PATH TOWARDS INDUSTRIALIZATION OF ENHANCED ACCIDENT TOLERANT FUEL

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ABSTRACT

This paper summarizes the development & deployment of Lead Test Assemblies of IronClad and ARMOR as fuel cladding concepts that provide enhanced accident tolerance as compared to conventional zirconium-based fuel cladding. IronClad is an iron-chromium-aluminum (FeCrAl) ferritic alloy that is the result of a broad industrial effort led by GE Global Research Center with partners from US national laboratories and universities as part of the US Department of Energy (DOE) effort on enhanced accident tolerance. ARMOR is a coating on Zircaloy that is Abrasion Resistant and More Oxidation Resistant relative to uncoated Zircaloy and has been developed by GNF and utility partners. This paper summarizes the development of IronClad and ARMOR, with emphasis on going from research/technology development to deployment as products for the nuclear industry that could be realized in the near term.

1. Introduction

As part of the continuous effort to improve fuel safety and performance, Global Nuclear Fuel (GNF) has been involved in technology development in areas such as Enhanced Accident Tolerant Fuel (EATF). GNF has been engaged since 2012 in the development of the iron-chromium-aluminum (FeCrAl), ferritic alloy concept as a robust, mid-term replacement for highly optimized zirconium-based cladding, working 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 [1-6]. 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.

These efforts have culminated in the insertion of two sets of Lead Test Assemblies (LTA's), one containing FeCrAl in product form, called IronClad, and one containing ARMOR Lead Test Rods (LTR), into the Edwin I. Hatch Nuclear Plant Unit 1 (HNP-1) Cycle 29 core during the spring 2018 refueling outage. Both sets are special variants of the GNF2 fuel design, containing full-length Lead Test Rods of the segmented rod design. This paper highlights the development of IronClad and ARMOR, with emphasis on going from research and development to the deployment of products in the form of LTAs.

2. IronClad Program Development

GE initiated its accident tolerant fuel (ATF) program in 2012 under the financial support of the US DOE. The GE project includes GE Global Research Center, GE Hitachi Nuclear, Global Nuclear Fuel, and several national laboratories including Oak Ridge National Laboratory (ORNL) and Idaho National Laboratory (INL). The GE ATF concept has been mainly focused on the development of iron-chromium-aluminum (FeCrAl) cladding for urania fuel.

DOE initially provided guidelines, timelines, and metrics for the ATF research [1, 2]. DOE envisioned a three-Phase program, of which Phase 1 was for Feasibility Studies (2013-2016), Phase 2 for Development and Qualification and Phase 3 for Commercialization. Currently, the GE ATF project is in the second year (2018) of Phase 2, and it is expected to continue for several more years. Phase 3, commercialization, begins consistent with the specific technology's time horizon.

The IronClad project started by investigating several candidate non-zirconium alloys, mainly focused on chromium containing ferritic steels [3]. Ferritic alloys are desirable for several technical reasons including 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 diminish the neutron penalty [4]. Currently, the focus is on the three alloys listed in Table 1 below. These 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 [5, 6]. Another evolving variant, FeCrAl ODS does not contain molybdenum, and relies on oxide dispersion strengthening for grain refinement and high temperature strength [7].

TABLE 1. Nominal Compositions of FeCrAl (in mass percent, balance is Fe).

Alloy	Cr	Al	Others
APMT	21	5	3Mo
C26M	12	6	2Mo + 0.05Y
FeCrAl ODS	12	6	0.5Ti + Zr +Y_2O_3 + Fe_2O_3

3. ARMOR Program Development

In parallel to the US DOE sponsored GE ATF effort, GNF has been developing fret resistant coatings as a solution for mitigating fuel failures resulting from debris fretting. Debris fretting is considered the principal failure mechanism affecting Boiling Water Reactor (BWR) fuel reliability – see e.g. Ref [8]. Developing a solution that mitigates debris fretting failures is therefore of high priority to GNF and the BWR fleet. A number of coating options on standard Zircaloy cladding have been investigated over the years, including, for example, FeCrAl-based coating. In more recent years, a proprietary coating has been identified that has good resistance to debris fretting without the chemical interaction that could take place between the underlying Zircaloy cladding and, for example, Fe(CrAl)-based coating under Loss-of-Coolant Accident (LOCA) relevant conditions.

Working directly with utility partners the ARMOR proprietary coating technology has been shown to not only provide fretting resistance but also provide improved oxidation resistance. The improved oxidation performance is reflected in terms of reduced corrosion under normal operation conditions and in terms of reduced interaction with steam, for example, under design basis accident conditions, i.e. providing ATF benefits compared with uncoated Zircaloy cladding. It is on account of the fret or abrasion resistance and the oxidation resistance that the coating is named ARMOR (Abrasion Resistant, More Oxidation Resistant).

4. IronClad Technology

4.1 Deployment plan for LTA

In the overall plan to introduce new technology, such as IronClad, on a reload asis, deployment of LTAs is a necessary intermediate step to acquire key technology performance data. The LTA deployment can serve multiple purposes, including ensuring manufacturing readiness or adequacy of the design in terms of sufficient material property data to enable analysis to confirm compliance with all licensing and fuel performance requirements.

Unlike introduction of a new variant of Zr-alloy based cladding, for which there is generally available a large body of properties information, established over decades of operational experience, on Zircaloy or Zr-alloy based cladding that could be used to provide corroborative information, introduction of a ferrous based cladding, such as the FeCrAl IronClad, must rely on newly generated material property information, especially under irradiated conditions.

4.2 Key properties

The main attribute for selection of FeCrAl IronClad is its unparalleled resistance to attack by air and steam at temperatures greater than 1200°C and approaching the melting temperature (severe accidents). This property of FeCrAl alloys has been known since the 1930s. The application of FeCrAl for cladding of nuclear fuel is a newer idea proposed by GE and ORNL in 2012 and is now being considered in several countries. In addition to its high temperature resistance to oxidation, the considered FeCrAl alloys have low general corrosion in environments typical of BWR and PWR operating reactors [6]. The use of FeCrAl cladding would also offer resistance to debris fretting and eliminate the occurrence of shadow corrosion. There are two properties that may be less desirable than in zirconium alloys, namely (i) higher neutron absorption and (ii) hydrogen/tritium permeability.

In order to utilize the benefit of the FeCrAl IronClad, a fuel rod must be designed to ensure compatibility with existing operational power reactors and meet the necessary evaluation and licensing requirements. A key area of interest is in ensuring that the fuel rod can comply with Specified Acceptable Fuel Design Limits (SAFDLs) when fully evaluated relative to thermal-mechanical requirements.

4.3 Material Properties

Material properties are the key input to many evaluations necessary to support the design and insertion of LTAs containing new cladding materials. For the FeCrAl-based IronClad, relevant material properties during irradiation are limited due to the nascent state of development for use in BWR, or more generally, LWR applications. While some useful data are available for the FeCrAl family of alloys, properties are lacking for the exact composition and processing schedule (i.e. microstructure) for the specific GNF IronClad candidate alloys, C26M and APMT, and for the effects of irradiation under BWR conditions.

Properties needed for fuel rod design were evaluated relative to the performance and thermal-mechanical behavior of a BWR fuel rod during normal, steady state operation and normal transients. The properties have been classified into three categories, as being impactful, not impactful, or unclassified/unknown. Sources of material properties data include published open literature data, manufacturer's data sheets, along with GE's and GNF's own published or unpublished test results for unirradiated C26M and APMT [3, 9-21]. Extensive research by Oak Ridge National Laboratory (ORNL) over the last 5 years for alloys in the same family as C26M, i.e. C35M and C36M, as well as APMT, has been particularly helpful in establishing initial design inputs.

Table 2 summarizes the classification and status of some material properties required to support design and licensing of reload quantities of C26M and APMT. None of the properties can be considered as being sufficient for detailed thermal-mechanical evaluations. Unirradiated mechanical property is the most available, but is still considered incomplete. Other properties are less available and considered limited, scant or lacking, in decreasing order of data availability.

Sufficient information is available to design and operate a limited number of LTRs in LTAs, but significant gaps are apparent in the context of complete understanding and description of how C26M and APMT will perform in a BWR environment. While the gaps, as indicated in Table 2, may appear large now, planned ex-reactor testing over the next two years, coupled with poolside and hotcell examination of the first LTRs after one or more irradiation cycle(s), will go very far towards closing them.

Table 2: Status of Material Properties for Design and Licensing of IronClad ATF Alloys in Reload Quantities

Property	Impactful	Not impactful	Unclassified	Data Source [3, 9-21]	Status
Mechanical properties (UTS, YS, E, n)	X			ORNL, GE, GNF, Sandvik	significantly insufficient
Fracture toughness	X			Sandvik	scant
Thermo-physical (e.g. density, conductivity, expansion)	X	X		ORNL, Sandvik	limited
Creep	X			ORNL, Sandvik	scant
Irradiation growth and swelling	X			ORNL	scant
Aqueous corrosion		X		GE, ORNL	limited
Other (wear, PCI, SCC, crud deposition)			X	N/A	lacking

The key properties discussed above 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. Testing to evaluate the material grain size and microstructure was conducted to help characterize the supporting material structure for the measured properties. While the standard material chemistry and room temperature mechanical properties were evaluated, additional mechanical tensile testing at different temperatures and strain rates was also used to provide data input at selected design conditions. Non-destructive testing was also used as part of the material validation process to validate that the material does not contain detrimental flaws. Additional destructive testing/ evaluation was also considered for some of the material processing steps.

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. Additionally, there are specific requirements for the transportation of nuclear fuel. Since the IronClad alloy is based on ferritic stainless steel, consideration should be given to the ductile-to-brittle transition at low temperatures postulated by the hypothetical accident conditions during transportation. These considerations also play a factor in determining the required material testing for accepting the IronClad material for use. The accident conditions during transport required by the 10 CFR 71 performance requirements include hypothetical accident conditions of a 9 meter (30 ft) drop at -40°C (-40°F) and a 3 meter (10 ft) drop at -20°C (-4°F).

4.4 Special considerations for LTA

The introduction of a new cladding material requires assessment and modification of Thermal-Mechanical (T-M) licensing method and the parameters that impact fuel design licensing limits. Modification to GNF’s T-M code, PRIME03 [22] is required to assure that adequate simulation of the new material mechanical properties and compliance with T-M SAFDLs are satisfied, including fuel temperature, cladding strain and rod internal pressure. In addition, the impact on downstream analyses, including LOCA and stability analysis, must also be assessed. GNF’s fuel rod Thermal-Mechanical code PRIME03 has been updated for application to the FeCrAl IronClad cladding material properties and thermal-mechanical analyses have been performed to confirm that compliance with SAFDLs is satisfied for IronClad. All verification testing performed demonstrated compliance with fuel temperature, cladding strain and rod internal pressure, including consideration of uncertainties.

The IronClad LTAs contain unfueled LTRs. T-M Analysis for unfueled IronClad LTRs included cladding creep collapse analysis since there is no pellet support for the unfueled segments, which would be otherwise accounted for as part of creep collapse analyses for fueled segments. Although the concern with creep collapse of unfueled segments is minimal, it is still assessed to assure that Post-Irradiation Examination (PIE) test plans and future irradiation plans for these segments are not compromised because of any excessive ovality increase due to creep collapse. The calculation was performed with a model accounting for tube initial ovality and the increase of ovality with time due to creep. In situations where creep collapse occurs, the ovality increases with time; the increase becomes very nonlinear as the ovality increases. At some value of ovality, the tube becomes elastically unstable, such that application and removal of a small instantaneous overpressure results in permanent ovality increase. That behavior is taken as creep collapse.

An unfueled IronClad tube with 0.4 mm (15.7 mil) nominal wall thickness with initial ovality of 0.019 mm (0.75 mil) was analyzed for creep collapse. The analytical calculation used the FeCrAl elastic modulus and FeCrAl creep relation based upon the models provided in References [17, 20]. Rod internal pressure was assumed to be at 1 atmosphere and external pressure was assumed to be 7.24 MPa (1050 psi) at 350 °C. The calculation results demonstrated that creep collapse did not occur at the end of 8 years. Figure 1 below shows Ovality vs. Time for the FeCrAl IronClad unfueled segment. There is no rapid ovality acceleration, which indicates that creep collapse does not occur.

Creep collapse analysis results were independently verified with an ANSYS calculation; the ANSYS results confirmed that creep collapse did not occur. Figure 2 shows ANSYS results indicating that there is almost no ovality change at the end of 8 years.

The methodology used for IronClad creep collapse calculation for unfueled segments was confirmed experimentally in high pressure autoclave tests performed at GRC. Tests were performed on IronClad tubes at 20.7 MPa (3000 psi) at 350°C in normal BWR water environment for 120 hours. The test was performed in an autoclave using tubing with welded end plugs having an internal pressure of 1 atmosphere to determine if they could withstand buckling under the severe test conditions above. Non-destructive measurements were made before and after the autoclave exposure to determine relative deformation of the tubing and propagation of any pre-existing weld flaws. Test results are summarized in Table 3 below, together with the analytical calculation results. The test results confirmed that IronClad tubes did not collapse at the end of the experiment.

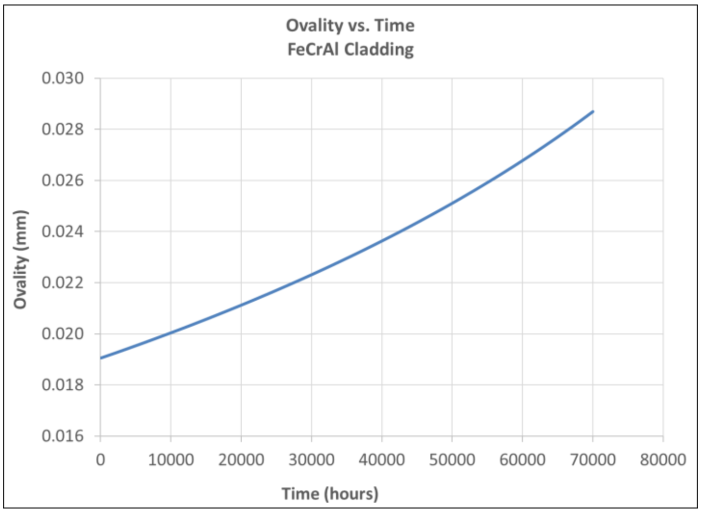

Figure 1. FeCrAl IronClad Ovality Increase over 8 years

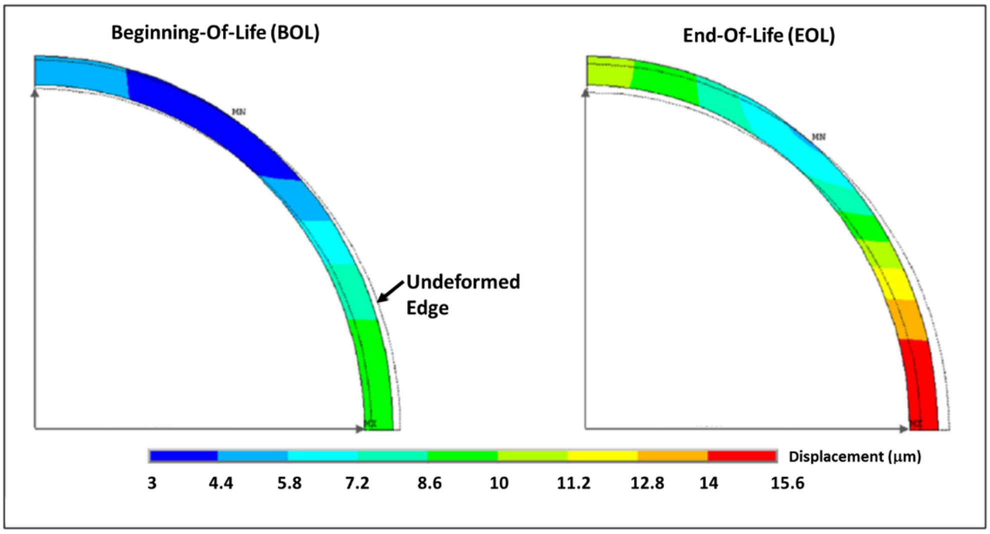

Figure 2. ANSYS results for FeCrAl IronClad Cladding Displacement at Beginning-of-Life (BOL) (left) and End-Of-Life (EOL) (right)

Table 3. Test Conditions for FeCrAl GRC Test and Analytical Calculations

Case	Outside Pressure, MPa(PSI)	Temperature (°C)	Cladding Wall Thickness, mm (mil)	Rod Internal Pressure MPa (atm)	Time	Cladding Initial Ovality mm (mil)	Change in Ovality mm (mil)
Analytical	7.24	350	0.4 (15.7)	0.101 (1)	8 yrs	0.019	~0.01 (0.4)

calculation 1	(1050)					(0.75)	
Analytical calculation 2	20.7 (3000)	350	0.4 (15.7)	0.101 (1)	120 hrs	0.019 (0.75)	~0
GRC Test	20.7 (3000)	350	0.4 (15.7)	0.101 (1)	120 hrs	0.019 (0.75)	Not detected

5. ARMOR Technology

5.1 Key attributes

ARMOR stands for “Abrasion Resistant, More Oxidation Resistant”. ARMOR is a thin, 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 following sections, 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 has been shown through testing to be very adherent. When taken to an extreme hoop strain of up to ~30%, the coating remained adherent to the Zircaloy cladding, despite cracking of the coating, and there was no coating loss. The coating is thermally compatible with the underlying Zircaloy cladding, as demonstrated through repeated thermal cycling between 350°C and a water quench without causing cracking or delamination of the coating. Since the coating offers protection against debris fretting, the coating is harder than the Zircaloy cladding being protected. However, it has a low risk of becoming significant debris source, should the coating become detached from the cladding, since the coating is very thin and will be difficult to be trapped and the impact energy at the impact point will be small.

5.2 Fret performance

Stray wires from steel wire brushes are considered a likely cause of fret failure in BWR fuel rods. To evaluate the resistance of ARMOR-coated Zircaloy-2 tubes against stainless steel, a wear test at room temperature was designed in which tubes are subjected to cyclical contact with stainless steel wire agitators. Figure 3 shows a schematic of the fret test setup. Circles represent tubes oriented so that the tube's central axis is normal to the page. Stainless-steel wires are arranged along the top and sides, and collectively move in the vertical direction. With the test configuration, tubes on the side underwent a sliding contact, and the top tubes underwent impingement with the steel wires.

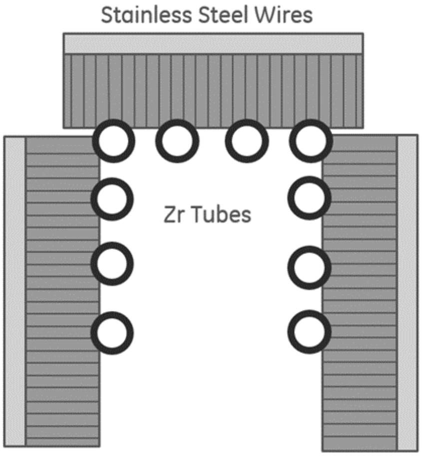

Figure 3. Fret Wear Test Setup.

At regular intervals, the degree of wear was measured through a digital imaging (Keyence) system. Wear was assessed by determining the surface roughness (R_a) and the depth (R_z) parameter, which is considered more informative regarding wear performance.

The wear depth (R_z) results for brushing contact are shown in Figure 4. The figure 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. The fret tests thus provide confirmation of the wear performance expected of a hard coating. The results are, however, qualitative in nature, in part because fuel rod fret failures are stochastic; the presence of debris, capture of debris, size of debris, contact force, and vibrational frequencies are all highly variable and not well defined.

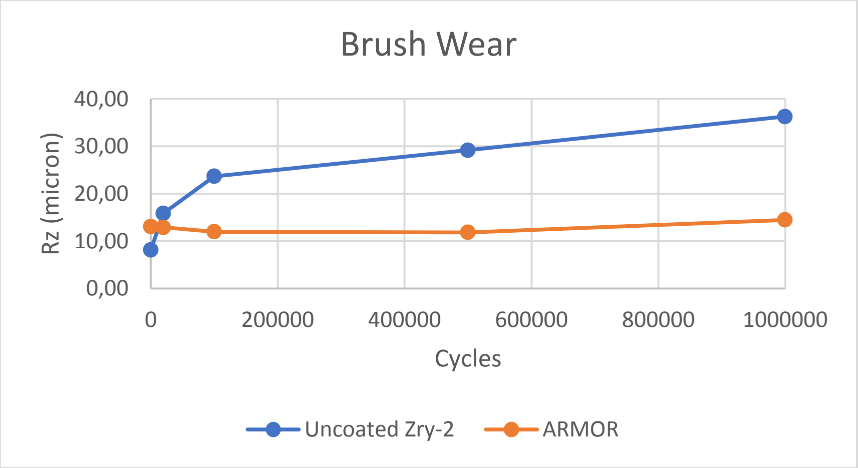

Figure 4. ARMOR Wear Resistance (Sliding Contact)

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5.3 Corrosion

ARMOR coated Zircaloy-2 performed well after GNF's routine corrosion tests. Two types of tests were conducted. The first is the ASTM G2 test conducted at 400°C in steam at 10.3 MPa for 72 hours. The second is a two-stage test, first at 410 °C for 4 hours, followed by 520 °C for 16 hours, both at 12 MPa in steam, used by GNF for nodular corrosion testing.

These tests showed significant difference between uncoated and ARMOR coated Zircaloy-2. Without the coating, a black, adherent oxide typically forms on the OD surface of the Zircaloy-2 tubes after these tests. With ARMOR, the shiny, silvery appearance of the pre-test sample is maintained after these tests. An example of the surface appearance after G2 testing is shown in Figure 5. Examination of the cross-sections after these tests showed no indications of oxide (ZrO_2) formation at the coating/Zircloy-2 interface, indicating that the ARMOR coating is protective against corrosion of the underlying cladding under these test conditions, which are already higher than typical operational temperatures.

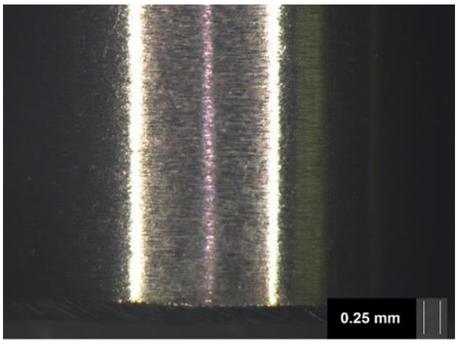

Figure 5. ARMOR coated Zircaloy-2 after G2 testing

ARMOR coated samples were also subjected to repeated G2 testing as a means of assessing longer term corrosion performance and durability. Figure 6 shows the weight gain per unit surface area of Zircaloy-2 with two-side ARMOR coating after several cycles of G2 corrosion testing. For reference, the typical weight gain for an uncoated Zircaloy-2 tube is also shown. The results in Figure 6 shows that weight gain with coating, as an indication corrosion of the underlying Zircaloy-2, was significantly lower than without coating after one cycle of testing, consistent with the visual and metallographic results discussed above. Importantly, the low weight gain is maintained with additional testing cycles, indicating the retention of the protective nature of the ARMOR coating.

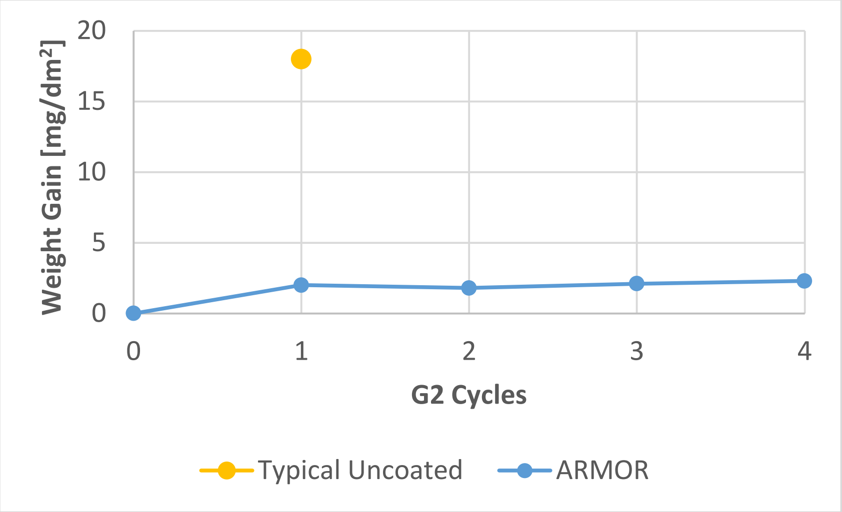

Figure 6. Weight Gain of ARMOR coated and uncoated Zircaloy-2 after repeated G2 testing

5.4 Oxidation

ARMOR coated Zircaloy-2 was tested under LOCA relevant (design basis) conditions. Oxidation tests in flowing steam were conducted in temperatures up to 1200 ^{o}C. Figure 7 shows a comparison of the ARMOR-coated outer surface region with the uncoated inner surface region following testing in steam at 1000 ^{o}C for 5000 s. The test condition is equivalent to 23% Equivalent Clad Reacted (ECR) based on the Cathcart-Powell 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 (between red arrows in the right part of Figure 7) 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 surface region showed reduced extent of reaction, in between the red arrows in the left part of Figure 7. 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.

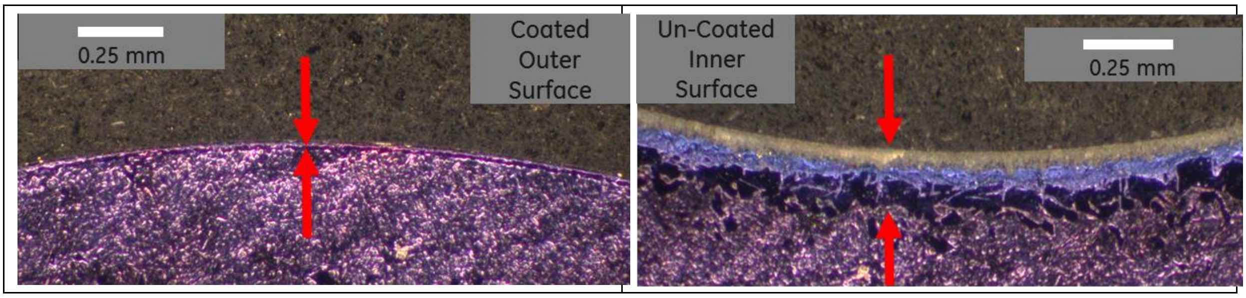

Figure 7. Comparison of ARMOR-coated outer surface region (left) and un-coated inner surface region after 5000 s steam oxidation at 1000 ^{o}C. Arrows indicate the extent of reacted layer for each region.

6. LTAs

6.1 LTA Description

Based on the foregoing discussions, sufficient information is available to design and operate a limited number of IronClad LTRs in LTAs. For ARMOR, the underlying Zircaloy-2 cladding is unchanged, and the coating does not result in significant changes to properties of the cladding; there is therefore sufficient basis for installing a limited number of ARMOR LTRs in LTAs.

Both the IronClad and ARMOR sets of LTAs are special variants of the GNF2 fuel design, a design with proven fuel performance [see e.g. 8]. Each set of LTAs contains full-length LTRs. Each LTR is made up from shorter segments. The ARMOR LTA's contained fueled coated rods. The FeCrAl IronClad LTA's contain unfueled rod segments made from C26M and connecting components from APMT.

6.2 LTA Operation

The IronClad and ARMOR LTAs were loaded into the Edwin I. Hatch Nuclear Plant - Unit 1 in spring of 2018 in Reload 28 to be operated starting in Cycle 29. The LTAs were loaded into core locations, as shown in Figure 8, that are projected to be non-limiting with respect to core operating limits. However, the LTAs and their operation have been designed to ensure adequate exposure, or fluence, is achieved so that the objectives of the LTA program are met.

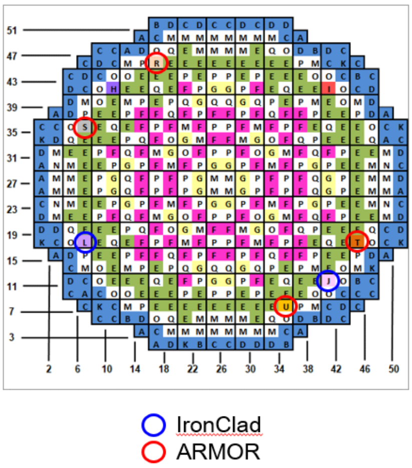

Figure 8. Core locations for the LTAs in Cycle 29 of HNP-1

One purpose of the LTA program 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 expected. The frequency and extent of these surveillances and rod removal evolutions will be determined by the operational constraints at the station as determined by the utility and the evolving goals of the DOE's ATF program.

6.3 Future Plans

IronClad: The leading alloy variants have been selected and are undergoing irradiation in commercial reactor conditions in product form. The significant data that are expected to be obtained starting in 2020 will form the basis for irradiated material performance specific to operation in a commercial BWR. In the coming years, additional LTA insertions are planned with fueled LTRs that will provide integral data (e.g. Fuel Cladding Chemical Interaction) to supplement the constituent cladding data deriving from the first installation. Poolside and hot cell examination of the LTRs is to be initiated as soon as material is discharged. In parallel, it is anticipated that irradiated material properties data obtained from various test reactor irradiations (e.g. ATR, HFIR) will be assessed and the thermal mechanical methods encoded into PRIME03 assessed. Also, fuel assembly design is planned to ascertain if further reductions in fuel requirements (i.e., front end fuel cost) are possible. History has shown that fuel costs have continuously reduced through the fuel design and new production introduction process. Also, plant performance and safety analysis is planned to better describe how the safety attributes of the fuel manifest themselves in the overall evaluated safety of the power plant. This work will enable the industry to perform a broad-based evaluation of the IronClad technology for application in a competitive electricity market and underpin regulatory approvals.

ARMOR: As ARMOR can be considered a variation of normal fuel cladding evolution, its time horizon is necessarily closer than IronClad. In the coming years, out-of-pile engineering tests are expected to be completed while the early LTRs are undergoing irradiation to affirm performance. Poolside and hot cell surveillances are anticipated to be performed as required. A particular focus will be enabling the manufacturing equipment readiness for production of coated fuel rods that conform to the expectations for accident tolerance. It is envisioned that ARMOR coated fuel can be deployed in advance of regulatory recognition of the safety benefit. Considering mixed core configurations, it is desirable to deploy the accident tolerant hardware as soon as possible to achieve the debris fret protection and transition cores to a higher degree of safety as regulatory processes evolve. It is anticipated that ARMOR coated ATF fuel will be available for production within a few years.

7. Summary

Two potential solutions, IronClad and ARMOR, that offer enhanced ATF benefits have been developed to the extent necessary for LTA deployment. Both types of LTAs contain the respective LTRs and started operation at HNP-1 in spring of 2018. This paper discussed the key developments leading to the deployment of the LTAs. For IronClad, availability of material property data limited the LTRs to be unfueled. For ARMOR, sufficient information justified the deployment of fueled LTRs. 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.

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