UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

March 29, 2019

Ms. Michelle P. Catts
Senior Vice President, Regulatory Affairs
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Wilmington, NC 28401

SUBJECT: FINAL SAFETY EVALUATION FOR LICENSING TOPICAL REPORT NEDC-33353P, "LICENSING TOPICAL REPORT APPLICATION OF GNF-ZIRON TO GNF FUEL DESIGNS" (EPID: L-2010-TOP-0003)

Dear Ms. Catts:

By letter dated December 22, 2010 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML103560845), Global Nuclear Fuel – Americas, LLC (GNF) submitted Topical Report (TR) NEDC-33353P and NEDO-33353, "Licensing Topical Report Application of GNF-Ziron to GNF Fuel Designs," to the U.S. Nuclear Regulatory Commission (NRC) staff for review.

By letter dated August 16, 2018, an NRC draft safety evaluation (SE) regarding our approval of NEDC-33353P and NEDO-33353, "Licensing Topical Report Application of GNF-Ziron to GNF Fuel Designs," was provided for your review and comment (ADAMS Accession No. ML18166A101). By letter dated December 5, 2018, GNF provided comments on the draft SE (ADAMS Accession No. ML18339A003). The NRC staff's disposition of the GNF comments on the draft SE are discussed in the attachment to the publicly available version final SE enclosed with this letter.

The NRC staff has found that TR NEDC-33353P is acceptable for referencing in licensing applications for nuclear power plants to the extent specified and under the limitations delineated in the TR and in the enclosed final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in licensing applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that GNF publish approved proprietary and non-proprietary versions of TR NEDC-33353P, within three months of receipt of this letter. The approved versions shall incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information (RAIs) and your responses. The approved versions shall include a "-A" (designating approved) following the TR identification symbol.

As an alternative to including the RAIs and RAI responses behind the title page, if changes to the TR were provided to the NRC staff to support the resolution of RAI responses, and the NRC staff reviewed and approved those changes as described in the RAI responses, there are two ways that the accepted version can capture the RAIs:

1. The RAIs and RAI responses can be included as an Appendix to the accepted version.
2. The RAIs and RAI responses can be captured in the form of a table (inserted after the final SE) which summarizes the changes as shown in the approved version of the TR. The table should reference the specific RAIs and RAI responses which resulted in any changes, as shown in the accepted version of the TR.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, GNF will be expected to revise the TR appropriately or justify its continued applicability for subsequent referencing. Licensees referencing this TR would be expected to justify its continued applicability or evaluate their plant using the revised TR.

Sincerely,

/RA/

Dennis C. Morey, Chief
Licensing Processes Branch
Division of Licensing Projects
Office of Nuclear Reactor Regulation

Project No. 99901376

Enclosure:
Final SE (Non-Proprietary)

SUBJECT: FINAL SAFETY EVALUATION FOR LICENSING TOPICAL REPORT NEDC-33353P, “LICENSING TOPICAL REPORT APPLICATION OF GNF-ZIRON TO GNF FUEL DESIGNS” (EPID: L-2010-TOP-0003) DATE: MARCH 29, 2019

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OFFICE OF NUCLEAR REACTOR REGULATION

DIVISION OF SAFETY SYSTEMS

SAFETY EVALUATION FOR GLOBAL NUCLEAR FUEL

LICENSING TOPICAL REPORT

NEDC-33353P REVISION 0, LICENSING TOPICAL REPORT

APPLICATION OF GNF-ZIRON TO GNF FUEL DESIGNS

1.0 INTRODUCTION AND BACKGROUND

By application dated December 22, 2010, Global Nuclear Fuel (GNF) submitted Licensing Topical Report (LTR) NEDC-33353P (NEDO-33353) Revision 0, "Licensing Topical Report Application of GNF-Ziron to GNF Fuel Designs" (Ref. 1) to the U.S. Nuclear Regulatory Commission (NRC) for review and approval. Additional information in response to a request (Ref. 2) was received by the NRC in letter dated October 23, 2015 (Ref. 3).

This report provides the licensing basis for the GNF-A (GNF) advanced cladding and structural material designated Ziron and requests full batch implementation of this material up to the currently approved rod-average burnup levels for their fuel designs for boiling water reactor (BWR) plants. GNF proposes to use Ziron for the fuel cladding (and endplugs), water rods (tubing and fittings), and spacer grids (ferrules and strip). GNF has produced and is currently testing BWR fuel channels composed of Ziron, however, in a response to a subsequent request for additional information (RAI), GNF has withdrawn the application of Ziron for channel use from the LTR in favor of an alternate Zr alloy, NSF.

The primary difference between the traditional Zircaloy-2 cladding currently used and Ziron is **[** **]**. The thermo-mechanical processing for Ziron is the same as for Zircaloy-2, which means that Ziron will have **[** **]** nominal mean second phase particle (SPP) size.

Pacific Northwest National Laboratory (PNNL) has acted as a consultant to the NRC in this review. As a result of the reviews of the LTR by NRC staff and their PNNL consultants, a list of questions was prepared and sent by the NRC to GNF as an RAI. GNF responded to the RAI questions in Reference 3. PNNL submitted a technical evaluation report to the NRC on the results of their review (Ref. 4).

Nuclear Performance and Code Review branch (SNPB) of the office of Nuclear Reactor Regulation has completed its review of the GNF-Ziron LTR. Following is the safety evaluation (SE) prepared by SNPB staff.

Enclosure

2.0 REGULATORY EVALUATION

Ziron was evaluated with respect to Section 4.2 of the Standard Review Plan (SRP NUREG-0800) which states that fuel system safety review must provide assurance that:

1. the fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs),

2. fuel system damage is never so severe as to prevent control rod insertion when it is required,

3. the number of fuel rod failures is not underestimated for postulated accidents, and

4. coolability is always maintained.

Evaluation criteria 1 listed above means fuel rods that do not fail, fuel system dimensions that remain within operational tolerances, and functional capabilities that are not reduced below those assumed in the safety analysis. This criteria is consistent with General Design Criteria (GDC) Title 10 of the *Code of Federal Regulation* (10 CFR) Part 50 Appendix A that states (Ref. 5)

> *The reactor core and associated coolant, control, and protection systems shall be designed with the appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.*

Evaluation criteria 3, "fuel rod failures," means that the fuel rod leaks and that the first fission product barrier (the cladding) has, therefore, been breached. Fuel rod failures must be accounted for in the dose analysis required by 10 CFR Part 100 (Ref. 6) for postulated accidents.

Coolable geometry means, in general, that the fuel assembly retains its rod-bundle geometrical configuration with adequate coolant channels to permit removal of residual heat for a design basis accident.

The general requirements to maintain control rod insertability and core coolability appear repeatedly in the GDC (e.g., GDC 27 and GDC 35). Specific coolability requirements for the LOCA are given in 10 CFR Part 50, Section 50.46 (Ref. 7).

GDC 27 states:

> *The reactivity control systems shall be designed to have a combined capability, in conjunction with poison addition by the emergency core cooling system, of reliably controlling reactivity changes to assure that under postulated accident conditions and with appropriate margin for stuck rods the capability to cool the core is maintained.*

GDC 35 states:

> *A system to provide abundant emergency core cooling shall be provided. The system safety function shall be to transfer heat from the reactor core following any loss of reactor coolant at a rate such that (1) fuel and clad damage that could interfere with continued effective core cooling is prevented and (2) clad metal-water reaction is limited to negligible amounts.*

In order to assure that the above stated objectives are met and follow the format of Section 4.2 of the Standard Review Plan (SRP, Ref. 7), Section 4.0 of this SE covers the following three major categories:

1) Fuel System Damage Mechanisms, which are most applicable to normal operation and AOOs (Section 4.1)

2) Fuel Rod Failure Mechanisms, which apply to normal operation, AOOs, and postulated accidents (Section 4.2)

3) Fuel Coolability, which are applied to postulated accidents (Section 4.3)

The GNF design criteria remain the same for fuel designs with Ziron as they are for Zircaloy-2. This SE provides a review as to whether adequate data has been provided for Ziron to demonstrate that GNF's fuel designs can operate satisfactorily up to the currently approved rod-average (and peak pellet exposure (PPE)) burnup levels (and corresponding fluences) as defined by the specified acceptable fuel design limits (SAFDLs) for normal operation, AOOs, and postulated accidents. In summary, the NRC staff has found Ziron to be an acceptable substitute for Zircaloy-2 in GNF BWR fuel designs up to the burnup, fluence, and time limits approved by the NRC.

3.0 TECHNICAL EVALUATION

3.1 ZIRON COMPOSITION AND MICROSTRUCTURE

GNF has developed a zirconium based alloy, GNF-Ziron in order to identify an alloy with thermal and mechanical properties equal to or exceeding those of Zircaloy-2 while improving the resistance of fuel components to in-service degradation effects in particular the effects due to absorbed corrosion-generated hydrogen. GNF-Ziron development focuses on its use for fuel assembly components in licensed GNF fuel designs which includes fuel rod cladding, water rods, fuel spacers, channels, and end plugs all of which have been currently manufactured using Zircaloy-2. This technical evaluation assess the material and mechanical performance of GNF-Ziron whether it meets relevant design bases for application to GNF fuel based on equivalency to other currently accepted fuel and assembly components.

3.1.1 GNF-Ziron Composition

The composition of Ziron is similar to that of the conventional Zircaloy-2 (UNS 60802), with the exception that the iron (Fe) content is elevated above the ASTM/UNS specifications. The composition of Ziron is compared in Table 1 with the compositions of Zircaloy-2 (from

ASTM B811) and GNF's controlled-chemistry (CC) version of Zircaloy-2. Traditionally, types of Zircaloy are fabricated near the mid-range for elements such as Sn and O, and toward the upper range for Fe. Over the decades, it has been discovered that Fe-content in the low end of the range contributes to poor corrosion performance.

Table 1 Comparison of Compositions of Zircaloy-2 (ASTM Standard), GNF CC Zircaloy-2, and Ziron (values in wt %)

Element	**ASTM**	**CC Zircaloy-2 Range <nominal>**	**Ziron Range <nominal>**
Sn	1.20-1.70	1.25-1.45 <1.35>	**[**
Fe	0.07-0.20	0.14-0.20 <0.17>	
Cr	0.05-0.15	0.05-0.15 <0.10>	
Ni	0.03-0.08	0.03-0.08 <0.05>	
O	0.09-0.15	0.10-0.14 <0.12>	**]**
Fe+Cr+Ni	0.18-0.38		-

Zircaloy-2 has an upper limit, 0.38 percent, on the sum of Fe+Cr+Ni, which is less than the sum (0.43%) of the upper limits of the three elements. Ziron does not have a range or upper limit on the sum of Fe+Cr+Ni, but based on the upper limits of the individual elements, the sum would have a maximum value of **[ ]** percent, with a nominal target of **[ ]** percent.

For the nominal composition of Ziron **[ ]**, the Zr mass fraction decreases from 0.9813 for Zircaloy-2 to **[ ]**, or a change of **[ ]** with corresponding atomic fractions changing from 0.9763 to **[ ]** (or a decrease of **[ ]**. More importantly, the mass fraction of the Zr+Sn portion is only slightly reduced from 0.9953 for Zircaloy-2 to **[ ]** for Ziron, or corresponding atomic fractions from 0.9870 to **[ ]**, respectively. These changes do not significantly impact the thermo-physical or mechanical properties of Ziron with respect to Zircaloy-2. At the upper limit of Fe content, the Zr+Sn mass and atomic fractions have only decreased by **[ ]** percent, which is not a significant change. The reported composition for HiFi (Fe-enhanced Zircaloy-2) has an Fe content of 0.4 wt%.

GNF is aware of potential manufacturing issues associated with higher iron levels. In US Patent 4810461 (Ref. 8), the inventors state "In order to obtain an appreciable effect, the Fe content should be at least 0.2 wt %. An Fe content exceeding 0.35 wt%, however, increases the neutron absorption cross section and degrades cold workability. The Fe content, therefore, should not exceed 0.35 wt%." This patent further states that the cold plastic workability is seriously reduced when the sum of Ni and Fe becomes 0.64 percent

NFI have demonstrated that even high Fe content (nominally 0.40% in the HiFi alloy derivative of Zircaloy-2) does not significantly change, or adversely affect, the properties of high-iron Zircaloy either in manufacturing or due to irradiation (Ref. 9).

The staff concludes that the **[ ]**, in Ziron is acceptable.

3.1.2 Microstructure

Particle size and distribution, in conjunction with surface finish, dislocation density and texture, has a profound influence on the corrosion (oxidation) behavior in an LWR environment. Section A.2 of the LTR states that the **[**

]

GNF describes the effect of heat treatment and composition in Section A.3.c of the LTR and the dispersion of the second phase particles (SPPs). The SPPs are formed because the solubility for alloying elements such as Fe, Cr, and Ni is very low below the solvus temperature of approximately 850° C. The distribution of SPPs affects primarily the corrosion characteristics of the zirconium alloy. SPP formation depends on the thermal treatment history. GNF provides a comparison of average SPP for Zircaloy-2 and Ziron **[**

]

In response to RAI 7b regarding fabrication specifications applied to texture and SPPs for GNF-Ziron, GNF provided further evidence of the **[**

]

The NRC staff concludes that the manufacturing process applied to Ziron produce an acceptable and satisfactory microstructure.

3.1.3 Texture

Texture refers to the anisotropic orientation of the crystals or grains in hexagonal close-packed (cubic) structure (hcp) material. Unlike face centered cubic (fcc) or body centered cubic (bcc) metals with their cubic crystal lattice structure, hcp grains have a long axis (c-axis or c-direction) and two shorter axes (a-direction) perpendicular to the c-axis. This results in a 'texture' of the material in which there is predominance in the orientation of the c-axis generally in the direction experiencing the greatest compressive stress during mechanical forming. Texture is important in the behavior of zirconium alloys, since during irradiation, the Zr-crystal structure shrinks in the c-axis and expands or grows in the a-direction, and creep and deformation are directionally dependent.

Figure A-2 of the LTR shows that the texture of Ziron **[**

] In response to RAI-7, GNF provides a comparison of textures (set of Kearns *f*-parameters) for Ziron and Zr-2 used in cladding, spacer strip and water rods. **[**

]

The staff reviewed the materials related to the texture of Ziron material and concludes that the texture of Ziron and Zircaloy-2 are **[** **]**.

3.2 ZIRON MATERIAL AND THERMAL PROPERTIES

This section will discuss the material properties that will be used for Ziron in various safety analyses. All of the properties that have been previously approved **[**
]. The staff will review the **[** **]**.

The Zircaloy-2/Ziron material properties addressed in this section are in general applicable to properties under normal operation and AOOs but some, such as thermal conductivity, thermal expansion, specific heat, α/β phase transformations, and emissivity up to fuel melting, are also applicable to design basis accidents. Other properties that are unique to accident conditions such as cladding rupture, ballooning, flow blockage, and high temperature oxidation will be addressed in Sections 3.4 and 3.5 of this SE. The Ziron properties in this section along with GNF analysis methodologies are used to demonstrate that GNF fuel designs meet the SAFDLs defined in Sections 3.3, 3.4, and 3.5 of this SE.

As noted earlier, the Ziron fuel cladding is different from Zircaloy-2 cladding in two respects:

1. **[** **]**
2. **[** **]**

Consideration given to the differences **[** **]** could potentially lead to differences in some material properties or behavior under irradiation. The microstructures of both Ziron and Zircaloy-2 components (fuel rod cladding, water rod tubing, endplugs and adapters, spacer ferrules and strip, and channels) are **[**

] depending on the component. Because the microstructure is **[**
] for some properties as would be the case **[**
]

For all of these material properties GNF claims that the properties of Ziron and Zircaloy-2 **[**

] for safety analyses is acceptable. It is true that when comparing the latest property measurements made by GNF, for both Ziron and Zircaloy-2, **[**

].

3.2.1 Specific Gravity (Density)

GNF has determined that the specific gravity of Ziron and Zircaloy-2 (and Zircaloy-4) is essentially unaffected by the [ ]. GNF notes that over the range of compositions allowed for Zircaloy-2 and Zircaloy-4, the industry standard, MATPRO, recommends the same density for all Zircaloy-2 and Zircaloy-4.

The NRC staff concludes that the GNF value for specific gravity is acceptable for Ziron licensing applications up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.2 Coefficient of Thermal Expansion

GNF has determined that the diametric thermal expansion of Ziron and Zircaloy-2 are essentially the same. Thermal expansion is used in stored energy estimates, loss-of-coolant accident (LOCA), rod pressure, fuel temperatures and cladding stress/strain analyses. Based on a review of the literature and the atomic fraction data provided in Table 1-2, the NRC staff concurs with GNF's assessment.

The NRC staff concludes that the GNF model for Zircaloy-2 thermal expansion is acceptable for Ziron licensing applications up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.3 Thermal Conductivity

GNF provided data from measurements of the thermal conductivity of Ziron for temperatures up to [ ] The data indicate that the thermal conductivity of Ziron [ ]. The staff compared the Ziron data with those reported from other sources, and found that Ziron data falls within the range of measurements of Zircaloy-2. The staff also compared the Ziron measurements with the PRIME model from NEDC-33256P, Rev. 0 (Eq. 3-23, Ref. 10) and found that the Ziron and Zircaloy-2 data fell below the curve, although the data fall within experimental uncertainty.

In addition, the current data has been compared against the thermal conductivity models proposed for licensing analyses (Appendix K and Best-Estimate) of GNF fuel designs with Ziron that show that both the GNF models are a reasonable representation of the data in some temperature ranges but not very good in others.

The NRC staff concludes that GNF's use of Zircaloy-2 thermal conductivity correlation in PRIME is acceptable for licensing applications up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.4 Specific Heat

Although no measurement data were provided, GNF has determined that the specific heat for both Zircaloy-2 and Ziron are very similar. Independent calculations performed by staff support this determination.

The NRC staff concludes that the GNF model for Zircaloy-2 specific heat is acceptable for Ziron licensing applications up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.5 Emissivity

Emissivity is important when high cladding temperatures are experienced in certain accident analyses such as LOCAs. GNF states that emissivity for Zircaloy-2 and Ziron depend on the oxide properties, and it is expected that the oxides are very similar, and therefore the emissivity is expected to be the same.

The staff concludes that the values used by GNF for emissivity of Zircaloy-2 (as oxidized) are acceptable for licensing applications with Ziron cladding up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.6 Tensile Strength

As described in Section 3.1.2 of this SE, the microstructure of both Ziron and Zircaloy-2 **[** **]** yield strength (YS) and ultimate tensile strength (UTS) as a function of irradiation and temperature. GNF has measured the UTS and YS of Ziron and Zircaloy-2 at room temperature, 25°C, and at elevated temperatures, **[** **]** (RAI-11). These measurements show that Ziron appears to have a **[** **]** content in the upper portion of the specified range (same range as that for Zircaloy-2) (Figures 3-1, 3-2, and 3-3 of the TER from PNNL staff). The **[** **]** would have the same effect on Zircaloy-2.

The NRC staff concludes that GNF's use of the PRIME correlations for yield strength and ultimate tensile strength of Zircaloy-2 for Ziron is acceptable for licensing and safety calculations involving Ziron components up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.7 Ductility

Cladding ductility needs to be retained to avoid brittle failures. Generally, irradiation damage and hydride formation (due to corrosion) have been found to decrease the ductility of zirconium alloys. The NRC does not have a specific minimum limit on cladding ductility; however, Section 4.2 of the SRP (Ref. 7) suggests a limit for total (elastic + plastic) cladding uniform strain of 1 percent that should not be exceeded during normal operation and AOOs. Therefore, the SRP would suggest a minimum total strain capability of at least 1% in order to prevent cladding failure below the 1 percent strain limit.

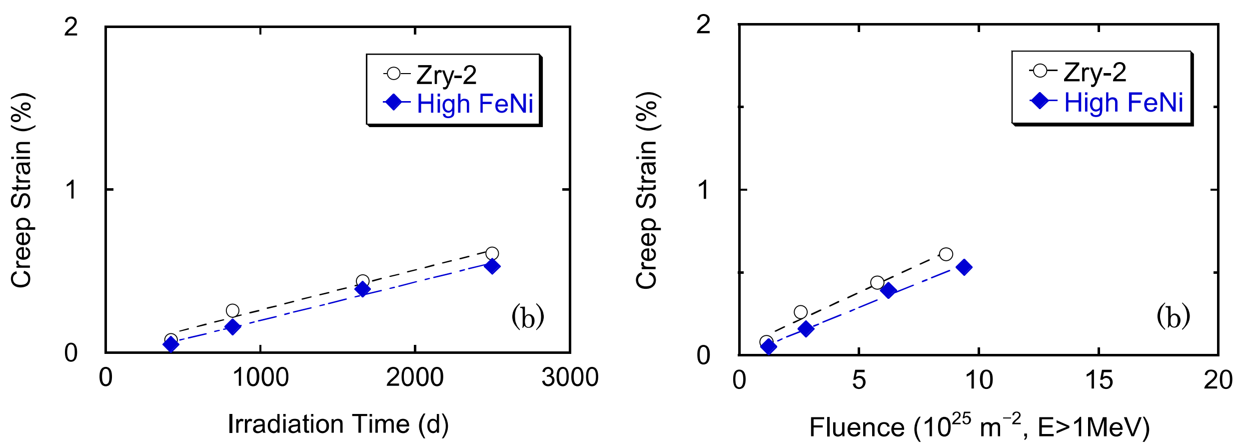
GNF has measured the total elongation of Ziron and Zircaloy-2 at room temperature 25ºC, and at elevated temperatures, **[ ]** (RAI-11). Figure 3-4 of the TER compares the total elongation for Ziron and Zircaloy-2 at room temperature and Figures 3-5 and 3-6 compare the total elongation for Ziron and Zircaloy-2 at elevated temperatures. The total elongation of unirradiated Ziron is **[ ]** at elevated temperature. As a function of irradiation, both alloys exhibit similar values of total elongation. However, at the highest fluences reported, Ziron shows a greater retention of ductility than Zircaloy-2.

The NRC staff concludes that the ductility of Ziron is equal to, or superior to, that of Zircaloy-2, and that the **[ ]** strain limit is acceptable for application to Ziron cladding in GNF fuel designs up to currently approved burnup levels. The improvement, or advantage of Ziron over Zircaloy-2, may be due to lower hydrogen content under the same irradiation conditions.

3.2.8 <u>Creep</u>

This section addresses cladding creep of Ziron during normal operation. Section 3.5 of the SE discusses high temperature thermal creep and rupture which are important for accidents such as LOCA.

The LTR (Ref. 1) provides creep data for closed cladding capsules pressurized to a cladding wall hoop stress of 150 MPa. Ishimoto et al (Refe. 12) report on cladding creep capsules pressurized to hoop stresses of 80 MPa (Zr-2 and Zr-high FeNi) and 150 MPa (Zr-2, Zr-2 high Fe, and Zr-2 high FeNi).



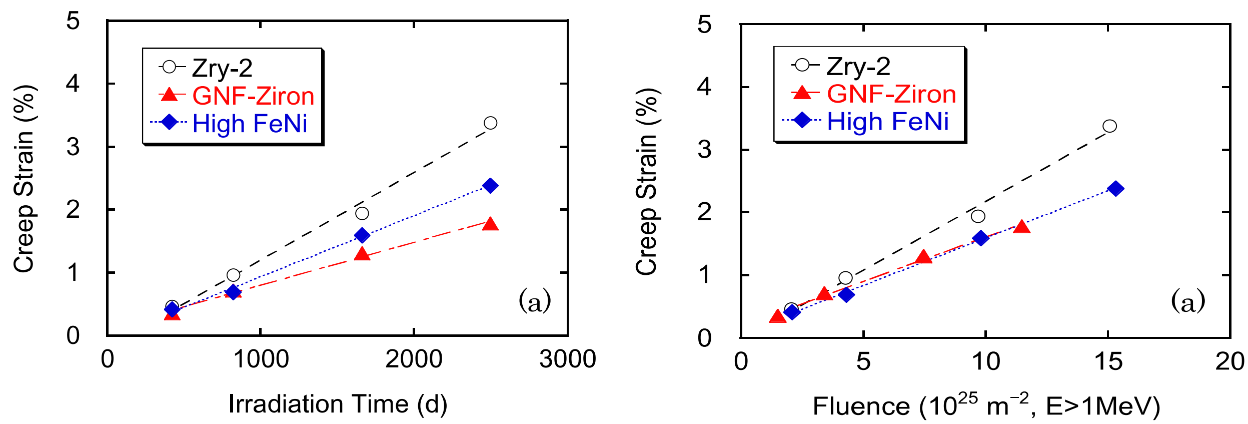


Figure 3-1. Creep strain for Zircaloy-2, Ziron and Zr-2 High FeNi from pressurized cladding capsules irradiated in Plant K (Ref. 12) – 80 MPa hoop stress (top) and 150 MPa hoop stress (bottom).

Figure 3-1 compares the creep strain measurements as functions of irradiation time and fluence. With respect to the 80 MPa capsules, the difference between Zr-2 and Zr-2 high FeNi was not significant, and it is expected that Ziron has similar creep behavior to the Zr-2 high FeNi, whereas for the 150 MPa capsules the creep rate for high Fe (Ziron) and high FeNi Zr-2 was about 15 percent lower than for Zr-2. In the LTR, GNF indicated that the **[** **]** since over the same period of irradiation (6 cycles, 2500 days), the Ziron cladding achieved **[** **]** GNF shows that the PRIME creep model predicts the creep behavior of Ziron well, and it is similar to that of Zircaloy-2.

The NRC staff concludes that GNF has addressed the creep characteristics of Ziron and use of the PRIME creep model for Zircaloy-2 is acceptable for Ziron for GNF fuel designs up to currently approved burnup levels for Zircaloy-2.

3.2.9 Poisson's Ratio

GNF uses a temperature-dependent value for Poisson's ratio of Zr-2 and proposes to use the same expression for Ziron. In addition, PNNL has proprietary data for Poisson's ratio from other zirconium alloys that show this property does not change with minor changes in composition or even relatively significant changes in fabrication for Zr-4 cladding.

The NRC staff concludes that the GNF model for Poisson's ratio for Zircaloy-2 is applicable to Ziron and is acceptable for licensing applications with Ziron cladding in GNF fuel designs up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.10 Modulus of Elasticity (Young's Modulus)

Young's modulus is used to determine the elastic strain experienced by the cladding or assembly structural component and, therefore, also impacts the amount of plastic deformation experienced.

GNF has measured the Young's modulus for both unirradiated Zircaloy-2 and Ziron and found that there is essentially no difference within the uncertainty of the data. GNF uses the same correlation for Young's modulus for Zircaloy-4, Zircaloy-2 and Ziron.

The staff concludes that the GNF correlation of Young's modulus for Ziron is acceptable for licensing applications with Ziron cladding in GNF fuel designs up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.11 Hardness (Meyer)

Meyer hardness is used in calculating the contact conductance between the fuel and cladding when the fuel-to-cladding gap is closed. It should be noted that a large change in Meyer hardness is required to make a significant effect on calculated fuel temperatures. GNF utilizes the same correlation for Meyer hardness for Zircaloy-2 and Ziron, and that correlation, which in PRIME is **[ ]**, is also applied to both alloys (Ref. 10).

GNF has measured the microhardness (Vickers hardness) for both unirradiated and irradiated Zircaloy-2 and Ziron (Figure B-7 of the LTR, Ref. 1). The data for Zircaloy-2 and Ziron overlap, with irradiated Ziron showing **[ ]**. Both alloys show dramatic increase in hardness over the range of fluence from 0 (unirradiated) to 1.5 x 10^{20} n/cm^2 (E > 1 MeV) with a slower and steady increase beyond.

The NRC staff concludes that this difference will have a negligible impact on fuel temperature calculations and the GNF correlation for Meyer Hardness for Zircaloy-2 is appropriate for Ziron and is acceptable for licensing applications with Ziron cladding in GNF fuel designs up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.2.12 Growth

Both fuel rod and assembly (tie rod) growth (and differential growth) are important in maintaining acceptable fuel rod and assembly configuration in-reactor that prevents fuel failures and allows for control rod insertions. Water rod growth needs to be evaluated to ensure that there is clearance to the upper tie plate (i.e., the water rods do not make hard contact with the upper tie plate) and that the assembly does not deflect such that it interferes with control rod insertion (see Section 4.1.7 of this SE). Excessive fuel rod growth can result in an interference fit with the upper assembly structure because the fuel rod cladding grows faster than the assembly water rods in the axial direction. Also, cladding irradiation axial growth needs to be considered in applicable fuel performance codes, e.g., PRIME fuel performance code (Ref. 10), for calculating fuel rod void volumes and rod internal pressures. Excessive growth, or excessive differential growth, does not appear to be a problem up to current approved and licensed burnup levels. Differential growth in BWR channels is a concern, but GNF has withdrawn Ziron for application to BWR channels.

In the LTR (Ref. 1), GNF reported that Ziron spacer strip coupons irradiated in the Advanced Test Reactor (ATR) up to a fluence of 6×10^{25} n/m^2 showed similar growth behavior as that of Zircaloy-2. GNF also irradiated Ziron and Zircaloy-2 cladding and strip material in BOR-60 up to a fast fluence of **[ ]** n/m^2 (equivalent to a fluence in a BWR of **[ ]** n/m^2). Measurements of growth show that the Ziron is similar to that of Zircaloy-2 up through a BWR fast fluence of 14×10^{25} n/m^2, and slightly lower at higher fluence.

GNF has measured both Ziron fuel rod and water rod irradiation growth from GE14 lead use assemblies (LUAs) in Plant H after two cycles of irradiation (to an assembly burnup of **[ ]** GWd/tU) and in Plant G after 5 cycles (to an assembly burnup of **[ ]** GWd/tU), and compared these measured values to measurements from Zircaloy-2 rods from both plants and from their experience base (Figures 1-10 and 1-9, RAI-1 and Figures 13-1 and 13-2, RAI-13; Ref. 3).

The Ziron fuel rod growth **[**

]. The growth for fuel rods and water rods is acceptable up to an assembly average burnup of about 60 GWd/tU, which is sufficient for a fuel rod average burnup of 62 GWd/tU and peak pellet (nodal) exposure of 70 GWd/tU.

Assembly growth measurements are provided in Figure 1-19 (RAI-1) of Reference 3. The data show well-behaved growth through 5, 6 and 8 annual cycles with corresponding assembly average burnups of **[ ]** GWd/tU, respectively.

In RAI-13b, GNF states, "No GNF-Ziron tie rod data is currently available." However, based on the measurements of Zircaloy-2 basic fuel rod and tie rod growth (Figure 13-3, RAI-13 (Ref. 3)) that the differential growth between Ziron basic fuel rods and tie rods is expected to be similar to that of the corresponding Zircaloy-2 fuel rods. According to the legend in Figure 13-3 of RAI-13, the Zircaloy-2 basic fuel rods and tie rod were in fuel irradiated in **[ ]**. The fuel is GNF2fuel.

GNF has also noted in their responses to the RAIs (particularly RAI 12) that there was an irradiation growth and creep program in Plant K to measure the growth and creep rate of both Ziron and Zircaloy-2 tubes (without fuel) along with tubes of their newer advanced alloys. The irradiation program has been completed and GNF has shared the results of this data with the NRC in the submitted LTR.

As mentioned above, GNF reported that Ziron and Zircaloy-2 strip materials were irradiated under similar conditions of fast flux and temperature. The growth behavior was effectively the same for both alloys. The modern GNF2 fuel design, which is currently replacing GE14 in US BWRs with GNF reloads, uses Inconel X750 spacer grids instead of the ferrule spacers used in GE14. Thus the lateral growth of Ziron is not a significant concern, even though it appears acceptable up to approved limits.

The NRC staff concludes that GNF has adequate testing programs in place to verify that the irradiation growth for Ziron is similar to Zircaloy-2 and use of Zircaloy-2 growth models is acceptable for licensing applications with Ziron components (cladding, water rods, and spacer grids) in GNF fuel designs up to currently approved burnup levels.

3.2.13 <u>Oxidation</u>

3.2.13.1 *Inner Surface Oxidation*

During the course of irradiation, oxygen is transported from the UO_2 or UO_2-Gd_2O_3 fuel to the cladding inner surface where the oxygen combines the Zr-alloy surface. Oxidation layers of a few microns to 20 microns have been reported (Refs 14 and 15). GNF was asked about inspections and measurements of LUAs (RAI-4), and GNF responded with results of PIE measurements of oxide thicknesses taken from several samples. The staff finds the measurements consistent with those reported by others in the literature (Refs. 14 and 15). The cladding inner surface oxide layer is not explicitly modeled in PRIME, or other fuel performance codes, but rather it is implicitly included in measurements of the surface conditions of hardness and emissivity. For liner cladding, the inner surface condition is independent of Zircaloy-2 or Ziron. Inner surface oxide measurements are simply used to ensure that the behavior is consistent with historical observations.

3.2.13.2 *Outer Surface Oxidation*

GNF compared Ziron corrosion measurements with calculations from the corrosion model used in PRIME (Figure 10-1, RAI-10; Ref. 3). The Ziron measurements fall **[**

] is missing from Figure 10-1 (RAI-10).

GNF has measured oxidation/corrosion on fuel rods containing Zircaloy-2 and Ziron cladding in the same assembly. The measured data show that the cladding corrosion under similar irradiation conditions **[**
].
Figure 2-11 in the LTR, GNF provided the results of MELO (maximum effective liftoff) measurements of oxide thickness for Ziron and Zircaloy-2 fuel rods irradiated in Plant G for up to 6 cycles (assembly average burnup **[** **]**) and in Plant V. The results show low oxide thickness of less than **[** **]** without acceleration at high burnup (up through **[**
].

GNF provided additional results of oxide thickness measurements in RAI-1 from several MELO (liftoff) measurements of Ziron and Zircaloy-2 fuel rods. GNF provided oxide thickness measurements from Plant H (GE14 LUA after two 24-month cycles), and these are compared in Figure 3-2 with Zircaloy-2 corrosion data taken from a GNF2 LUA program in Peach Bottom 3 (RAI-4). As with the data presented for Ziron and Zircaloy-2 oxidation measurements from Plant G and V in Figure 2-11 of the LTR, the data from Plant H show **[**

] with respect to cladding oxidation. Furthermore, the Plant P data show a rising trend with burnup while the Plant H data fall on the low side of the Plant P data and GNF's experience base. This observation indicates a dependency on plant conditions and/or fuel operating history.

[

]

Figure 3-2. Comparison of GNF-Ziron and Zircaloy-2 (Zry2) corrosion operating in Hatch (GE14, RAI-1) and Peach Bottom 3 (GNF2 Zircaloy-2, RAI-4) from MELO liftoff oxide thickness measurements.

3.2.13.3 *Shadow Corrosion*

Shadow corrosion is a concern with the use of Inconel X750 grids or springs (in bimetallic grids) in BWR fuel designs. GNF addresses shadow corrosion in the LTR, RAI-4, RAI-16, and has provided assessments in other reports (MFN 10-045, Ref. 16). GNF observes that shadow corrosion with GNF2 is consistent with historical experience with GE12 with X750 Inconel grids. In Reference 16, GNF commits to continuing inspections (surveillance) of GNF2 with respect to shadow corrosion.

In general, the staff concludes that Ziron exhibits an improved corrosion resistance compared to that of Zircaloy-2 from GNF's overall database. However, the corrosion of the fuel rod cladding (and the benefit of Ziron over Zircaloy-2) seems dependent on the irradiation conditions, particularly for assembly burnups beyond [ ] when comparing the cladding oxidation from plants G, H and V with those of plant P as discussed above (Section 3.2.13.2). The NRC staff is requesting more complete corrosion measurements for Ziron fuel rods.

Such opportunities are available from GE14 LUAs discharged from Hatch 1 (Plant H) in March 2016 and from GNF2 LUAs operating in Hatch 2 (Plant H) through February 2017.

Ideally, corrosion measurements should be made on more Ziron fuel rods and water rods (particularly from GNF2 assemblies) in uprated plants, particularly those operating with MELLLA+, e.g., Peach Bottom, LaSalle, Nine Mile Point 2, or Grand Gulf and River Bend.

3.2.14 <u>Hydrogen Pickup and Hydriding</u>

Hydrogen and hydrides increase with increased corrosion and have been shown to have a degrading effect on cladding ductility. As a result, GNF has a limit on hydrogen pickup from waterside corrosion (see Section 3.3.1.5 of this SE). In the LTR, GNF states, "In conjunction with this cladding strain limit **[ ], [**
]
(radial and circumferential average) are specified to prevent localized cladding ductility loss." However, while it appears that Ziron will exhibit more margin relative to the oxide thickness and hydrogen limits than Zircaloy-2, ***there is insufficient evidence to indicate that Zircaloy-2 or Ziron cladding will remain in compliance with the hydrogen limit in <u>all possible operating conditions</u>.*** It is noted, however, that evidence does suggest that Ziron will accumulate less hydrogen than Zircaloy-2*.*

GNF has obtained limited measurements of the hydrogen content and hydrogen pickup fraction for Ziron. The limited data on hydrogen pickup of Ziron show that the hydrogen pickup is **[ ]** than that of Zircaloy-2 (Ref. 1). In addition, the corrosion is reduced for Ziron such that the overall hydrogen pickup and impact on cladding performance should be improved over that for Zircaloy-2.

In some of the earliest testing, Ziron demonstrates an advantage over Zircaloy-2 with respect to hydrogen pickup. Ishimoto et al reported the relative hydrogen pickup between Ziron and Zircaloy-2 (Reference 13) irradiated in Kashiwzaki-Kariwa 5 (Plant K)). Zircaloy-2 of two compositions, Zry-2(1) with Fe in the upper range of the ASTM specification and Zry-2(2) Fe in the mid-range of the ASTM specification, and with the fabrication process and accumulated annealing parameter of Zry-2(1) the same as those of GNF-Ziron and High FeNi were provided as references. Zry-2(1) is more typical of currently used Zircaloy-2, with Fe content toward the upper end of the ASTM range. Ziron shows a relative hydrogen pickup of approximately 0.71 of that exhibited by Zry-2(1), whereas with respect to Zry-2(2), Ziron shows a relative hydrogen pickup of 0.29. This should be interpreted as Ziron showing less acceleration of hydrogen pickup than Zry-2(1), and much less than Zry-2(2). However, GNF is not taking credit at this time for the reduction in hydrogen pickup for Ziron.

In the LTR, GNF provides plots of hydrogen content as a function of fluence (Figures 2-2, 2-3, 2-5, and 2-7 of Ref. 1). For four cycles or about 1661 days, or roughly equivalent to three cycles in a U.S. plant, the data show that the hydrogen content for Ziron and Zircaloy-2 is similar through two cycles. In the third and fourth cycle, the hydrogen pickup in Ziron tends to be lower than that for Zircaloy-2, and during the fifth (~2000 days) and sixth cycles (~2500 days), the hydrogen content of Ziron is significantly lower than that of Zircaloy-2. After five cycles, the hydrogen content of Ziron exceeds 350 ppm (> 500 ppm) with even greater hydrogen content in Zircaloy-2. These data are likely taken from samples exposed to two-sided oxidation conditions, so that they would be expected to experience high hydrogen pickup at some point.

The data plotted in Figure 2-5 of the LTR show that Ziron tends to have a lower pickup fraction than Zircaloy-2 throughout the irradiation. During irradiation to 10 x 10^{25} n/m^2, the pickup fraction of Ziron starts around 15 to 16 percent and increases to 18 to 24 percent while Zircaloy-2 exhibits considerable scatter in H-pickup fraction from 12 to 32 percent early in life and increasing to a range of 30 to 44% over the fluence range of 6-10 x 10^{25} n/m^2. Above 10 x 10^{25} n/m^2, the pickup fraction of Ziron increases to 37 to 38 percent, while that of Zircaloy-2 has increased to the range of 40 to 70 percent, with four of five data points in the range of 60 to 70 percent.

In Figure 2-7 of the LTR, comparison is made between Ziron hydrogen content measurements after 6 cycles of operation (~5.6 years) in Plant G with hydrogen content measurements of Zircaloy-2 in plant G and other reactors. The Ziron measurements from Plant G are taken from GE14 cladding while the Zircaloy-2 data represent different cladding designs (with different wall thicknesses and diameters) including GE14, and so the Zircaloy-2 data are renormalized to the GE14 geometry. If the measurements were renormalized to GNF2, all the data would increase by a factor of **[ ]**, which is not significant for the hydrogen contents < 100 ppm, but would be significant if hydrogen contents approached whatever limit is established.

In EPRI report 1016624 (Ref. 17) on PIE of Ziron and Zircaloy-2 water rods irradiated in Gundremmingen (Plant G), the abstract states “The fuel bundles were maintained at rather high power of 10-12 GWd/MTU per cycle throughout the irradiation period to achieve the high burnup,” which was ~67 GWd/tU in ~5.6 years over 6 annual cycles. The significance with respect to hydrogen pickup in the cladding will become apparent in the following discussion.

In page 2-4 of the LTR, GNF acknowledges that the hydrogen content in cladding is lower than in water rods with similar residence time (in the reactor). This difference is consistent with “reduced hydrogen absorption due to the temperature gradient across the cladding in the heat-generating portion of the cladding.” Conversely, if the fuel rod operates at sufficiently low power, such that the temperature gradient is sufficiently low, then an increase in hydrogen pickup would be expected. At high power (> 12 kW/m, and particularly > 15 kW/m), based on the AREVA observations, it would be expected that the cladding would have low hydrogen pickup.

The staff acknowledges that Ziron exhibits a reduction in hydrogen pickup as compared to Zircaloy-2, and Ziron cladding (and material properties) should be considered acceptable in GNF fuel designs and licensing applications up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs. Nevertheless, GNF has provided limited data (from one unit in which the fuel operated at high power) on hydrogen content of cladding operating up to a burnup of ~67 GWd/tU, which is well beyond the approved burnup limits. However, it is not clear to the staff how GNF confirms that hydrogen content of fuel rod cladding (either Ziron or Zircaloy-2) remains below their proposed limit of 350 ppm for the GNF2 fuel designs under all possible operating conditions, particularly beyond 6 years up to 8 years of residence time, and particularly operating at low power for an extended period, would be the case for fuel operation for a third or fourth 24-month cycle on the core periphery.

Based on the above assessment, the staff has determined that it is prudent for GNF to perform hot cell measurements of hydrogen content, or, alternatively, provide poolside length measurements as a means of assessing hydrogen pickup of Ziron (or Zircaloy-2) cladding and water rods from GNF2 fuel, which has operated for at least 6 years (either 3 x 24 month cycles, or 4 x 18 month cycles) and preferably up to 8 years (4 x 24 month cycle). For Zircaloy-2, two GNF2 LUAs were discharged from Peach Bottom 3 after 4 x 24-month cycles of operation (Ref. 18) and two sets of LUAs irradiated for four 24-month cycles are available from Hatch 1 and 2 (Refs. 19 and 20).

While the Ziron hydrogen pickup seems to be lower than that of Zircaloy-2 under some conditions, the staff feels that GNF should provide some further evidence based on typical US BWR operating experience to the approved design burnup limits (**[ ]**) and corresponding fluence, and residence time of at least 2100 days (6 years) and up to 2800 days (8 years). The NRC staff requires that GNF provide additional poolside inspection data, including fuel rod length measurements, and provide discussions on how such measurements can be used to assess, qualitatively, the absence of excessive hydrogen pickup by the fuel rod. (See Section 5.0, Limitations and Conditions).

3.2.15 <u>α/β Phase Transformation Temperatures</u>

The $\alpha \rightarrow \alpha + \beta$ and $\alpha + \beta \rightarrow \beta$ transformation temperatures are only important for those accidents where the cladding temperatures exceed these temperatures, i.e., get relatively hot. The phase transition temperatures determine the break points in many cladding properties such as specific heat, thermal conductivity, thermal expansion, and rupture strain. GNF has measured the $\alpha \rightarrow \alpha + \beta$ phase transition temperature for Ziron as a function of Fe content that shows the phase transition temperature is not significantly affected by Fe content over the specified range (RAI-20).

The staff concludes that GNF has adequately determined the impact of the phase transformation temperature on the performance of Ziron for licensing applications with Ziron cladding in GNF fuel designs up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

3.3 <u>IMPACT OF ZIRON ON FUEL LICENSING AND SAFETY</u>

This section provides the results of review for compliance to GNF fuel design licensing criteria including compliance to NRC approved methodologies. Licensing calculations and safety analyses are addressed through GESTAR-II and the US supplement (Ref. 21), and fuel design (e.g., GNF2) specific compliance documents (Ref. 22), and documents describing methods downstream of PRIME (Ref. 23). There is no change made to the design bases or the associated evaluation methodologies for the Ziron relative to those used for Zircaloy-2.

3.3.1 Fuel System Damage

The design criteria presented in this section should not be exceeded during normal operation including AOOs. The evaluation portion of each damage mechanism evaluates the Ziron properties and analysis methods used for GNF fuel designs to demonstrate that the specific design criteria are not exceeded during normal operation including AOOs for their fuel designs utilizing Ziron. The bases/criteria and evaluation methods have not changed with introduction of Ziron in place of Zircaloy-2.

3.3.1.1 *Stress*

Base/Criteria: In conformance with GDC 10 with respect to SAFDLs, fuel damage criteria for cladding stress should ensure that fuel system dimensions remain within operational tolerances and that functional capabilities are not reduced below those assumed in the safety analysis. GNF cites GESTAR II Section 1.1.2.B.i (Ref. 21): "The fuel rod and fuel assembly component stresses, strains, and fatigue life usage shall not exceed the material ultimate stress or strain and the material fatigue capability."

The GNF design basis for fuel assembly, fuel rod, burnable poison rod, and upper end fitting spring stresses is that the fuel system will be functional and will not be damaged due to excessive stresses.

Evaluation:

Fuel rod stress analyses are performed using PRIME code (Ref. 10) using a Monte Carlo statistical method to calculate the effects of pressure differential, cladding ovality, radial thermal gradients, spacer contact, thermal bow, and circumferential thermal gradients. For each calculation, the stresses are combined into an effective stress using the Von Mises theory and compared with the appropriate design limit to produce a design ratio.

It is noted in Section 3.2.6 of this SE that Ziron has a **[**

] of the specification.

The NRC staff concludes that the design bases/criteria and evaluation methodology for cladding stress for Zircaloy-2 is acceptable for Ziron.

3.3.1.2 *Strain*

Bases/Criteria: The GNF design basis for fuel rod cladding strain is that the fuel system will not be damaged due to excessive cladding strain. In order to meet this design basis, the GNF design limit for cladding strain during steady-state operation is that the **[**

]. These design strain bases and limits are intended to preclude excessive cladding deformation during normal operation and AOOs.

Evaluation: Section 3.2.7 of this SE concluded that the observed ductility of Ziron is sufficient to meet the GNF 1 percent cladding strain limit criterion. The thermo-mechanical properties of Ziron and Zircaloy-2 are essentially identical, and in fact, Ziron exhibits **[ ]**. GNF proposes to use Zircaloy-2 materials properties for Ziron with PRIME and other methods.

The strain limit is actually applied to the design, which is mostly GNF2 with some GE14 in current US BWRs. The GNF strain analysis methods have not been changed for Ziron and the use of Ziron in place of Zircaloy-2 has no adverse impact on the analyses. The NRC staff concludes that the GNF methods and **[ ]** strain limit are applicable to Ziron for application in GNF fuel designs up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs.

The staff concludes that the design bases/criteria and evaluation methodology for cladding strain for Zircaloy-2 is acceptable for Ziron.

3.3.1.3 *Strain Fatigue*

Bases/Criteria: The GNF design basis for fuel rod cladding fatigue is that the fuel system will not be damaged due to cladding strain fatigue. In order to assure that this design basis is met, GNF imposes a design limit for strain fatigue such that the fatigue life usage factor is less than 1.0. That is, for a given strain range, the number of strain fatigue cycles are less than those required for failure when a minimum safety factor of 2 on the stress amplitude or a minimum safety factor of 20 on the number of cycles, whichever is the more conservative, is imposed. This criteria is essentially the same as that described in Section 4.2 of the SRP (based on the Langer-O'Donnell curve for Zircaloy) and, thus, has been approved for application to all GNF fuel designs using Zircaloy-2 and Zircaloy-4 up to currently approved burnup levels.

Evaluation: GNF has performed fatigue tests on Ziron that show the fatigue is somewhat below the best-estimate Langer-O'Donnell curve. GNF provided some results in the LTR (Figure B-8) and has published data in the literature (Ref. 12) shown in Figure 3-3. The data sit above the Langer-O'Donnell curve, and it demonstrates that Ziron has similar, or otherwise improved, fatigue resistance capability compared to that of Zircaloy-2.

The GNF fatigue analysis methods have not been changed for Ziron and the use of this material has no impact on the analyses.

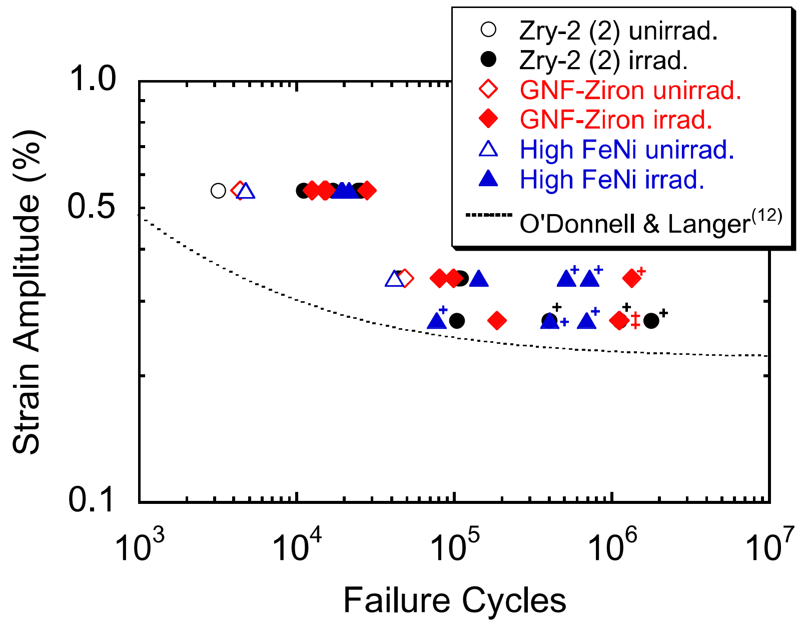


Figure 3-3. Cycle Strain Amplitude as a Function of Cycle for 9x9 BWR Cladding (Ref. 12)

The staff concludes that the design bases/criteria and evaluation methodology for cladding strain fatigue for Zircaloy-2 is acceptable for Ziron.

3.3.1.4 *Fretting Wear*

Bases/Criteria: Fretting wear has not been a traditional concern for BWR fuel. BWR fuel assemblies with the surrounding square channel are rather stiff and not subject to assembly vibration. In addition, the fuel rods are fixed at each end through the interface of the end plug shank and upper and lower tie plates.

Although Section 4.2 of the SRP does not provide numerical bounding value acceptance criteria for fretting wear, it does stipulate that the allowable fretting wear should be stated in the safety analysis report and that the stress/strain and fatigue limits should presume the existence of this wear.

Evaluation: GNF addresses fretting wear in GESTAR II Section 1.1.2.B.ii (Ref. 21): “Mechanical testing will be performed to ensure that loss of fuel rod and assembly component mechanical integrity will not occur due to fretting wear when operating in an environment free of foreign material.”

The GNF2 fuel assembly was tested to assure that the design features do not result in a significant increase in flow induced vibration (FIV) response and thereby do not increase the potential for fretting. The method used to demonstrate the adequacy of the fuel assembly from a FIV perspective was to compare the vibration response of the GNF2 design with the GE14 design during FIV tests. The response comparison was based on accelerometer data from various locations in the fuel assemblies. The GE14 fuel assembly's performance is considered acceptable based upon its reliable performance in reactor operation.

The results of FIV testing were found to be acceptable for GNF2, and the GE14 fuel design has not experienced FIV-induced fretting. The use of Ziron does not impact these results.

The staff concludes that the design bases/criteria and evaluation methodology for fretting wear for Zircaloy-2 is acceptable for Ziron.

3.3.1.5 *Oxidation and Crud Buildup*

Bases/Criteria: GNF addresses oxidation in GESTAR II Section 1.1.2.B.iii (Ref. 21): "The fuel rod and assembly component evaluations include consideration of metal thinning and any associated temperature increase due to oxidation and the buildup of corrosion products to the extent that these effects influence the material properties and structural strength of the components."

Evaluation: GNF models the effect of cladding oxidation and crud with a best estimate and bounding model in PRIME (RAI-10). The correlations are based on a database of corrosion measurements. GNF has an adequate surveillance program to monitor corrosion through measurements of individual fuel rods from LUAs (RAI-1, RAI-4, and RAI-10). See Section 3.2.13.

GNF has proposed a limit on hydrogen pickup from waterside corrosion of **[ ]** (see SE Section 3.4.1 below). GNF claims that this hydrogen limit will restrict corrosion to at or below GNF's proposed oxide thickness limit of **[ ]**, but hydrogen is generally not measured in poolside examinations performed on LUAs while oxide thickness is measured.

The staff concludes that the design bases/criteria for oxidation and CRUD buildup is acceptable, but GNF has not demonstrated a robust methodology for ensuring that hydrogen will remain below the set limit of **[ ]**.

3.3.1.6 *Rod Bowing*

Bases/Criteria: Fuel and burnable poison rod bowing are phenomena that alter the design-pitch dimensions between adjacent rods. Bowing affects local nuclear power peaking and the local heat transfer to the coolant. Rather than place design limits on the amount of bowing that is permitted, the effects of bowing are included in the critical heat flux (CHF) analysis by a critical power ratio (CPR) penalty when rod bow is greater than a predetermined amount.

Evaluation: Rod bowing has been found to be dependent on rod axial growth, the distance between grid spacers, the rod moment of inertia, flux distribution, and other assembly design specific characteristics. All of these parameters are design dependent and not material dependent with the exception of rod growth. Therefore, the potential impact of Ziron on rod bowing would be an increase fuel rod axial growth (see Section 3.3.1.7).

GNF has measured both fuel rod irradiation growth of Ziron from two LTAs in Plants H and V (GE plant) after two cycles of irradiation and compared these measured values to those from Zircaloy-2 rods in the same assemblies (RAI-1). The growth measurements for Ziron cladding **[ ]**. Differential growth did not appear to be significant. Furthermore, GNF has been monitoring fuel rod-to-fuel rod gap in their GNF2 surveillance program, and GNF has committed to notifying the NRC if gap closure exceeds 50 percent of the as-fabricated gap (Ref. 22) as part of the GNF2 surveillance program. The staff concludes that the design bases/criteria and evaluation methodology for rod bowing for Zircaloy-2 is acceptable for Ziron based on GNF's commitment to collect Ziron growth data up to currently approved burnup levels from GNF fuel designs to confirm that this data is enveloped by the Zircaloy-2 growth model.

3.3.1.7 Axial Growth

Bases/Criteria: Failure to adequately design for axial growth of the fuel rods can lead to fuel and fuel rod bowing and possible failure. Failure to adequately design for assembly growth can lead to collapse of the assembly hold-down springs, guide tube bowing, and control rod insertion problems. The GNF design bases are similar in that the fuel rods will be designed with adequate clearance between the fuel rod ends and the upper tie plate to accommodate the differences in the growth of the fuel rods and the growth of the fuel assembly

Evaluation: The GNF design limits for fuel rod growth are similar in that no interference between the fuel rods and the fuel assembly upper tie plate is allowed taking into account adequate uncertainties in the predictions.

GNF currently uses the same axial rod growth model for Zircaloy-2 for application to Ziron clad rods and water rods in GNF fuel designs. In addition, GNF has a surveillance program to look at fuel rod and assembly growth, and perform measurements on LUAs and selected reload fuel assemblies (RAI-1).

The staff concludes that the design bases/criteria and evaluation methodology for axial growth for Zircaloy-2 is acceptable for Ziron.

3.3.1.8 *Rod Internal Pressure*

Bases/Criteria: Rod internal pressure is a driving force for, rather than a direct mechanism of, fuel system damage that could contribute to the loss of dimensional stability and cladding integrity. Rod internal pressure is also an important parameter of input for LOCA analyses. Section 4.2 of the SRP presents a rod pressure limit of maintaining rod pressures below system pressure that is sufficient to preclude fuel damage.

Evaluation: GNF has demonstrated that there is **[**

], the PRIME calculations of the same fuel rod design and power history would produce essentially the same results for both Ziron and Zircaloy-2, and the impact on the calculation of rod internal pressure would be the same.

The NRC staff concurs with GNF. Use of GNF's approved code (PRIME) and approved methodology using Zircaloy-2 properties for Ziron cladding is acceptable to design burnup limits approved for Zircaloy-2. The NRC staff concludes that the design bases/criteria and evaluation methodology for rod internal pressure for Zircaloy-2 is acceptable for Ziron.

3.4 FUEL ROD FAILURE

In the following sections, fuel rod failure thresholds and analysis methods for the failure mechanisms listed in the SRP will be reviewed. When the failure thresholds are applied for normal operation including AOOs, they are used as limits (and hence SAFDLs) since fuel failure under those conditions should not occur according to the traditional conservative interpretation of the GDC 10. When these thresholds are used for postulated accidents, fuel failures are permitted, but they must be accounted for in the dose assessments required by 10 CFR Part 100 (Ref. 8). The basis or reason for these failure thresholds is established by GDC 10 and Part 100, and only the threshold values and the analysis methods used to assure that they are met are reviewed below. The bases/criteria and evaluation methods have not changed with introduction of Ziron in place of Zircaloy-2.

3.4.1 Hydriding

Bases/Criteria: Internal hydriding as a cladding failure mechanism is precluded by controlling the level of hydrogen impurities in the fuel during fabrication; this is an early-in-life failure mechanism. The moisture level for the fuel in GNF fuel designs is limited to **[** **]**, and this specification is compatible with the ASTM C776 specification (Ref. 24), which allows two micrograms of hydrogen per gram of uranium (i.e., 2 ppm). GNF addresses internal hydriding in GESTAR II Section 1.1.2.B.iv (Ref. 21): "The fuel rod internal hydrogen content is controlled during manufacture of the fuel rod consistent with ASTM standards C776-83 and C934-85 to assure that loss of fuel rod mechanical integrity will not occur due to internal cladding hydriding."

Evaluation: Internal hydriding is not generally impacted by the introduction of a new cladding material unless its reaction with water or hydrogen is significantly different from previous Zircaloy. This is not the case for Ziron and Zircaloy-2 cladding. The staff concludes that the moisture limit on the fuel remains applicable for fuel rods clad with Ziron up to currently approved burnup levels.

Internal hydriding is controlled by controls in the manufacturing process. The GNF corrosion analysis methods and, therefore, hydrogen pickup due to corrosion for Zircaloy-2 are applied to Ziron. This appears to be conservative because Ziron corrosion and resulting hydrogen levels appear to be significantly lower than for Zircaloy-2. In addition, GNF has committed to monitor oxidation up to currently approved burnup levels in several BWR plants with LUAs utilizing Ziron. The NRC staff concludes that GNF has adequately addressed waterside oxidation but not hydrogen levels for application of Ziron in GNF fuel designs based on their commitment to measure waterside corrosion in their LTA program up to currently approved burnup limits for Zircaloy-2 and GNF fuel designs. In order to use oxidation as a proxy for hydrogen pickup, a detailed hydrogen pickup model needs to be developed, and a set of measurements of hydrogen content must be obtained against which to validate the model. However, GNF is not planning on using oxidation as a proxy for hydrogen.

The NRC staff concludes that the design bases/criteria and evaluation methodology for internal hydriding for Zircaloy-2 is acceptable for Ziron.

As discussed in Section 3.2.14, GNF also has proposed upper bound limit of **[ ]** (volume average) of hydrogen pickup due to waterside corrosion up to the current burnup limit for GNF fuel designs. In the absence of a robust methodology specific for GNF Ziron for hydrogen uptake, the NRC staff accepts this limit based on surveillance and tests described in Section 3.2.14 of this safety evaluation.

3.4.2 Cladding Collapse

Bases/Criteria: If axial gaps in the fuel pellet column were to occur due to densification, the cladding would have the potential of collapsing into this axial gap (i.e., flattening) due to irradiation creep of the cladding. Because of the large local strains that would result from collapse, the cladding is assumed to fail. It is a GNF design basis that fuel and burnable poison rod failures due to flattening will not occur. In order to meet this design basis, GNF imposes a GNF fuel design limit for fuel rod cladding flattening such that the core residence time shall not exceed the calculated core residence time corresponding to a flattened rod frequency of 1.0. These criteria are not impacted by the use of Ziron in place of Zircaloy-2 cladding.

Evaluation: GNF has developed a cladding collapse analysis methodology (Ref. 25), which the NRC has approved along with approval of GESTAR-II.

The cladding model that has a significant impact on the cladding collapse analysis is the irradiation creep model discussed in Section 3.2.8 above. GNF utilizes the irradiation creep model developed for Zircaloy-2 cladding for application to irradiation creep of Ziron cladding for both GNF fuel designs. GNF has claimed that there is **[ ]** based on a tubing creep specimen pressurized to a hoop stress of 150 MPa. The creep is compared in Figures B-9 and B-10 of the Ziron LTR (NEDC 33353P, Ref. 1).

The NRC staff concludes that the design bases/criteria and evaluation methodology for cladding collapse for Zircaloy-2 is acceptable for Ziron.

3.4.3 Overheating of Cladding

Bases/Criteria: The GNF fuel design basis for the prevention of fuel failures due to overheating is that there will be at least a 95 percent probability at a 95 percent confidence level that boiling transition (dryout) will not occur on a fuel rod having the minimum CPR ratio during normal operation and AOOs. This design basis is consistent with the thermal margin criterion of Section 4.2 of the SRP. The use of Ziron in place of Zircaloy-2 cladding does not impact the critical heat flux (CHF) correlations for these designs.

Evaluation: As stated in the SRP, Section 4.2, adequate cooling is assumed to exist when the thermal margin criterion to limiting CPR (or MCPR) or boiling transition in the core is satisfied. GNF thermal hydraulic codes used to demonstrate that satisfactory thermal margin exists are not impacted by the change from Zircaloy-2 cladding to Ziron cladding.

The staff concludes that the design bases/criteria and evaluation methodology for overheating of the cladding for Zircaloy-2 is acceptable for Ziron.

3.4.4 Overheating of Fuel Pellets (Fuel Melting)

Bases/Criteria: NEDO-33270, Rev. 5, Section 3.2.9 (Ref. 22) references GESTAR II, Section 1.1.2.B.ix, which states, "Loss of fuel rod mechanical integrity will not occur due to fuel melting."

The fuel center temperature evaluation is performed using the PRIME thermal-mechanical performance model in conjunction with the standard error propagation statistical method.

The standard error propagation analysis results in a mean and standard deviation for the fuel center temperature during AOOs at uniformly spaced exposure points throughout the design lifetime. These results are used to specify a Thermal Overpower (TOP) limit that assures with 95 percent confidence that the fuel center temperature will not exceed the fuel melting temperature for the maximum duty fuel rod during an AOO at any point in the licensed design lifetime of the fuel. This design basis and the limit are not impacted by use of Ziron in place of Zircaloy-2 cladding.

Evaluation: The GNF evaluation methods used to verify that the fuel melting limit is met have not been changed by replacing Zircaloy-2 with Ziron in GNF fuel designs.

The staff concludes that the design bases/criteria and evaluation methodology for overheating of the fuel pellets for Zircaloy-2 is acceptable for Ziron.

3.4.5 Excessive Fuel Enthalpy

Bases/Criteria: NEDO-33270, Rev. 5, Section 3.12.3 (Ref. 22) refers to "Fuel Enthalpy Analysis," which is consistent with Amendment 10 to NEDE-24011-P (Ref. 21), which states "For a severe reactivity initiated accident (RIA) in a BWR at zero or low power, fuel failure is assumed in the SRP to occur ~ the radially averaged fuel rod enthalpy is greater than 170 cal/g at any axial location." In NEDO-33270, Rev. 5, Section 3.12.3, citing *NEDE-31152P, Rev. 8*, GNF states that "based on a bounding postulated Control Rod Drop Accident (CRDA) analysis, it was conservatively determined for the 8x8 fuel designs that approximately **[ ]** fuel rods would reach a fuel enthalpy of 170 cal/g. This is the enthalpy limit for eventual cladding perforation. For the 9x9 GE11 and GE13 fuel designs, approximately **[ ]** fuel rods would reach a fuel enthalpy of 170 cal/g, and for the 10x10 GE12 and GE14 fuel designs, approximately **[ ]** fuel rods would reach a fuel enthalpy of 170 cal/g.

As with the other 10x10 designs, when the bounding analysis is applied to GNF2, approximately **[ ]** fuel rods are calculated to reach a fuel enthalpy of 170 cal/g."

In the LTR, GNF acknowledges the recent changes in criteria (Ref. 1):

a) For zero power conditions, peak radial average fuel enthalpy greater than 170 cal/g for fuel rods with an internal rod pressure at or below system pressure and 150 cal/g for fuel rods with an internal rod pressure exceeding system pressure; for intermediate and full power conditions, fuel cladding is assumed to be failed if local heat flux exceeds thermal design limits, and;

b) For BWRs, radial average fuel enthalpy greater than the hydrogen-dependent limits, in which the limiting radial average fuel enthalpy is lowered from 150 cal/g at 75 ppm hydrogen in cladding to 60 cal/g at 150 ppm hydrogen and greater.

GNF further states that these criteria are "addressed through core design and energy deposition calculations," and that since the properties of Ziron and Zircaloy-2 are **[** **]**, as is concluded in Section 3 of this TER, the "GNF-Ziron cladding complies with current criteria by following the same energy deposition based approach to core design."

Evaluation: The GNF analysis methods for RIA events are not significantly impacted by the use of Ziron in place of Zircaloy-2, and therefore, NRC-approved methods are acceptable for application to GNF fuel designs with Ziron cladding and components.

The staff concludes that the design bases/criteria and evaluation methodology for excessive fuel enthalpy for Zircaloy-2 is acceptable for Ziron.

3.4.6 Pellet-Cladding Interaction

Bases/Criteria As indicated in Section 4.2 of the SRP, there are no generally applicable criteria for PCI failure. However, two acceptable criteria of limited application are presented in the SRP for PCI: 1) less than 1 percent transient-induced cladding strain, and 2) no centerline fuel melting. Both of these limits are used by GNF for GNF fuel designs as discussed in Sections 4.1.2 and 4.2.4 of this SE and, therefore, have been addressed by GNF.
Evaluation: The GNF evaluation methods (with the PRIME code) used to verify that the cladding strain and fuel melting limits are met have not been changed for Ziron for GNF fuel.

The staff concludes that the design bases/criteria and evaluation methodology for pellet-cladding interaction for Zircaloy-2 is acceptable for Ziron.

3.4.7 Cladding Rupture

Bases/Criteria: There are no specific design limits associated with cladding rupture other than the 10 CFR Part 50, Appendix K (Reference 26) requirement that the degree of swelling not be underestimated. The GNF rupture models comprise an integral portion of the GNF emergency core cooling system (ECCS) evaluation models for determining the peak cladding temperature (PCT) for the respective GNF fuel designs. The GNF design basis also states that the degree of cladding swelling or ballooning not be underestimated. This design basis is not impacted by use of Ziron in place of Zircaloy-2 cladding.

Furthermore, in recognition of the limited amount of GNF-Ziron data, GNF plans to treat GNF-Ziron in the same way as Zircaloy-2 (i.e., any advantage of GNF-Ziron over Zircaloy-2 in corrosion and hydriding in LOCA analyses will not be utilized in analyses or design) until a broader database for GNF- Ziron has been established.

Evaluation: The high temperature creep and rupture models used by GNF in their LOCA-ECCS analysis are directly coupled to their models for cladding ballooning and flow blockage. A detailed discussion of the cladding ballooning and flow blockage models is provided in Section 3.5.3 below. GNF has proposed using the cladding rupture model for Zircaloy-2 to be applied to GNF fuel designs using Ziron cladding. Burst tests were performed on GNF-Ziron, and GNF provided data showing hoop stress from the experiments compared with curves developed from the literature in Figure B-6 of the LTR (Ref. 1). The hoop stresses for Ziron **[**

] is applicable to GNF-Ziron.

The staff asked GNF to compare the rupture strains corresponding to the data provided in LTR Figure B-6 (RAI-14). In response, GNF compared the measured rupture strains for Ziron with those available for Zircaloy-2 from the literature (RAI-14c).

The staff concludes that the design bases/criteria and evaluation methodology for cladding rupture for Zircaloy-2 is acceptable for Ziron.

3.4.8 Fuel Rod Mechanical Fracturing

Bases/Criteria: The term "mechanical fracture" refers to a cladding defect that is caused by an externally applied force such as a load derived from core-plate motion or a hydraulic load. These loads are bounded by the loads of a safe-shutdown earthquake (SSE) and LOCA, and the mechanical fracturing analysis is usually done as a part of the SSE-LOCA loads analysis, see Section 3.5.4 of this SE.

Evaluation: The discussion of the SSE-LOCA loading analysis is given in Section 3.5.4 of this SE.

3.5 FUEL COOLABILITY

For postulated and design basis accidents such as LOCA in which severe fuel damage might occur, core coolability must be maintained as required by several GDCs (e.g., GDC 27 and 35). In the following paragraphs, limits and methods used to assure that coolability is maintained are discussed for the severe damage mechanisms listed in the SRP. The bases/criteria and evaluation methods have not changed with introduction of Ziron in place of Zircaloy-2.

3.5.1 Fragmentation of Embrittled Cladding

Bases/Criteria: In GESTAR II (Ref. 21), GNF states, “the most severe occurrence of cladding oxidation and possible fragmentation during an accident results from a LOCA. In order to limit the effects of cladding oxidation for a LOCA GE uses (References 27 and 28) acceptance criteria of 2200°F on peak cladding temperature and 17% on maximum cladding oxidation as prescribed by 10CFR50.46." GESTAR II originally applied to GE 8x8 fuel designs, but has been extended to 9x9 and 10x10 designs, including GNF2 (Ref. 25).

In the GNF2 compliance document, GNF states "The SAFER/GESTR-LOCA ECCS evaluation methodology is used to determine the effects of the postulated loss-of-coolant accident (LOCA) in accordance with the requirements of 10 CFR 50.46 and Appendix K. This methodology is NRC-approved and is described in Section S.2.2.3.2 of the US Supplement to GESTARII (Reference 1) and its references. The SAFER/GESTR-LOCA evaluation methodology is used for all GE BWRs."

In the LTR (Ref. 1), Appendix B, GNF provided data on high temperature oxidation. Ziron was tested at 1000°C and 1200°C. At 1000°C (Figure B-13 in the LTR), the weight gain results from both sets of tests are **[ ]** based on the CP relationship. At 1200°C (Figure B-14 in the LTR), the weight gain results from both sets of tests are **[ ]** the expected CP relationship. GNF notes that in both figures, two sets of experimental measurements (Ziron 1 and Ziron 2) reveal differences between the results obtained by the two laboratories. One set (Ziron 2) shows **[ ]** weight gain than Ziron 2 or Zircaloy-2.

The results (in Figure B-17 and Figure B-19 of the LTR) show that both Ziron samples exhibited ductility greater than the embrittlement criteria at 135°C for 17 percent ECR (CP). The ductility of Ziron was observed to be **[ ]**. GNF asserted that additional data for ECR > 17 percent might show that **[ ]**. The NRC staff agrees with GNF's assessment.

Evaluation: Based on the similarities in thermo-mechanical properties of Zircaloy-2 and Ziron, and the test results for high temperature oxidation, the staff finds that Ziron has adequate oxidation resistance and ductility at high temperature comparable to Zircaloy-2.

The NRC staff concludes that the design bases/criteria and evaluation methodology for fragmentation of embrittled cladding for Zircaloy-2 is acceptable for Ziron.

3.5.2 Violent Expulsion of Fuel

Bases/Criteria: In a severe reactivity insertion accident (RIA), such as a control rod drop accident (CRDA), large and rapid deposition of energy in the fuel could result in melting, fragmentation, and dispersal of fuel into the primary coolant. The mechanical action associated with fuel dispersal might be sufficient to destroy the fuel cladding and rod bundle geometry and provide significant pressure pulses in the primary system. To meet the guidelines of the SRP as it relates to the prevention of widespread fragmentation and dispersal of fuel and the avoidance of pressure pulse—generation within the reactor vessel, GNF has traditionally used a radially averaged enthalpy limit of 280 cal/g. As indicated in References 29 and 28, GE/GNF methods employed the 280 cal/g criterion as a control rod drop accident design limit that was consistent with the previous revision of the SRP. The applicability of this limit to extended burnup fuel was addressed in the review of NEDE-22148.

Recent RIA testing has indicated that fuel expulsion and fuel failure may occur before the 280 cal/gm limit and the onset of dryout, respectively (Ref. 20). The NRC has introduced revised limits (Ref. 7). In the LTR, GNF acknowledges what was then an interim criterion, 230 cal/g, and states:

a) Peak radial average fuel enthalpy must remain below 230 cal/g,
b) Peak fuel temperature must remain below incipient fuel melting conditions,
c) Mechanical energy generated as a result of (a) non-molten fuel-to-coolant interaction and (b) fuel rod burst must be addressed with respect to reactor pressure boundary, reactor internals, and fuel assembly structural integrity, and
d) No loss of coolable geometry due to (a) fuel pellet and cladding fragmentation and dispersal and (b) fuel rod ballooning.

GNF further states that these criteria are "addressed through core design and energy deposition calculations," and that since the properties of Ziron and Zircaloy-2 are **[** **]** as is concluded in Section 3 of this TER, the "GNF-Ziron cladding complies with current criteria by following the same energy deposition based approach to core design.

Evaluation: The GNF analysis methods for RIA events are not significantly impacted by the use of Ziron in place of Zircaloy-2, and therefore, NRC-approved methods are acceptable for application to GNF fuel designs with Ziron cladding and components.

The NRC staff concludes that the design bases/criteria and evaluation methodology for violent expulsion of fuel for Zircaloy-2 is acceptable for Ziron.

3.5.3 Cladding Ballooning and Flow Blockage

Bases/Criteria: Zircaloy cladding will balloon (swell) under certain combinations of temperature, heating rate, and stress during a LOCA (Ref. 22). There are no specific design limits associated with cladding ballooning other than the 10 CFR Part 50, Appendix K (Ref. 26) requirement that the degree of swelling not be underestimated. GNF states that the models utilize applicable test data in such a way as to properly estimate the pre-rupture clad strain, the rupture (burst) strain at the location of clad rupture and not under-estimate the assembly flow blockage.
Evaluation: The GNF cladding ballooning is addressed in the approved report NEDE-20566-P-A (Ref. 27). In RAI-14, GNF compares the burst strains measured for Ziron with a population of data for Zircaloy-2 taken from NUREG-0630. The burst strain for Ziron are **[** **]** (in the temperature range from 600 to 1150ºC). These data fall in the lower portion of the population of Zircaloy-2 data.

In recognition of the limited amount of GNF-Ziron data, GNF plans to treat GNF-Ziron in the same way as Zircaloy-2 (i.e., any advantage of GNF-Ziron over Zircaloy-2 in corrosion and hydriding in LOCA analyses will not be utilized in analyses or design) until a broader database for GNF- Ziron has been established.

The staff concludes that the design bases/criteria and evaluation methodology for flow blockage for Zircaloy-2 is acceptable for Ziron.

3.5.4 Fuel Assembly Structure Damage from External Forces

Bases/Criteria: Earthquakes and postulated pipe breaks in the reactor coolant system would result in external forces on the fuel assembly. Section 4.2 of the SRP and associated Appendix A stated that fuel system coolability should be maintained and that damage should not be so severe as to prevent control rod insertion when required during these low probability accidents.

The GNF design basis is that the fuel assembly will maintain a geometry that is capable of being cooled under the worst case design basis accident and that no interference between control rods and channels will occur during a safe shutdown earthquake (SSE). This is nearly identical to the design basis presented in the SRP and, therefore, the staff concludes that this basis is acceptable for application to GNF fuel designs.

Evaluation: GNF has considered using Ziron in their water rods and spacer grids of GNF GE14 fuel designs, and the fuel channels that surround the bundle and form the primary cooling channel in-core. GNF has however removed Ziron from consideration of BWR channel material in favor of NSF, a Zr-1Nb-1Sn-0.35Fe alloy similar to ZIRLO™ and the Russian alloy E635 (Anikuloy). The NRC approved the use of NSF channels October 2015 (Ref. 30).
The spacer grids are one of the main structural components maintaining fuel geometry and control rod insertability due to loading from seismic-LOCA accidents; therefore, the structural strength of this component is important for these accidents.

GNF customers are currently replacing GE14 (10x10), or GE11 (9x9) in two BWR/2s, with GNF2 (10x10). The GNF2 design uses Inconel X750 grids, so use of Ziron does not affect the material properties or mechanical performance of the grid structure. On the other hand, if a customer requested GNF2 with ferrule grids, which are used in GE14, then use of Ziron would potentially impact the grid material properties and performance. However, GNF has demonstrated that Ziron properties are essentially equivalent to those of Zircaloy-2, except that the corrosion and hydrogen pickup are less for Ziron than for Zircaloy-2 under equivalent operating conditions.

The NRC staff concludes that the design bases/criteria and evaluation methodology for fuel assembly structural damage from external forces for Zircaloy-2 is acceptable for Ziron.

3.6 MATERIALS TESTING AND FUEL SURVEILLANCE

The development of Ziron is the culmination of a program that began in the late 1980s. GNF (then GE), Siemens, and ABB had separate programs to investigate the effects of composition and microstructure on the corrosion and hydrogen pickup behavior of Zircaloy-2. This included the effects of principal alloy content, e.g., Fe, Cr, Ni, impurity levels, P, C, Si, and additional alloying elements, e.g., Te, Bi (Etoh et al., Ref. 35).

In the LTR, GNF provide a summary table (Figure 2-1 in LTR) of the various programs for alloy development and testing. The earliest programs consisted of strip coupons or tubing specimens irradiated in ATR, in two commercial reactors (Cooper (Plant C) and Kashiwazaki Kariwa-5 (KK5, Plant K), Ref. 11) in dummy neutron source holders, and in special rigs (Halden) (Refs. 11, 12, and 13).

The Cooper tests provided the earliest testing in a commercial reactor (Refs. 11, 12, and 13), which according to the LTR began in 1988 (Cycle 12, June 1988). Corrosion tests followed in LTR (Ref. 1), and in various water chemistries in Halden (Refs. 11, 12, 13, and 32), and then tests followed in KK5.

The Halden test program is discussed in detail in EPRI report TR-106830 (with tables mostly illegible, Ref. 32) and by Shimada (Ref. 33). The results of testing in various water chemistries do indicate an advantage of Ziron over Zircaloy-2 in terms of corrosion resistance.

GNF was asked about recent and ongoing fuel surveillance programs involving Ziron fuel cladding and components (RAI-1 and RAI-17) beyond those provided in NEDC-33353P (Ref.1). A summary of the LUA programs in commercial BWRs is provided in Table 2.

Table 2. Summary of GNF Surveillance Program on Ziron Cladding and Fuel Components

Unit (Code)	Fuel Design	Cycles, Burnup	Dates	No. of LUAs
Gundremmingen C (G)	GE14	6, **[ ]** GWd/tU	1999-2005	**[**
	GE14	8, **[ ]** GWd/tU	2008-2010	
Vermont Yankee (V)	GNF2	2, **[ ]** GWd/tU 5, **[ ]** GWd/tU	2007-2010	
[ ] (F)	GNF2	2.5, **[ ]** GWd/tU 5, **[ ]** GWd/tU	2008	
Hatch 2 (H)	GE14	2, **[ ]** GWd/tU	2009-2013	
Hatch 1 (H)	GE14	3, ??	2014-2016	
Hatch 2 (H)	GNF2	3, ??	2011-2017	**]**
Perry (P)	LUC – GE14	-	2005-2011	
Clinton (N)	LUC – GE14	-	2006-2012	

Table 3 provides a summary of the water chemistries, assembly burnups, and residence times of the different LUA programs in commercial BWRs. The Hatch water chemistry is more typical of US BWRs, while that of Vermont Yankee is similar. The NWC and annual cycle operation of Gundremmingen and **[ ]** plants are atypical of US plants, and in fact, may contribute to low hydrogen pickup in their respective programs, in conjunction with the relative high power of the assemblies in the last cycle. The Hatch program will be important with respect to hydrogen pickup.

Table 3. Summary of Water Chemistries and Operating Experience of GE14 and GNF2 Fuel Assemblies with Ziron Cladding

Plant	**Fuel Design**	**Water Chemistry**	**Assembly Burnup, GWd/tU**	**Number of Days**
Gundremmingen (G)	GE14	NWC, High Fe FW	**[ ]** (5.6 years), **[ ]** (7.5 years)	2086, 2723
Hatch 2, Hatch 1 (H)	GE14	OLNC, Zn, HWC	**[ ]** (3.5 years) 5.6 years	1293, 2029
Hatch 2 (H)	GNF2	OLNC, Zn, HWC	**[ ]** (3.6 years)	1318
Vermont Yankee	GNF2	NMCA, Zn, HWC	**[ ]** **[ ]**(7.2 years)	 2622
[ ]	GNF2	NWC, Low Fe FW	**[ ]** (5.4 years)	1979

The program at Gundremmingen C is the earliest lead use assembly (LUA) program from which data are available for Ziron. **[ ]** GE14 LUAs were inserted in 1999 and operated through six cycles through 2005 when they were discharged with assembly average burnups of **[ ]** GWd/tU and subject to poolside examinations. **[ ]** assemblies were then selected for reinsertion for two additional cycles in 2008 and were discharged in May 2010. The two assemblies achieved a peak burnup of **[ ]** GWd/tU.

GNF initiated GNF2 LUA programs in Vermont Yankee in 2007 and **[ ]** in 2008. MELO corrosion measurements were made after one (2008) and two cycles (2010) (Ref. 1, RAI-1 in Ref. 3). However, in the responses to RAIs, no further measurements are reported after 2010.

[ ] GE14 LUAs, with selected fuel rods (29 rods in each assembly) fabricated from GNF-Ziron cladding material, were loaded into Plant Hatch Unit 2 during Cycle 21, with planned operation through Cycles 22 and 23 (Ref. 34). The LUAs completed operation in Hatch Unit 2 during Cycles 21 and 22, but were not irradiated during Cycle 23. One of these LUAs is being irradiated in Hatch Unit 1, Cycle 27. Due to issues unrelated to the cladding material inspection results, the other LUA is not being used during Unit 1 Cycle 27. Based on plant status reports, the third cycle GE14 operated through February 7, 2016, with a cumulative in-core time of 2029 days (~ 1933 EFPD).

A set of GNF2 LUAs were inserted in Hatch 2, Cycle 22, and operated in a third 24-month cycle in Cycle 24, which ended in early 2017 (Ref. 35). According to GNF, “All fuel rods in these LTAs will have GNF-Ziron cladding. This operating experience, along with the revised GNF2 compliance report to be issued once GNF-Ziron is licensed by the NRC, will form the basis for future reload applications of GNF2 fuel with GNF-Ziron cladding in domestic BWRs.” If Cycle 24 runs beyond 700 days, then the four LUAs may operate in excess of 2020 days.

In RAI-15, “GNF commits to perform **[**

] under mutually agreeable terms with a host utility." GNF provided a proposed inspection plan for Ziron containing assemblies, which is summarized in Table 4 (from Table 15-1, RAI-15), and it is expected that the fuel design will be GNF2. With respect to the hydrogen level, it is not clear how measuring length is appropriate, except for excessive hydrogen uptake.

Table 4. Proposed Inspection Plan for GNF-Ziron Reload Bundle

Task	**Method**	**Comment**
General Condition	Bundle, fuel rod, water rod and spacer* visual	Corrosion, spalling, mechanical integrity
Cladding oxide thickness	Rod eddy current lift-off	Corrosion, includes crud
Cladding creep down	Rod diameter profilometry	Includes oxide and crud
Fuel rod and water rod growth	Visual and tape measure Length	N/A
Hydrogen level	Visual and tape measure Length	Gross excessive condition

*if GNF-Ziron is used in the inspected bundle

While poolside examinations with measurements are an important aspect in confirming sound fuel performance, the NRC staff expects the applicant to perform fuel inspection described in the response to RAI-15 and the inspection plan summarized in Table 15-1 (Reference 3). This requirement is listed in Section 5.0 *Limitations and Conditions* of the SE.

Recent cycles at Limerick station frequently exceed 700 days, and fuel in three such cycles may exceed 2100 days, while fuel in four cycle cycles will exceed 2800 days. Aside from the GE14 LUA discharged from Hatch 1, Cycle 27 (spring 2016) and the four GNF2 LUAs to be discharged in Hatch 2, Cycle 24 (spring 2017), there is a dearth of data available regarding hydrogen pickup under conditions of low power operation during third or fourth cycles (2100-2800 days) of operation.

The GNF surveillance program seems to rely on observation of acceleration of fuel rod or assembly growth to indicate an increase in hydrogen pickup, an approach which is consistent with the Westinghouse experience at KKL. (See Section 5).

4.0 CONCLUSIONS

The NRC staff has reviewed the GNF submittal of the LTR, entitled "Application of GNF-Ziron to GNF Fuel Designs" (Ref. 1), as Enclosure 1 to letter MFN 10-358, December 2010 (Ref. 1), for application of Ziron in GNF BWR fuel designs up to currently approved burnup levels. Ziron is chemically similar to Zircaloy-2 with [ ] and a corresponding reduction in Zr.
The staff concludes that the differences in composition, microstructure and texture will not adversely affect the alloys' performance (Section 2.0).

The staff concludes that the thermo-physical and thermal-mechanical properties of Ziron are essentially identical or the same as those of Zircaloy-2. Furthermore, Ziron exhibits greater oxidation (corrosion) resistance than Zircaloy-2, and it appears that the hydrogen pickup of Ziron is less than that of Zircaloy-2. GNF did not provide a hydrogen pickup model for Ziron, or for Zircaloy-2. Measurements on Ziron and Zircaloy-2 irradiated or tested under different conditions demonstrate that in a majority of campaigns, the hydrogen pickup of Ziron is less than that of Zircaloy-2 in the same environment. In one comparison of hydrogen pickup in BWR cladding, Ziron showed no significant advantage compared to Zircaloy-2 with respect to hydrogen pickup, and both alloys showed low hydrogen content (typically < 100 ppm). The use of Zircaloy-2 properties for Ziron is acceptable.

No changes have been made to the design bases or the associated evaluation methodologies for Ziron relative to those used for Zircaloy-2. These have been reviewed and the staff concludes that the design bases for Zircaloy-2 are acceptable for ZIRON and the associated evaluation methodologies are also acceptable.

Implementation of Ziron material, as a substitute for Zircaloy-2 in fuel assembly components, other than fuel cladding (e.g., water rods, spacer grids, etc.) for reloads of GNF fuel is acceptable.

The NRC staff recommends approval of Ziron as a suitable substitute or replacement for Zircaloy-2 subject to the following conditions and limitations listed in Section 5.

5.0 LIMITATIONS AND CONDITIONS

1. The fuel rod burnup limit for this approval shall remain at currently established limits as specified in the safety evaluation for the topical report, “The Prime Model for Analysis of Fuel Rod Thermal-Mechanical Performance (NEDC-33256P, NEDC-33257P, and NEDC-33258P)” Section 3.9.6.

2. All the conditions listed in previous NRC Safety Evaluation approvals for methodologies used for Zircaloy-2 fuel analysis shall continue to be met, except that the use of Ziron cladding in addition to or in place of Zircaloy-2 cladding is now approved.

3. Based on the schedule listed in the response to RAI-21 (Reference 3) and procedures described in the response to RAI-15 (Reference 3), GNF should provide the NRC staff with a letter(s) containing the following information:

   - Ziron data from Hatch 1 (GE14) and Hatch 2 (GNF2),
     i) Visual
     ii) Oxidation of fuel rods, water rods, and spacer grids
     iii) Profilometry
     iv) Fuel rod length (including qualitative assessment of fuel clad hydrogen content)
     v) Fuel assembly length

6.0 REFERENCES

1. Letter MFN 10-358 from A. Lingenfelter (Global Nuclear Fuel) to US NRC Document Control Desk, “NEDC-33353 and NEDO-33353 Licensing Topical Report Application of

GNF-Ziron to GNF Fuel Designs," Global Nuclear Fuel, December 22, 2010 (ADAMS Accession No. ML103560838).

2. Joseph A. Golla (NRC) to Jerald G. Head (GEH), "Request for Additional Information RE: GEH Licensing Topical Report NEDC-33353P, 'Licensing Topical Report Application of GNF-Ziron to GNF Fuel Designs,'" February 4, 2015 (ADAMS Accession No. ML14261A264, proprietary).

3. Letter MFN 15-059 from Brian R. Moore (GNF) to US NRC Document Control Desk, Enclosure 1, "GNF Response to NRC RAIs for Licensing Topical Report NEDC-33353P, 'Licensing Topical Report Application of GNF-Ziron to GNF Fuel Designs,'" October 23, 2015 (ADAMS Accession No. ML15296A043).

4. Technical Evaluation Report of the Topical Report Enclosure 1, MFN 10-358, "NEDC-55553P, Revision 0 Application of GNF-Ziron to GNF Fuel designs," Dion Sunderland and Ken Geelhood, PNNL, November 30, 2016.

5. *Code of Federal Regulations*, 10 CFR Part 50 Appendix A General Design Criteria

6. *Code of Federal Regulations*, 10 CFR Part 100

7. *Code of Federal Regulations*, 10 CFR Part 50, Section 50.46.

8. Masahisa Inagaki et al, "Zirconium-Based Alloy with High Corrosion Resistance," US Patent 4810461, March 7, 1989.

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Attachment: Resolution of Comments

Principal Contributor: Mathew Panicker, NRR/DSS/SNPB

Date: MARCH___, 2019

Comment Summary for NEDC-33353P and NEDO-33353, "Application of GNF-Ziron to GNF Fuel Designs"

Location	Comment	NRC Resolution
Section 3.1.1 GNF-Ziron Composition Table 1	Page 8 Last row of Table 1: Delete this information as it was not provided in the LTR *Suggested changes shown in the markup.*	Staff accepts the change.
Section 3.1.1 GNF-Ziron Composition	Page 8: GEH recommends the following change. (Lines 28-29): Delete the last sentence as this limit is not in the LTR. "The upper limit of Fe+Ni in Ziron is 0.38 percent." *Suggested changes shown in the markup.*	Staff accepts the change.
Section 3.2.11 Hardness (Meyer)	Page 15: GEH recommends the following change. (Line 2): Delete "which" and Ref. 9 should be Ref. 10. *Suggested changes shown in the markup.*	Staff accepts the change.

Section 3.2.12 Growth	Page 16: "Plant K" is incorrect, the referenced plant is **[ ]** and the fuel is GNF2. GEH suggests the following changes (Lines 12 and 13): "…irradiated in **[ ]** ~~Plant K~~. The fuel is ~~likely Step III (9x9)~~ GNF2 fuel." *Suggested changes shown in the markup.*	Staff accepts the change.
Section 3.2.12 Growth	Page 16: Change to reflect the completion of the irradiation program. GEH suggests the following change (Lines 17-20): "The irradiation program has been completed and GNF ~~committed to sharing~~ has shared the results of this data with the NRC ~~as it became available and to notify the NRC if it demonstrated that the Ziron has different creep or growth behavior from Zircaloy-2~~." *Suggested changes shown in the markup.*	Staff accepts the change. However, the staff will use the following wording to also indicate where the transfer of data was made: "The irradiation program has been completed and GNF has shared the results of this data with the NRC in the submitted LTR."
Section 3.2.13.3 Shadow Corrosion	Page 18: Change to reflect the agreed upon actions based on the conference call on June 27, 2018 with Joe Golla (NRC), Paul Cantonwine (GE Power), Yang-Pi Lin, (GE Power), James F. Harrison (GE Power), and Jerry Head (GE Power). GEH suggests the following change (Lines 21 – 23). "The NRC staff is requesting ~~additional~~ more complete corrosion measurements for Ziron fuel rods ~~and water rods after 3 x 24 month and 4 x 24 month cycles, particularly from GNF2 fuel assemblies~~." *Suggested changes are shown in the markup.*	Staff accepts the change.

Section 3.2.14 Hydrogen Pickup and Hydriding	Page 20: Change to allow flexibility in methodology to assess hydrogen pickup. GEH suggests the following change (Lines 41 and 42): "…hot cell measurements of hydrogen content, or, alternatively, provide some other means of assessing hydrogen pickup such as poolside length measurements of Ziron (or Zircaloy-2)…" and Page 21: GEH suggests the following change (Lines 5 - 10) "The NRC staff requires that GNF provide additional poolside inspection data, including fuel rod length measurements, and provide discussions on how such measurements can be used to assess, qualitatively, the absence of excessive hydrogen pickup by the fuel rod. ~~measurements of hydrogen content in fuel cladding that has operated for three 24-month cycles, with one cycle on the core periphery, and greater than 2000 days, with one or two cycles on the core periphery.~~" *Suggested changes shown in the markup.*	The staff accepts a change to allow for flexibility in methodology to assess hydrogen pickup but is revising the wording to specify the alternative means to be length measurements only: "…hot cell measurements of hydrogen content, or, alternatively, provide poolside length measurements as a means of assessing hydrogen pickup of Ziron…" Staff accepts the change.
Section 3.3.1.1 Stress	Page 22: Correct the section reference. GEH suggests the following change (Line 17): Change Section 3.2.7 to 3.2.6. *Suggested change shown in the markup.*	Staff accepts the change.

Section 3.3.1.2 Strain	Page 22: Correct the section reference. GEH suggests the following change (Line 38): Change Section 3.7 to 3.2.7. *Suggested change shown in the markup.*	Staff accepts the change.
Section 3.3.1.7 Axial Growth	Page 25: Some of the text uses PWR fuel assembly nomenclature. GEH suggests the following changes (Lines 35, 38-39, and 43): Line 35: "…~~rod-to-nozzle gap closure~~ and fuel rod bowing and possible failure." Lines 38-39: "…rods will be designed with adequate clearance between the fuel rod ends and the ~~top and bottom nozzles~~ upper tie plate to accommodate the differences in the growth of the fuel rods…" Line 43: "…between the fuel rods and the fuel ~~top and bottom nozzles~~ upper tie plate tie plate is allowed…" *Suggested changes shown in the markup.*	Staff accepts the changes.

Section 3.4.1 Hydriding	Page 27: Change to reflect the agreed upon actions based on the conference call on June 27, 2018 with Joe Golla (NRC), Paul Cantonwine (GE Power), Yang-Pi Lin, (GE Power), James F. Harrison (GE Power), and Jerry Head (GE Power). GEH suggests the following changes (Lines 20 – 23): "<u>However, GNF is not planning on using oxidation as a proxy for hydrogen.</u> ~~Also, the applicant needs to confirm that the Ziron (or Zircaloy-2) cladding does indeed meet whatever limits are approved by the NRC (see Section 3.2.14.~~" *Suggested changes shown in the markup.*	Staff accepts the changes.
Section 3.4.2 Cladding Collapse	Page 27: Correct the section reference. GEH suggests the following change (Line 49): Change Section 3.8 to 3.2.8. *Suggested change shown in the markup.*	Staff accepts the correction.
Section 3.4.7 Cladding Rupture	Page 30: Correct the section reference. GEH suggests the following change (Line 26): Change Section 4.3.3 to 3.5.3. *Suggested change shown in the markup.*	Staff accepts the correction.
Section 3.4.8 Fuel Rod Mechanical Fracturing	Page 30: Correct the section reference. GEH suggests the following change (Line 46): Change Section 4.3.4 to 3.5.4. *Suggested change shown in the markup.*	Staff accepts the correction.

Section 3.6 Materials Testing and Fuel Surveillance	Page 36: Correct statement tense. GEH suggests the following change (Line 14): Change “are currently operating” to “operated” *Suggested change shown in the markup.*	Staff accepts the change.
Section 3.6 Materials Testing and Fuel Surveillance	Page 36: SE suggests a future decision that has not yet been made. GEH suggests the following change (Lines 19 - 20): “~~GNF is also introducing GNF3, so Ziron will become a standard cladding material in GNF3 as well~~.” or change to “GNF is also introducing GNF3, so Ziron may become a standard cladding material in GNF3 as well.” *Suggested change shown in the markup.*	Staff accepts the change.
Section 3.6 Materials Testing and Fuel Surveillancee	Page 37: Revise to be consistent with Section 5. GEH suggests the following change (Lines 8 - 12): “~~While t~~The GNF surveillance program seems to rely on observation of acceleration of fuel rod or assembly growth to indicate an increase in hydrogen pickup, an approach which is consistent with the Westinghouse experience at KKL.~~, the NRC staff recommends GNF to provide measurements of hydrogen content on selected Zircaloy-2 and Ziron cladding, which have operated for long residence time (6-8 years, or 2000 – 2800 days) at low power.~~” *Suggested change shown in the markup.*	Staff accepts the change.