTORES DE AGUA EN EBULLICIÓN - INTRODUCCIÓN AL DISEÑO DE COMBUSTIBLE GNF3

Este artículo describe los resultados del esfuerzo de Global Nuclear Fuel (GNF) para conseguir la implementación de una vaina que proporcione una tolerancia mejorada a los accidentes en comparación a la vaina actual. IronClad es una aleación ferrítica con adiciones de hierro-cromo-aluminio (FeCrAl). ARMOR es un recubrimiento propiedad de GNF aplicado en la superficie de las vainas de las aleaciones actuales de zirconio y sus siglas en inglés (*Abrasion Resistant, More Oxidation Resistant*) indican sus características: resistente a la abrasión, Más Resistente a la Oxidación.
Este artículo también ofrece una breve descripción del último diseño de combustible, el GNF3, que es un diseño mecánico avanzado basado en la red 10x10. El diseño de combustible GNF3 es una evolución natural del GNF2, motivada por la búsqueda de GNF de la mejora continua.

Alloy	Cr (wt%)	Al (wt%)	Others	Fe (wt%)
APMT	21	5	3Mo	balance
C26M	12	6	2Mo + 0.05Y	balance
FeCrAl ODS	12	6	0.5Ti + Zr +Y2O3 + Fe2O3	balance

Table 1.

The key properties are controlled by the material chemistry and chemical homogeneity of the material. A uniform distribution of elements results in aluminum providing the high temperature oxidization resistance of the material and chromium providing the corrosion resistance at normal operating conditions. However, grain size and material microstructure are dependent on the process path used to manufacture the final product form. Since a large database of material properties is not available for all the potential product forms of IronClad, selected material testing was performed to ensure that key material properties in final product form meet design requirements.

The properties tested for the IronClad material were selected to validate the operating domain of the fuel component. This includes normal reactor operating conditions and normal transients, accident conditions such as LOCA, severe accidents such as station blackout, as well as material handling at room temperature.

ARMOR

ARMOR is a thin, GNF proprietary coating applied to the outer surface of normal production Zircaloy fuel rods. As the name implies, its purpose is to improve the fret resistance of the cladding and to improve oxidation performance of the Zircaloy substrate. As discussed in the next paragraphs, laboratory tests show ARMOR coated Zircaloy-2 has improved wear resistance at room temperature, and improved corrosion/oxidation resistance over uncoated Zircaloy-2 under operational corrosion environments and in high temperature steam.

In the as-coated condition, the coating is silvery in appearance without visible defects under adequate lighting. When examined metallographically, the coating is fully dense without microcracks or pores. Coating thickness is consistent around the circumference and along the length of the coated tubes.

ARMOR coated Zircaloy-2 was tested under BWR LOCA relevant (design basis) conditions. Oxidation tests in flowing steam were conducted at 1000 °C for 5000 s and at 1200 °C for 600 s. Figure 1 shows visuals of an as-coated ARMOR Zircaloy-2 tube prior to high temperature oxidation testing and post-test visuals of uncoated and ARMOR coated samples. Reduction in oxidation is clearly visible in the ARMOR coated samples.

Figure 2 shows a comparison of the ARMOR-coated outer surface region with the uncoated inner surface region following testing in steam at 1000 °C for 5000 s. The test condition is equivalent to 23% Equivalent Clad Reacted (ECR) based on the Cathcart-Pawel formulation for two-side oxidation, i.e. greater than the current 17% ECR limit. As the inner surface was not coated, the extent of the steam oxidation on the inner surface (between red arrows in the right part of Figure 2) was consistent with expectations in terms of presence of a ZrO_2 layer and an Oxygen-stabilized alpha-Zr layer. In contrast the ARMOR-coated outer surface region showed reduced extent of reaction, in between the red arrows in the left part of Figure 2. Closer examination of the outer surface region showed the presence of a thin Oxygen-stabilized alpha-Zr layer, much thinner than seen for the un-coated inner surface region, but there was no indication of ZrO_2. These results indicate that ARMOR coating provides some accident tolerance benefits in terms of oxidation (and resulting embrittlement) compared with uncoated Zircaloy-2 under these design basis test conditions.

Using an inner diameter (ID) expansion method it was determined that at both room temperature RT and 315 °C, ARMOR coating did not exhibit cracking at 1% hoop strain, a level that is relevant to fuel performance. When the ARMOR coated tube has been subjected to a high degree of strain, such at 30% hoop strain (Figure 3), the coating remained adherent to the substrate tubing. The test was interrupted prior to rupture of the sample, and it can be seen that the surface of the test specimen is extensively cracked. One interesting feature is that there is little evidence of coating flaking off, despite the ballooning of the test specimen, indicating that the coating is adherent to the substrate even at the achieved strain level.

Preliminary results show that a statistically significant difference between ARMOR coated and uncoated tubes was noted for Ultimate Tensile Strength (UTS) at 315 °C (higher for coated tubes) and modulus at RT (lower for coated tubes). It is anticipated that increasing the sampling size through more tests will be needed to confirm these preliminary findings.

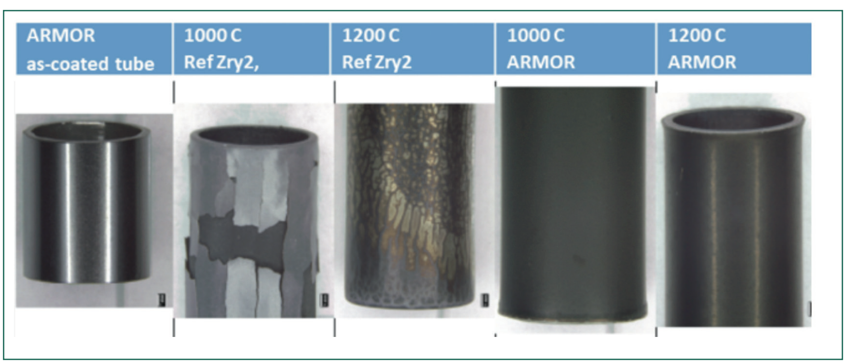

Figure 1. ARMOR coated and un-coated tubes after High Temperature Oxidation Testing

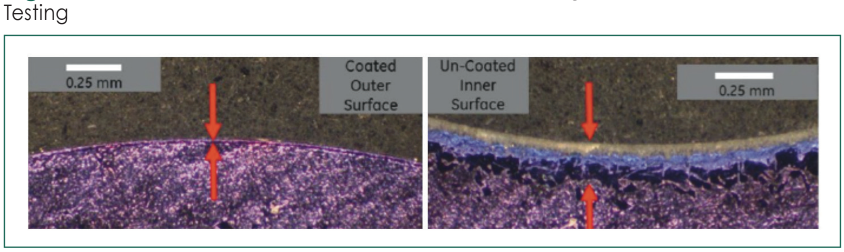

Figure 2. ARMOR coated outer surface vs un-coated inner surface

Figure 3. ARMOR coated tube after ID expansion test at RT

To evaluate the resistance of ARMOR-coated Zircaloy-2 tubes against stainless steel, a wear test at RT was designed in which tubes are subjected to cyclical contact with stainless steel wire agitators. The wear depth results for brushing contact are shown in Figure 4.

Figure 4 shows that ARMOR coated tubes had significantly less wear than the reference, uncoated Zircaloy-2 up to 1 million cycles of testing. Similar results were obtained for impinging contacts.

GNF3 FUEL DESIGN

The GNF3 fuel assembly is designed to offer customers improved fuel cycle economics, increased performance and flexibility in operation while maintaining or improving the superior reliability of GNF2. GNF3 has been designed to improve critical power ratio and operational flexibility. In addition, GNF3 is designed and manufactured to be even more resistant to debris capture than GNF2, to mitigate channel – control blade interference concerns with NSF (Zirconium alloy with Niobium, Tin, and Iron) channel materials, and to exhibit proven corrosion resistance. While delivering fuel cycle savings and reliability benefits with GNF3, GNF maintains a similar licensing and operating basis to GNF2, thereby minimizing fuel transition risks for utility customers. GNF3 has been designed for channeled shipping, saving refuel floor costs and dose.

GNF3 Product Description

The general GNF3 product description is provided below:

- Optimized short and long part length rod configuration.
- More Uranium mass per bundle.
- Increased fuel rod length (otherwise the fuel rod is the same as GNF2).
- Improved Alloy X-750 grid spacer with flow wings that exhibits substantial increases in mechanical durability in shipping and handling, along with a simplified robust spring and stop design. The GNF3 spacer has fewer potential debris capture locations.
- Channel designed for reduced absorptions in zircaloy.
- Standard NSF Channel material – the leading industry solution to channel/control blade interference.

GNF3 Fuel Design Features

The following is a description of the key GNF3 design features.

Fuel Rod Design

The GNF3 fuel rod is based on the high energy GNF2 fuel rod. GNF3 fuel rods provide improved performance at high exposures and provide flexibility in operating limits to promote enhanced fuel utilization.

GNF3 Spacer Design

The GNF3 spacer is very similar to the GNF2 spacer design. The GNF3 spacer, like the GE12 & GNF2 spacers, is made entirely of Alloy X-750 and contains integrated springs and stops. The spacer spring configuration has been re-designed in the GNF3 spacer to improve spacer fatigue and seismic durability and a deflection-limiting emboss feature was introduced to prevent plastic deformation of the spring during manufacturing, testing, and/or shipping. Based on operational experience with GNF2, the spacer parts were also modified to reduce debris capture sites. Continued use of an Alloy X-750 material assures potential hydrogen embrittlement and growth is minimal which is desirable for spacer reliability and bundle disassembly at higher exposures.

GNF3 Upper Tie Plate (UTP)

The GNF3 Upper Tie Plate design is a web and boss design similar to the GNF2 UTP design, and is designed consistent with the partial length rod

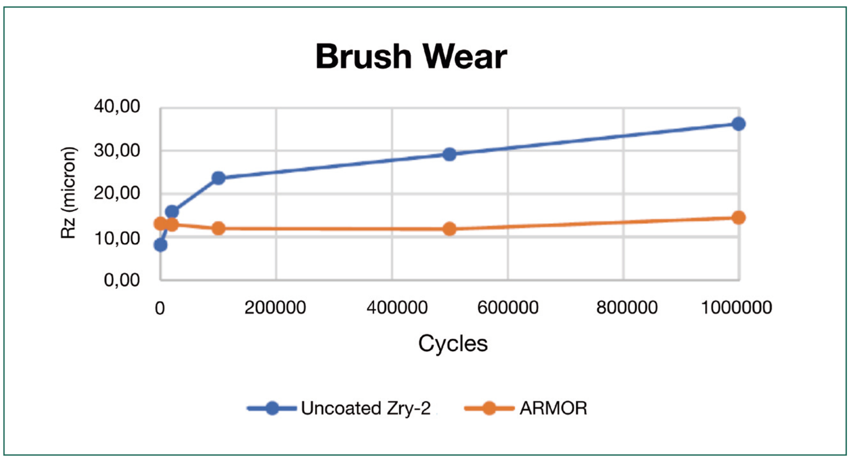

Figure 4. ARMOR Wear Resistance (Sliding Contact).

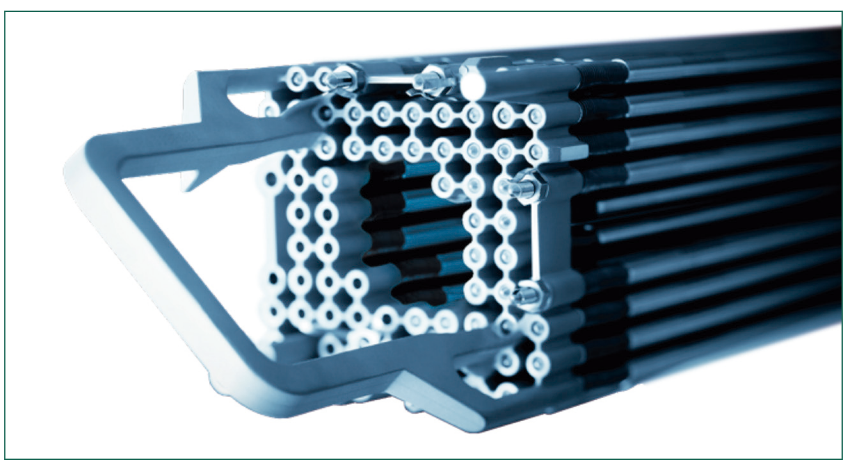

Figure 5. GNF3

locations to minimize the flow resistance at the assembly exit. The GNF3 UTP has been reduced in height to accommodate the longer fuel rod length, but the overall length of the GNF3 assembly is the same as GNF2.

GNF Debris Resistant Lower Tie Plates

GNF-designed fuel products feature advanced debris filters. Debris filters are used across the industry to reduce the likelihood of fuel failure via fretting against the fuel rod. In this part of the fuel assembly the critical design elements are effective debris filtration while maintaining hydraulic performance. Defender™ PLUS, the most advanced filter, is the standard option for GNF3. Currently there are new designs under development with improved filtering effectiveness which are expected to be deployed starting 2021.

Channel Assembly

The GNF3 channel assembly design has been improved and two channel thickness options are available. The channels were designed to provide nearly equivalent mechanical performance when compared to the current GNF2 contoured channel designs and reduce absorptions in zircaloy for reduced fuel cost.

GNF3 standard channels will be fabricated from NSF material. NSF has demonstrated improved resistance to both fluence gradient-induced and shadow corrosion-induced bow while maintaining excellent corrosion resistance and is now a preferred channel material for mitigation of channel distortion. NSF has been approved by the USNRC and the experience base in the fleet exceeds 8,500 channels as of fall 2019.

GNF3 Improved Economics

GNF3's advanced design features and industry-leading GNF core designs seek to lower reload costs by requiring fewer bundles, less uranium, and/or lower enrichment costs for the same energy output.

The GNF3 bundle is designed to improve critical power ratio, resulting in the ability to design to higher bundle powers which enables reduced fuel costs and improved fuel cycle economics. GNF3's advanced spacer design improved the mechanical structure of the bundle for ease of manufacturing, reduced debris entrapment opportunities and enabled the potential to ship in the pre-channeled configuration. Pre-channeled fuel shipments save utilities on refuel floor operation and maintenance costs and worker dose.

GNF3 Enhanced Operating Performance

Arguably one of the most significant fuel performance issues in the BWR fleet is channel-control blade interference which is largely attributed to a channel bow mechanism. GNF3 comes standard with GNF's channel bow resistant material, NSF (Zirconium alloy with Niobium, Tin, and Iron). GNF3 with standard NSF channels offers channel-control blade interference resistance enabling utilities to reduce inspections and minimize or eliminate re-channeling.

GNF3 coupled with GNF's power maneuvering guidelines offers the highest fuel reliability product in the industry with little to no impact on capacity factor.

GNF3 Excellence in Fuel Reliability

Another significant fuel performance issue for the BWR fleet is debris induced cladding perforation. The GNF3 product offers improved fuel reliability, deploying the latest debris resistant filter technology, Defender™ PLUS, and design improvements reducing susceptibility to trapped debris in its advanced spacer. The advanced lower tie plate debris filter further decreases the size of debris that can enter the bundle. Coupled with the increased debris capture-resistant advanced spacer design, the features together reduce the risk of in-reactor fuel cladding perforations.

A key advantage of GNF3 fuel is that it is built on about two decades of experience with 10x10 bundle designs. These designs have operated in the entire spectrum of BWR conditions including annual cycles, 18 month cycles, 24 month cycles, residence times at discharge from nominally 4 years to 8 years, a large range of power densities, wide range of nuclear designs (enrichment and Gad concentration), and virtually every BWR water chemistry environment, from Normal Water Chemistry (NWC) through On-Line Noble Chemistry (OLNC) and in ultra-low as well as higher feedwater metals (crud) environments.

Industry Challenges	GNF2 Legacy	GNF3 Prediction
PCI (Pellet Cladding Interaction) failures	**Improved relative to GE14**	Same 10x10 fuel rod design and fuel operating guidelines maintain "barrier" protection
Corrosion failures	**ZERO**	**Zero** ... same corrosion resistant cladding, proven in every BWR water chemistry environment
Fuel shadow corrosion failures	**ZERO**	**Zero** ... same corrosion resistant cladding, proven in every BWR water chemistry environment
Dryout failures	**ZERO**	**Zero**
Manufacturing defect-induced failures	**ZERO**	**Zero** ... continued excellence in bundle fabrication with same component & rod processes
Structural failures	**ZERO**	**Zero** ... same robust, 100% redundant fuel bundle structure (no single point of failure ... weight supported by 8 tie-rods)
Debris failures	~30% reduction from GE14	Improved resistance ... eliminated potential debris capture sites in spacers. Defender™ PLUS debris filter is the standard option for GNF3.
Channel distortion (bow)	Issues with current materials & certain plant configurations	Nearly **zero** monitoring / no shadow bow distortions ... NSF channels standard on GNF3

Table 2. Response to Industry Challenges.

GNF3 is designed to offer substantial fuel cycle savings and reliability benefits while minimizing fuel transition risks.

GNF3 Fuel Design Performance Characteristics

Nuclear Design

A wide range of nuclear design options are available with GNF3. Owing to the high power producing capability of the GNF3 fuel assembly, GNF3 nuclear designs can be developed that focus primarily on fuel efficiency.

Exposure Capability

Just as with GNF2 fuel designs, GNF3 has been designed mechanically to support operation up to 80 GWd/MTU peak pellet exposure to be applied when licensing authorizations are obtained. In designing GNF3, every component was developed to conform to key high exposure considerations.

OPERATING EXPERIENCE

The first IronClad and ARMOR lead test assemblies (LTAs) were loaded into the Edwin I. Hatch Nuclear Plant - Unit 1 in spring of 2018 and are currently operating normally as the end of their first 2-year cycle is approaching. The second IronClad and ARMOR LTAs were loaded into the Clinton - Unit 1 Nuclear Power Plant in Fall 2019 and are also operating normally early in the beginning of their first cycle. In the coming years, additional LTA insertions are being considered. One purpose of the LTA programs is to obtain irradiated material for post-irradiation examination and testing to characterize material properties and performance, and to support alloy or coating optimization and development of fuel rod design for potential reload application. Poolside surveillance is planned throughout the irradiation period and selected harvesting of segments for laboratory examination is also planned. Collectively, the IronClad and ARMOR LTAs will provide integral rod data to support reload licensing activities.

GNF3 has been delivered in Lead Use Assembly (LUA) quantities since 2015 and reload quantities since 2018: there are two reloads in operation, beginning in spring 2019 outages; three more reloads are being delivered and will start operation in spring 2020.

CONCLUSIONS

Two potential solutions, IronClad and ARMOR, which offer enhanced ATF benefits have been developed to the extent necessary for LTA deployment. IronClad and ARMOR LTAs containing respective rods and started operation at HNP-1 in spring of 2018. The operational experience of the LTAs and the potential PIE and testing of irradiated LTR materials, coupled with continued laboratory testing are expected to bridge data gaps and support licensing and future deployment of the ATF solutions on a full reload basis. As ARMOR can be considered a variation of normal fuel cladding evolution, its time horizon is necessarily closer than IronClad.

GNF3 is an evolutionary change with optimized design features yielding improved fuel utilization and performance. Fuel cycle analyses have indicated significant design flexibility and reductions in fuel requirements from the application of GNF3 over GNF2. The increased power producing capability, both bundle and axial, combine with the unequaled uranium loading to provide excellent fuel cycle economics.

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