November 9, 2015

Mr. Jerald G. Head
Senior Vice President, Regulatory Affairs
General Electric-Hitachi
Nuclear Energy Americas, LLC
P.O. Box 780, M/C A-18
Wilmington, NC 28401-0780

SUBJECT: FINAL SAFETY EVALUATION FOR GENERAL ELECTRIC HITACHI NUCLEAR ENERGY AMERICAS, LLC TOPICAL REPORT NEDC-33406P, REVISION 2, "ADDITIVE FUEL PELLETS FOR GNF FUEL DESIGNS" (TAC NO. ME3082)

Dear Mr. Head:

By letter dated December 18, 2009 (Agencywide Documents Access and Management System (ADAMS) Package Accession No. ML093560114), GE Hitachi Nuclear Energy Americas, LLC (GEH) submitted Topical Report (TR) NEDC-33406P, Revision 2, "Additive Fuel Pellets for GNF [Global Nuclear Fuel – Americas, LLC] Fuel Designs," to the U.S. Nuclear Regulatory Commission (NRC) staff for review.

By letter dated December 11, 2014, an NRC draft safety evaluation (SE) regarding our approval of TR NEDC-33406P, Revision 2, was provided for your review and comment. By letter dated February 16, 2015, you provided comments on the draft SE. The NRC staff's disposition of the GEH comments on the draft SE are discussed in the attachment to the final SE enclosed with this letter. Please note the enclosed SE is a non-proprietary version prepared for public release.

The NRC staff has found that TR NEDC-33406P, Revision 2, 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 license 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 GEH publish approved proprietary and non-proprietary versions of TR NEDC-33406P 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 and your responses. The approved versions shall include an "-A" (designating approved) following the TR identification symbol.

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

Sincerely,

/RA/

Mirela Gavrilas, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 710

Enclosure:
Final Safety Evaluation (Non-Proprietary)

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Sincerely,

/RA/

Mirela Gavrilas, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

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Enclosure:
Final Safety Evaluation (Non-Proprietary)

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NAME	JGolla	DHarrison	JDean	AMendiola	MGavrilas
DATE	10/26/2015	10/08/2015	10/26/2015	10/30/2015	11/09/2015

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SAFETY EVALUATION BY THE

OFFICE OF NUCLEAR REACTOR REGULATION

LICENSING TOPICAL REPORT

ADDITIVE FUEL PELLETS FOR GNF FUEL DESIGNS

NEDC-33406P, REVISION 2

(TAC NO. ME3082)

1.0 INTRODUCTION AND BACKGROUND

By letter dated December 18, 2009, Global Nuclear Fuel (GNF) submitted a Licensing Topical Report (LTR), "Additive Fuel Pellets for GNF Fuel Designs," NEDC-33406P, Revision 2, December 18, 2009 (Reference 1). GNF desires to introduce aluminosilicate additive fuel pellets in to GNF fuel products to increase fuel reliability and operational flexibility of GNF nuclear fuel. The scope of this LTR focuses on relevant fuel material properties and in-core behavioral characteristics that are affected by the addition of additive to the UO_2 fuel. Material properties of fuel with additive such as melting, density, thermal expansion, thermal conductivity, grain size and grain strength, stored thermal energy, creep, yield strength, elastic modulus, strain hardening coefficient and tangent modulus, plastic Poisson's ratio, and swelling are treated using the PRIME thermal-mechanical code (Reference 2).

This LTR describes the proposed introduction of aluminosilicate additive fuel pellets into normal core reloads. A nominal value of **[**

]

Pacific Northwest National Laboratory (PNNL) has supported this review as a consultant to the NRC staff. Several rounds of request for additional information questions from both the NRC staff and the PNNL staff were sent to GNF. The first round of RAIs is listed in Reference 2. All responses to the RAI questions are listed in Reference 3.

This review focused on the following major areas of the material properties (Section 2.0 of Reference 1) that includes microstructure, melting temperature, theoretical density, thermal expansion, thermal conductivity, specific heat, grain size and growth, creep, yield stress, modulus of elasticity, strain hardening coefficient and tangent modulus, plastic Poisson's ratio, and rim structure effects. The review also covers the following in-reactor performance concerns (Section 3.0 of Reference 1) from the use of additive fuel; impact of fuel oxidation resulting in fuel washout when exposed to primary coolant water in the event of fuel failure, impact of fuel melting limits, impact on reactivity insertion accident (RIA) thresholds, impact on in-reactor densification, and impact on release of fission products and accident source terms. The review covers the in-reactor data used to verify the performance of additive fuel (Section 4.0) and the licensing criteria (Section 5.0) used to verify satisfactory performance of the additive fuel.

The PRIME code (Reference 4) was used by GNF for stored energy and rod pressure inputs to loss-of-coolant accident (LOCA), determining maximum rod internal pressure, cladding strain, cladding fatigue, and fuel melting analyses. Comparative calculations have been made with the NRC-developed FRAPCON-3 fuel performance code (References 5 and 6) for comparison to typical PRIME specified acceptable fuel design limit (SAFDL) calculations for maximum rod internal pressure, LOCA temperature (stored energy) and pressure, fuel melting, and clad strain analyses. An evaluation of the use of PRIME and design limits for these licensing applications is discussed in Sections 3.3 and 3.4. Operating experience of additive fuel is discussed in Sections 3.3 and 3.5. The conclusions and recommended limitations are presented in Section 4.2.

The NRC audit code, FRAPCON-3 (Reference 5), has been used as an aid in this review to assess the models and calculation results from PRIME. This code was originally assessed against a large volume of low and high burnup fuel performance data (Reference 6) and has been continually assessed against newer high burnup data (Reference 7) as it became available.

2.0 REGULATORY EVALUATION

The NRC staff used the guidance of Standard Review Plan (SRP), NUREG-0800, Section 4.2, “Fuel System Design” for the review of NEDC-33406P, Revision 2. SRP Section 4.2 acceptance criteria are based on meeting the requirements of General Design Criteria (GDC) 10 of Appendix A of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50.

GDC 10 states: *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.*

GDC 10 establishes SAFDLs to ensure that the fuel is “not damaged.” That means that fuel rods do not fail, fuel system dimensions remain within operational tolerances, and functional capabilities are not reduced below those assumed in the safety analysis.

In accordance with SRP Section 4.2, the objectives of the fuel system safety review are to provide assurance that:

a. The fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs), fuel system damage is never so severe as to prevent control rod insertion when it is required,

b. The number of fuel rod failures is not underestimated for postulated accidents, and

c. Coolability is always maintained.

The NRC staff reviewed the additive fuel pellet topical report to: (1) ensure that the material properties and in-core behavioral characteristics of additive fuel as analyzed using the PRIME code and supported by confirmatory calculations using the FRAPCON audit code are capable of accurately (or conservatively) ensuring the fuel system safety criteria, (2) identify any limitations on the behavioral characteristics of the additive fuel, and (3) ensure compliance of fuel design criteria with licensing requirements of fuel designs and is capable of ensuring compliance with SRP Section 4.2 guidance criteria.

3.0 TECHNICAL EVALUATION

Global Nuclear Fuels (GNF) submitted the LTR on additive fuel pellets for its fuel designs in order to increase the reliability and operational flexibility of nuclear reactor fuel bundles and cores.

This review focused on the following major areas of the material properties and in-reactor performance issues such as washout behavior, fuel melting, RIA behavior, in-reactor densification, validity of alternate source term (AST) assumptions, and long term fuel storage. The review also covered the in-reactor data used to verify the performance of additive fuel and the licensing criteria used to verify satisfactory performance of the additive fuel.

3.1 Additive Fuel Material Properties

The GNF additive fuel material properties addressed in this section are, in general, applicable to properties under normal operation and AOOs but some are also applicable to design basis accidents such as thermal conductivity, thermal expansion, specific heat, and stored thermal energy. Other properties which are unique to in-reactor fuel performance such as washout behavior that results in oxidation of the fuel upon introduction of water in to the fuel rod after a breach of fuel rod cladding, fuel melting limits, RIA failure thresholds, in-reactor densification, and release of fission products will be addressed in Section 3.2.

3.1.1 *Microstructure*

Microstructure is not usually defined as a material property, however, it can impact the properties of a material, and as a result it is included in this section. The material properties it can impact are the fuel melting temperature and may impact the fission gas release (FGR). During fabrication the aluminosilicate additive **[**

] as depicted in Figure 2-1 of the topical report. The additive has a **[**

] for this phase composition.

Therefore, [ ] can exist at the grain boundaries and will be discussed in Section 3.1.2 on fuel melting. The additive fuel microstructure is not modeled explicitly in the PRIME fuel performance code but is implicitly included in the models for fuel melting and FGR.

[ ]. This will be discussed in Section 3.3.2 on the comparison of the FGR model comparisons to additive fuel FGR data.

3.1.2 *Fuel Melting*

Fuel melting is generally not allowed during normal operation nor during AOOs to ensure that the fuel does not (1) relocate within the fuel rod, (2) result in excessive FGR that could exceed the rod pressure limit, and (3) prevent deleterious reaction between the molten fuel and cladding. The intent of no fuel melting for UO_2 criteria is to assure geometric stability of the pellet and preclude the migration of liquid UO_2. For normal operation and AOOs fuel relocation is more limiting than reaction with the cladding because relocation will have to be present for the reaction with the cladding to take place.

The melting temperature for additive fuel is [ ] is called the eutectic temperature. Therefore, a small amount of liquid begins just above the eutectic temperature. GNF has provided a significant amount of data to determine the eutectic temperature for their composition of additive fuel. The NRC staff finds the GNF determination of eutectic temperature acceptable.

For the purpose of additive fuel pellets, in order to define the point of melting that is acceptable for fuel performance, GNF has proposed a [ ] has been determined based on experimental testing of single additive fuel pellets in a furnace under isothermal temperatures (no temperature gradients in the fuel pellet). The isothermal temperature of [ ].

The NRC staff requested (Reference 3, RAI 24) information regarding whether fuel [ ] has been examined in full length (12 foot) fuel rods because the weight of a 12 foot fuel column is significant compared to testing of a single fuel pellet. The staff also requested the length of time for the [ ] along with a suggestion/ question on whether there should be a time limit for an AOO event [ ].

GNF responded that they do not have slumping tests for **[** **]** that is above the eutectic temperature where the **[** **]** for AOO events. The center region of the pellet has **[** **]** but the outer region of the pellet is well below the eutectic temperature.

The fuel pellets above and below the small number of pellets with **[** **]** will also be solid (no liquid). That will help contain the **[** **]** in the center of the pellet. GNF also stated that power ramp tests to simulate AOO events on fuel rods with additive fuel have shown a small amount of **[** **]** movement due to pellet-cladding mechanical interaction (PCMI) but the **[** **]** did not extend beyond the eutectic temperature such that the outer fuel below the eutectic temperature constrained the **[** **]** fuel. GNF further noted that for both thermal overpower (TOP) and mechanical overpower (MOP) events of **[** **]** overpower (OP) and **[** **]** OP, respectively, the **[** **]** for the nominal additive concentration of **[** **]**. It is also noted that since both conditions must be met, the TOP event is the most limiting as it provides a limit on the maximum fuel centerline temperature. GNF provided an additional analysis demonstrating that the **[** **]** cannot be achieved at any axial node for a TOP event. GNF responded to the staff request regarding the limitation in time with a significant fraction of fuel above the eutectic temperature. The objective of the current additive fuel rod and core design methodologies is to assure that the licensing requirement of no fuel melting during normal operation, including AOOs, is satisfied. To meet this objective, a **[** **]** TOP limit is defined on the basis of a limiting slow transient. The duration of the transient is assumed to be **[** **]** and is based upon the expected spectrum of slow boiling water reactor (BWR) transients. To confirm the adequacy of **[** **]** time limit for the additive fuel, Table 2-1 from Reference 1 was reproduced in Reference 3 (NRC RAI 24-S01) and was expanded to include both the additive concentration and the time at temperature. This table lists additive concentration, time in minutes at temperature, liquid volume (%), and **[** **]**. The table data confirm that for the planned GNF upper bound additive concentration of **[** **]**. Therefore, the assumed **[** **]** duration for the determination of TOP limit for additive fuel is acceptable. The NRC staff finds the data and the response acceptable.

The NRC staff asked whether a limit should be placed on the amount of **[** **]** during normal operation because the amount of time at temperature during normal operation could be considered longer than those tested for a TOP event (Reference 3, RAI 24-S02). GNF provided an analysis of the amount of fuel above the eutectic temperature at their thermal-mechanical operating limit (TMOL) for steady-state power operation at their **[** **]** limit. This analysis demonstrated that there may be a very small amount of additive fuel **([** **])** that will be **[**

]. GNF noted that this

small amount of [ ] and will remain contained by the cooler radial outer solid fuel pellet and cooler solid pellets axially above and below. GNF also provided calculations of the extent of fuel melting at the TMOL as a function of burnup that demonstrated a very limited range of burnup [ ] and no melting above [ ]. The NRC staff agrees that this extremely small amount of [ ] and should be easily contained by the cooler portions of surrounding (radial and axial) fuel. The staff finds this response acceptable but the amount of [ ] unless further testing at long time periods typical for steady-state operation or analyses are provided (See Section 4.2).

3.1.3 Theoretical Density

GNF has proposed to use the linear rule of mixtures to determine the theoretical density of the additive fuel. The room temperature theoretical density of the additive fuel differs from the standard UO_2 due to the higher density UO_2 displaced by the lower density additive phase. This approach of calculating the theoretical density has been used for gadolinia [ ] fuel previously approved by NRC in the PRIME fuel performance (Reference 4). The NRC staff finds this approach to determining fuel density acceptable.

3.1.4 *Thermal Expansion*

The thermal expansion of additive fuel below [ ] additive has been shown to be the same as for UO_2 when temperatures are below the eutectic temperature. Above eutectic temperature, the thermal expansion of additive fuel is slightly different than that of standard UO_2. Above the eutectic temperature there is an increasing fraction of [ ] in essentially no net change in density relative to standard UO_2.

Above the [ ] temperature there is a volume change of ~ 9.6 percent due to the change from solid to liquid phase. However, due to the very low concentration of additive fuel [ ] the change in thermal expansion is very small. This is illustrated in Figure 1 where the thermal expansion of UO_2 in the GNF PRIME fuel performance code and that for additive fuel is plotted versus temperature. Also, included in this figure is the thermal expansion model in the FRAPCON-3.4 fuel performance code.

[

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Figure 1. Thermal Expansion Strains Predicted by PRIME UO_2 (non-additive), FRAPCON-3.4, and the GNF Additive Fuel Models.

It can be seen from Figure 1 that there is little difference in thermal expansion between additive fuel and the models in PRIME and FRAPCON-3.4 for UO_2 fuel up to the bulk melting temperature of additive fuel (>2750°C). This demonstrates that for the concentrations proposed by GNF for additive fuel there is little change in thermal expansion compared to that for UO_2 fuel up to the bulk melting temperature of additive fuel. Because GNF does not allow fuel melting for normal operation or AOOs, additive fuel has little impact on fuel thermal expansion for these conditions. The NRC staff agrees that for the very small additions of additive fuel there is little impact on fuel thermal expansion, i.e., it is well within the uncertainty of the UO_2 thermal expansion data. The staff finds the GNF model for thermal expansion of additive fuel acceptable.

3.1.5 *Thermal Conductivity*

The thermal conductivity variation with small aluminosilicate additions results in a very small decrease and this decrease is well within the uncertainty of the UO_2 thermal conductivity data. GNF has provided laboratory thermal conductivity measurements performed on pellets and the data are plotted for additive concentrations above [ ] in Figure 2-14 of the LTR (Reference 1). GNF has also provided plots for thermal conductivity as a function of temperature for additive concentrations ranging from 0 wt% to [ ] for various burnups ranging 0.0 GWd/MTU to 60 GWd/MTU (Reference 3, Figure RAI 6-1) and is reproduced here as Figure 2. The model derived from the GNF data is illustrated in Figure 3 where GNF PRIME thermal conductivity model for additive fuel ([ ] additive) at a burnup of 1 GWd/MTU and fuel density of 95% TD) is plotted versus temperature (up to the bulk melting temperature of additive fuel) and compared with the FRAPCON-3.4 model for UO_2 fuel. The small difference between these two models from 1400°C to 2200°C is primarily due to the difference in the PRIME and FRAPCON-3.4 UO_2 models and not due to additive fuel. The model for determining the thermal conductivity of additive fuel is very similar to that for gadolinia fuel that was previously approved by NRC.

[

]

Figure 2. Thermal Conductivity as a Function of Temperature, Additive Concentration, and Exposure

[

]

Figure 3. Comparison of GNF PRIME Code Thermal Conductivity for Additive Fuel ([ ] Al_2O_3-SiO_2) to UO_2 Thermal Conductivity in FRAPCON-3.4

Responding to a staff question why the thermal conductivity dropped significantly at [ ], GNF responded that the additive liquid has a lower thermal conductivity than the solid phase and the volume of liquid additive becomes significant at this temperature significantly reducing the thermal conductivity. The staff finds this explanation acceptable.

The NRC staff concludes that the GNF thermal conductivity model for the additive fuel additions proposed is within the uncertainty of the UO_2 thermal conductivity data. The staff finds the GNF model for thermal conductivity of additive fuel acceptable.

3.1.6 *Specific Heat and Stored Energy*

The specific heat of additive fuel is calculated by applying the linear rule of mixtures similar to that used for fuel density. Specific heat is used in the calculation of fuel stored energy for LOCAs. The specific heat of additive fuel is nearly identical to that for UO_2 because of the small additions of Al_2O_3-SiO_2 additive to UO_2 fuel. A comparison of PRIME calculated stored energy versus fuel temperature compared to that calculated with FRAPCON-3.4 code for UO_2 fuel in Figure 4 demonstrates little difference between additive and UO_2 fuel. The NRC staff concludes that the GNF thermal conductivity model for the additive fuel additions proposed is within the uncertainty of the UO_2 specific heat data and finds the GNF model for specific heat of additive fuel acceptable.

[

]

Figure 4. Comparison of GNF PRIME Stored Energy for Additive Fuel ([ ] Al_2O_3-SiO_2) To That Calculated With The FRAPCON-3.4 Code for UO_2 Fuel

3.1.7 *Grain Size and Growth*

Grain size and growth are important in the sense that there is a tendency for larger grains to suppress FGR at low and moderate temperatures. Initial grain size and grain growth during reactor operation are conservatively assumed to be same in additive fuel as that for the standard UO_2 fuel. [

]. The GNF models for fuel densification and creep are also dependent on the initial grain size but grain growth is not used for these two parameters.

The staff requested the assumed as-fabricated grain size used for FGR calculations in the PRIME code and the coefficients used for grain growth for additive fuel (Reference 3, RAI 18). GNF responded that the assumed initial grain size for additive fuel was conservatively (the GNF FGR model predicts higher FGR with smaller grain size) assumed to be the same as used for UO_2 fuel of [ ] (based on 3-D dimensions) even though the initial as-fabricated grain size for additive fuel is [ ]. GNF also stated that the additive fuel grain growth is assumed to be the same as UO_2 grain growth, i.e., the UO_2 grain model applied to additive fuel, and they limit the maximum grain size the same as for UO_2 fuel.

This same RAI (Reference 3, RAI 18) asked for the impact of grain growth on rod pressures (due to FGR), creep and cladding strain; and also the impact of additive fuel on LOCA stored energy and peak cladding temperature (PCT) compared to UO_2 fuel. GNF responded that grain growth and thus the grain growth model impacts the rod internal pressure (RIP) licensing calculation but not the centerline temperature and cladding plastic strain licensing calculations. Since the same initial grain size and grain growth model is used for both additive and non-additive fuel, the impact of grain growth model on the pressure calculation will be approximately identical for additive and non-additive fuel. GNF further responded that the impact of additive fuel on LOCA stored energy at the highest stored energy value was negligible ([ ] difference).

The NRC staff concludes that the assumption of initial grain size of [ ] is conservative in relation to FGR (rod pressure) and application to fuel creep and densification will be dependent on how well the PRIME code compares to measured fuel temperatures and cladding strain (see Sections 3.3.1 and 3.3.3) from additive fuel. In addition, the application of the UO_2 grain growth model to FGR will depend on the PRIME predictions of FGR data from additive fuel (see Section 3.3.2).

3.1.8 *Creep*

Experimental demonstration has shown that the creep behavior of additive fuel is significantly different from that of standard non-additive fuel at elevated temperatures. Fuel creep rate has a significant impact on cladding strain analysis. GNF performed PRIME calculations of steady state creep rates as a function of stress at various temperatures for both [ ] additive and standard UO_2 fuel (Figure 2-15 of Reference 1). GNF has determined that the creep rate for additive fuel compared to UO_2 fuel, e.g., at 1473K and 5 ksi stress additive fuel is [ ] greater creep than UO_2. The comparative study provided by GNF of predicted steady-state creep rates for several different temperatures between 1473°K to 1773°K and stresses between 1,000 psi to 18,000 psi at additive concentrations of [ ] in Figures 2-16 through 2-18 of the submittal (Reference 1) compared reasonably well to the creep data for additive fuel.

The staff's RAI (Reference 3, RAI 26) noted that the creep rates at high stresses reached values as high as [ ] and asked how these high creep rates could be verified and applied when the measured creep rates from the data were at several orders of magnitude less than those calculated. GNF responded that these high creep rates are only obtained at stresses above the yield stress and the fuel is assumed to result in immediate plastic deformation when above the yield stress, therefore, these high creep rates are not applied in fuel strain calculations.

Responding to the above mentioned RAI for a comparison of actual measured strains from three different creep measurements to those predicted by the GNF creep model for additive fuel, GNF provided only one comparison to creep data at 1813°K for 1.7 psi stress and

[ ] additive that demonstrated the GNF additive creep model over predicted fuel strains initially
[ ] but at longer times the GNF model predicted the data well.

The same RAI asked if fuel mass is conserved when hard contact is experienced that results in the cladding pushing back on the fuel resulting in fuel movement due to creep or plastic strain above the yield strength. The staff requested that if the fuel mass is conserved, has the movement of the fuel, if any, been confirmed experimentally based on direct observation of porosity and dish filling due to creep. GNF responded that fuel volume is [ ], as discussed in Section 3.1.12. The flow of material to conserve volume occurs primarily at the pellet center where temperatures are high and result in fuel movement to [ ]. Direct measurement of this [ ] has not been compared to the model predictions. However, GNF provided a comparison of observed cladding strains from [ ] with additive fuel to those calculated by PRIME assuming UO_2 fuel creep rates and those assuming additive fuel creep rates in Figure 21-2 of Reference 3. This comparison demonstrated that the use of additive creep model provided a much better comparison to the measured strain data that provided an indirect validation of the additive creep model for this [ ].

The staff noted in an earlier draft response that the measured strains in Figure 21-2 did not match up with those quoted for this ramped rod in Table 21-1of Reference 3. GNF responded that the figure in this earlier response was in error and provided a corrected figure in a subsequent response.

The NRC staff's conclusion on the validity of the GNF creep model for additive fuel will be dependent how well the PRIME code compares to measured cladding strains from power ramping tests on additive fuel rods (see Section 3.3.3). This is because fuel creep has a significant impact on calculated cladding deformation (SAFDL strain limit) during AOO events.

3.1.9 *Yield Stress*

Additive fuel has a significant impact on yield strength above the critical temperature (the [ ]). Below the critical temperature the yield stress is considered same as standard UO_2.

Yield stress has an impact on the cladding strain analysis. GNF has performed mechanical testing of additive fuel with additives up to [ ] to determine the yield strength versus temperature. The yield strength of additive fuel has been found to be similar to that for UO_2 fuel when the temperature is below [ ] and then decreases to be approximately a factor of [ ] lower than UO_2 at [ ] where it is assumed to be constant at [ ] with increasing temperature. This [ ] lower limit for yield strength is used to maintain
[ ].

The staff's RAI (Reference 3, RAI 17(a)) noted that no data were presented to verify the yield strength for additive fuel. Also the RAI requested an explanation of why no strain rate dependence exists in the additive fuel model since the submittal (Reference 1, Section 2.9) indicated that yield stress experimental results showed strain rate sensitivity for the yield stress.

However, the strain rate dependence was not provided in the submittal. GNF responded by providing a limited amount of yield stress data for additive fuel that demonstrated the decrease compared to UO_2 fuel above a **[ ]** temperature. Additionally, GNF provided the explicit strain rate sensitivity and showed that the strain rate dependency for yield stress was small for rates in the range of **[ ]**. GNF noted that, as discussed in the response to the referenced RAI, PRIME analyses of power increases are performed using a series of **[**

].

This same RAI also asked what the assumed ductile-brittle transition temperature was for additive fuel. GNF responded that it was assumed to be the same as for UO_2 fuel because it is below the **[ ]** temperature where additive fuel yield strength deviates for that for UO_2 fuel and further claim this has little impact on fuel performance analyses.

The NRC staff conclusion on the validity of the GNF yield strength model for additive fuel will be dependent on how well the PRIME code compares to measured cladding strains from power ramping tests on additive fuel rods (see Section 3.3.3). This is because fuel yield strength has a significant impact on calculated cladding deformation (SAFDL strain limit) during AOO events.

3.1.10 *Modulus of Elasticity*

GNF calculates the modulus of elasticity for additive fuel based on the rule of mixtures similar to that used for determining fuel density and specific heat. The application of the rule of mixtures is illustrated in Attachment 17.A of Reference 3.

In response to a staff RAI (RAI 17(b), Reference 3) for data to substantiate the assumption that the rule of mixtures applies to calculating the modulus of elasticity, GNF responded that even though the elastic modulus of Al_2O_3-SiO_2 is significantly lower than that for UO_2 or for $(U,Gd)O_2$ the impact on additive fuel is not significant because of the very small concentrations of Al_2O_3-SiO_2 and within the accuracy of the measurement of elastic modulus up to the yield strength.

The staff's conclusion on the validity of the GNF modulus of elasticity model for additive fuel will be dependent on how well the PRIME code compares to measured cladding strains from power ramping tests on additive fuel rods (see Section 3.3.3).

3.1.11 *Strain Hardening Coefficient and Tangent Modulus*

The strain hardening coefficient and tangent modulus both impact the cladding strain analysis for AOO events (power ramping). GNF has a small adjustment on the strain hardening coefficient and tangent modulus that they note provides only slight effect on PRIME analysis results.

The NRC staff conclusion on the validity of the GNF strain hardening coefficient and tangent modulus for additive fuel will be dependent how well the PRIME code compares to measured cladding strains from power ramping tests on additive fuel rods (see Section 3.3.3).

3.1.12 *Plastic Poisson's Ratio*

The plastic Poisson's ratio impacts the cladding strain analyses for AOO events (power ramping). GNF has assumed that there is **[**

]. GNF noted that they have incorporated this effect to better predict the cladding strains during power ramp tests on additive fuel.

The staff conclusion on the validity of the GNF plastic Poisson's ratio model for additive fuel will be dependent how well the PRIME code compares to measured cladding strains from power ramping tests on additive fuel rods (see Section 3.3.3).

3.1.13 *Effect of Additive on the High Burnup Fuel Pellet Rim Structure*

Irradiation of fuel to high burnup results in changes to the structure of UO_2 pellets. These changes begin when the local burnup exceeds around 60 GWd/MTU and occur in the lower temperature region or near the periphery of the pellet and result in a structure known as the high burnup structure (HBS) or rim structure. Formation of the HBS is attributed to recrystallization which starts at grain boundaries and propagates into the affected grains and to the formation of small pores on and within grains.

The staff requested a comparison of fuel rim formation data from high burnup additive fuel to the standard fuel for rim formation identifying concentration and ratio of Si:Al_2O_3 (RAI 17(c) Reference 3). Also the staff requested data to show that the structure and chemical composition of additive does not change on the old grain boundaries in the rim due to restructuring. In its response, GNF stated that the impact of alumina-silica additive effect on the HBS was evaluated relative to standard and large grain UO_2 fuel in test rods that operated to average exposures of the standard fuel to **[ ]**. The 3-dimensional grain size of the standard large grain non-additive and additive pellets were **[ ]**, respectively. The fuel samples were irradiated in the Halden reactor at linear hear generation rates (LHGRs) that ranged from **[ ]** at the beginning of life (BOL) to **[ ]** at the end of life (EOL). The additive concentration range of **[ ]** and the composition of aluminosilicate was **[ ]**. The resulting pellet structure was examined after irradiation. As Figure RAI 17-3 (Reference 3) illustrates, the HBS formed at the edge of both standard UO_2 and additive pellets and extended radially inward to a greater extent in the standard pellet than in the additive pellet.

For normal operation and AOOs, the primary concern arising from the formation of the HBS is the impact on fuel temperature that in turn impacts FGR and thermal expansion, and thus RIP and cladding strain. The thickness of the HBS is lower for additive fuel than UO_2 fuel and High Burnup Effects Program (HBEP) results indicate that the structure is similar in terms of porosity and retained fission gas. Thus the thermal impact of the HBS rim for additive fuel is expected to be lower than for UO_2 fuel.

The area where the rim could impact behavior important to safe operation is in the dispersal of fission products and fuel during LOCA and RIA events because the strength of the grain boundaries may change due to the additive precipitated on these boundaries during fabrication, however, there is no data to determine these effects. There is some proprietary evidence that larger grain sizes suppress the high burnup rim formation but this data has not been presented by GNF. If the rim formation was suppressed it could possibly reduce the amount of fuel dispersal during a LOCA or RIA event.

In summary, GNF has proposed that the high burnup rim structure in additive will not change the in-reactor performance from that in UO_2 fuel including the following: 1) the formation or properties of the rim with the exception of a different initial as-fabricated grain size, 2) the thermal or mechanical properties, 3) the storage or dispersal of fission products and fuel material in postulated accidents (LOCA or RIA), and 4) the microstructural stability and chemical properties of the rim.

The NRC staff concludes that the additive is not expected to affect the HBS or alter the behavior of the HBS with respect to in-reactor and post irradiation performance. The licensing impacts of HBS for additive fuel will be conservatively assessed using the HBS rim formation model for UO_2 fuel. The staff concludes that the impact of additives on rim structure is conservative and acceptable.

3.2 <u>In-Reactor Performance Assessment</u>

The use of additive fuel could potentially impact the following in-reactor fuel performance issues; fuel oxidation and washout as a result of fuel failure, lower fuel melt limits, RIA failure threshold, fuel densification, FGR, and accident source terms.

3.2.1 *Fuel Oxidation and Washout Due to Fuel Rod Failure*

Washout behavior can be described as that after a breach of the fuel rod cladding. Water is introduced in to the fuel rod interior and can interact with the fuel inside. At BWR conditions, water is mildly corrosive to UO_2. Corrosivity depends on several factors, mainly, the grain structure of the fuel.

GNF has performed a significant amount of testing of the effect of water at BWR conditions on the possible washout of additive fuel due to fuel oxidation with the BWR water. Past testing has shown that the oxidation due to water proceeds along the grain boundaries such that the [ ] could impact oxidation and washout. These oxidation tests have demonstrated that the oxidation for additive fuel is similar to UO_2 fuel with the exception of one set of data which had a higher oxidation rate than UO_2. GNF has presented data that is convincing that the fuel with the higher oxidation rate was due to surface defects not typically found in their production of additive fuel. GNF was not able to determine definitively the cause of these surface defects.

The NRC staff (RAI 25, Reference 3) requested GNF to provide details of corrections made to the fuel oxidation data to account for the effect of surface defects with respect to the number of additive pellets that underwent reactor operation and were examined. This RAI also asked GNF to confirm whether sampling be performed on production of fuel batches of additive fuel and to confirm that no surface defects exist. GNF responded that the pellets with the surface defects were fabricated before GNF was facilitized to produce additive fuel and thus this earlier additive fuel had uncertainties in additive concentration, powder pressing, and sintering; such that these uncertainties would be minimized in batch production of additive fuel. In addition, GNF noted that they will be performing qualification tests on additive fuel before full production begins that will include **[ ]** to verify that no surface defects exist. GNF further noted that once full production begins, microstructure examination is also part of the standard monitoring of pellet quality to determine that pellet characteristics do not change from the earlier qualification tests. This examination includes **[ ]** measurements that may detect surface defects.

The NRC staff requested GNF to address the production qualification and how on-going monitoring will ensure that the pellets meet specifications and whether the qualification and quality monitoring will be sufficient to detect surface defects. GNF responded that the qualification includes **[ ]**. For the production qualification of additive fuel, pellets from press-feed blends of **[ ]** were subjected to extensive microstructure examination to assure that additive distribution is uniform and that grain size and structure are as expected. **[ ]** to assure that pellet characteristics do not change, although to a lesser extent. GNF production pellets have closed, stable pores, and as a result have very low open porosity. For the additive pellet production qualification, the nominal measured open porosity is reported to be approximately **[ ]**. Examination of **[ ]** lead use assembly (LUA) pellets reveal surface flaws equivalent to approximately **[ ]** of pellet volume. Since open porosity testing **[ ]** of pellet quality, open porosity is expected to identify the presence of surface flaws such as those in some of the **[ ]** additive pellets if they were to occur in production pellets.

An extension of RAI 25 requested GNF to provide information on any specification for **[ ]** and how the flaws will be detected if the flaw is outside of normal distribution. The estimate of **[ ]** surface defect of pellets is based on an assumed defect geometry and distribution. Since this volume is at the surface of the pellet it will be included as open porosity resulting from the normal fabrication process and additional porosity due to anomalous surface defects. GNF has shown that pellets with the anomalous open porosity will have much higher oxidation in a corrosion test [

].

The staff reviewed the GNF responses on detection of surface defects similar to those in the additive fuel with high oxidation and concludes that due to the small size of these defects, it may be difficult to identify these defects in production batches based on standard testing done on these batches.

However, the staff notes that if washout were to occur in additive fuel rods, the release activity will be quickly detected in plant offgas systems. Past experience with fuel washout in commercial plants have shown that a plant can detect this activity and shutdown before exceeding coolant and offgas activity limits.

3.2.2 *Fuel Melting*

In addition to fuel melting behavior described in Section 3.1.2, few other considerations for fuel melting behavior during its in-reactor performance is described in this section. One such aspect of melting behavior is evolution of the fuel microstructure upon thermal cycling that causes repeated increases and decreases in [ ] in the pellets. During testing of pellets at high additive concentrations up to [

]. This indicates the possibility of microstructural evolution due to thermal cycling. In factory-produced pellets [

], thus resulting in a microstructure that is indistinguishable from that present before thermal cycling. Because of this, thermal cycling is not considered to have any new effect on additive fuel properties or performance. The NRC staff accepts this conclusion.

3.2.3 *Reactivity Insertion Accident (RIA) Characteristics*

An RIA is an important postulated accident for the design of LWRs. This postulated accident results from an inadvertent insertion of reactivity due to the ejection of a control rod assembly in a PWR or the drop of a control blade in a BWR. In the unlikely event that sufficient reactivity is inserted into the reactor core by the ejected/dropped control rod, prompt energy deposition into the fuel can occur, which when sufficiently high can lead to fuel rod failure.

GNF has presented RIA testing performed in the Nuclear Safety Research Reactor (NSRR) at the Japan Atomic Energy Research Institute (JAERI) from 30 fuel rods with different additive compositions and concentrations. These tests were all performed on unirradiated fuel rods. Those with concentrations near those proposed by GNF for their additive fuel demonstrated a higher failure level than for UO_2 fuel rods. PNNL has performed an evaluation of failure threshold of MOX fuel compared to UO_2 fuel (Beyer and Geelhood 2013, Reference 11) that concluded no difference in failure threshold between these two fuel types. MOX fuel is similar to additive fuel in a couple of areas such as higher creep rate than UO_2 fuel for both and higher storage of fission gas on grain boundaries. Therefore, the failure threshold for additive fuel may be similar to that for UO_2 fuel.

An RAI (RAI 23, Reference 3) noted that the higher content of fission gas on grain boundaries and the higher creep rate than for UO_2 fuel, the additive fuel has the potential to increase the dispersal of additive fuel if fuel rod failure is experienced during a RIA event.

This RAI also noted the additional gas on the grain boundaries could result in higher fission product release when the grain boundaries are fractured during the RIA. This may result in higher radiological releases than for UO_2 fuel. GNF states that since the GNF additive **[**

]. Also, the dispersal of MOX fuel during an RIA is impacted by increased gaseous swelling relative to UO_2 due to increased fission gas bubbles on grain boundaries. Since the additive fuel has **[**

].

GNF has responded that there are currently no in-reactor nor prototypical ex-reactor heating tests of high burnup additive fuel to determine whether fuel dispersal is similar or different than for the UO_2 or MOX fuel tested at high burnup.

GNF's response to RAI 17 indicates that since the additive **[ ]**, the impact of additive is expected to cause a **[ ]** HBS for additive fuel with similar thermal-mechanical properties as for UO_2 pellets. The impact of additive on HBS has been studied by Post Irradiation Examination (PIE) of 9x9 LUAs with additive and standard pellets. Rapid heating of the pellets caused cracks in the pellets at around **[ ]** which is higher than the temperature required to generate cracks in high burnup of **[ ]** UO_2 during rapid heating with no restraint. From the results of these tests, it is concluded that no major impacts of the additive on the HBS have been observed to date.

The NRC currently does not have a limit on fuel dispersal during a RIA event other than it should be considered if the fuel fails during this event. In the event the failure threshold is exceeded, fuel dispersal in additive fuel will be considered using the same basis as standard UO_2 fuel.

In regards to a higher radiological release in additive fuel during a RIA event, GNF has responded that this should also be less than or similar to that for UO_2 fuel based on the fact that they conclude FGR during steady-state power operation and AOOs is similar to UO_2. The staff notes that an evaluation of release from MOX fuel has concluded that it has a higher release than for UO_2 fuel due to the higher fission gas on grain boundaries in MOX fuel (Reference 8). The issue of radiological release of additive fuel will be addressed in Sections 3.2.6 and 3.3.2 on FGR during normal operation and AOOs.

3.2.4 *Fuel Densification and Swelling*

GNF proposes to use the previously approved UO_2 densification and swelling models in PRIME for application to GNF additive fuel (Reference 9). With the approval of TR NEDE-33241P-A, the requirement for routine densification was replaced by qualification of densification for a new design or fabrication process followed by density monitoring of 100 percent of pellet lots. GNF has stated that the in-reactor densification and swelling of additive fuel is expected to be unchanged with respect to standard UO_2 fuel. They state the evidence for similar densification is based on ex-reactor densification tests on unirradiated additive fuel pellets and a limited amount of in-reactor tests.

However, no data were provided in the submittal to verify the above conclusions of similar behavior to standard UO_2 fuel. The staff requested GNF (RAI 17(d), Reference 3) provide in-reactor densification and swelling data to confirm the similar behavior of additive fuel to standard UO_2 fuel. GNF confirmed that they conducted a 10 year program to irradiate additive fuel in the Halden reactor with six instrumented fuel assemblies (IFAs) that included two UO_2 rods, two additive rods with **[ ]** additive, and 2 additive rods with **[ ]** additive. **[ ]**. These rods were operated in the range **[ ]** to burnups of **[ ]**. The results listed in Table RAI 17-1 (Reference 3) show that the densification response of UO_2 and additive fuel within the range of data used in the development of the PRIME model and are similar. Table RAI 17-2 lists the fuel swelling rates for UO_2 and additive fuel for a limited number of rods. Results indicate that the swelling rates for both UO_2 and additive fuel are similar.

The staff notes that GNF provided a limited amount of data that confirmed more or less similar behavior with respect to densification (**[ ]** for additive than for UO_2 fuel). The application of the previously approved UO_2 densification model to GNF additive fuel is conservative if additive fuel has **[ ]**. The NRC staff concludes that the application of the previously approved UO_2 densification model to GNF additive fuel is acceptable. The very small amount of additive fuel swelling data that was within the range of UO_2 fuel swelling from Halden tests at burnups less than 75 GWd/MTU was compiled by PNNL staff for developing the FRAPCON-3.4 swelling model (Reference 10). The staff concludes that the application of the previously approved UO_2 swelling model to GNF additive fuel is acceptable.

3.2.5 *Fission Gas Release (FGR)*

GNF proposes to use the previously approved UO_2 FGR model in PRIME for application to GNF additive fuel. GNF has provided FGR data from additive fuel with PRIME predictions of this data to verify that the UO_2 FGR model adequately predicts this data. The staff evaluation of the PRIME FGR model predictions to the additive fuel data will be discussed in Section 3.3.2 below.

3.2.6 *Alternate Source Term (AST)*

The AST used in plant licensing should apply equally well to additive and non-additive fuel. NRC's NUREG-1465 (Reference 12) provides a realistic estimate of the radiological species released to the containment in the event of a severe reactor accident involving substantial meltdown of the core. Of specific interest for additive fuel is the reaction of Cesium (Cs) with the **[ ]** in the additive fuel and its effect on Cs release under accident conditions. The alternate source term assumes 95 percent of the released iodine is in the chemical form of cesium iodide (CsI) with the remainder elemental iodine (I) and organic iodide (Reference 13).

The CsI is soluble in water and since the source term assumes the pH of water within the containment above 7.0, this minimizes the irradiation-induced conversion of ionic iodine in pools of water and wet surfaces to elemental iodine. Cs can form a relatively stable compound with **[ ]** from additive and fission generated Cs co-resides on the grain boundaries with the additive phase. **[ ]**. The combination of the residence of Cs within the grain boundary and the CsI solubility property in pools of water contribute to the total quantity of Cs to be substantially less than the core-wide inventory of fission-generated Cs. The fact that there is an adequate quantity of Cs expected to reside in the pellet-cladding gap during the initial stage of an accident to react with all of the iodine, and the Cs has sufficient instability at later accident conditions to maintain availability of Cs, the alternate source term assumptions used in design of plant systems should not be affected by the use of additive fuel. The NRC staff accepts the fact that the source term is not affected by the additive fuel.

3.3 <u>In-Reactor Data to Verify Qualification of Additive Fuel</u>

GNF has performed several experiments to investigate additive fuel behavior. The qualification data base for additive fuel includes fuel temperature, FGR, cladding deformation (strain), and RIP measurements in-reactor. The sections below reflect these four different data measurements.

3.3.1 *Fuel Temperature*

The PRIME predicted temperatures for the small additive concentrations proposed results in a very small change in fuel thermal conductivity (see Section 3.1.5) from UO_2 fuel. This should result in very similar temperatures to those for UO_2 fuel because the maximum additive concentration is only [ ]. GNF has provided validation of the PRIME code temperature predictions of additive fuel by demonstrating that the code adequately predicts additive fuel temperatures of in-reactor temperature measurements for additive fuel from Halden Reactor tests. The code data comparisons are provided in Figures 4-1 and 4-2 of the submittal that demonstrate the predictions of additive fuel are within those for UO_2 fuel up to a burnup of [ ]. The thermal conductivity burnup dependence of additive fuel should be the same as for UO_2 fuel because the additive fuel is [ ] UO_2, this similar burnup dependence with UO_2 is also consistent with UO_2 fuel with small gadolinia additions up to 8 wt%.

PNNL concludes the PRIME code predicts temperatures of additive fuel adequately up to the burnups requested.

3.3.2 Fission Gas Release (FGR)

FGR and resulting internal pressure is an important aspect of fuel behavior and it can be a limiting factor for fuel thermal-mechanical limit. The FGR is dependent on the fuel microstructure and chemistry, and the fuel temperature that is highly dependent on the power history and burnup.

The prediction of FGR is very important in the rod pressure analysis. GNF has provided FGR data for both steady-state power operation and power ramping to simulate fuel power changes due to control rod movement and AOOs in the submittal. In addition, GNF added additional power ramped rods from the Segmented Rod Program (SRP) in their response to RAIs. The power ramped rods were irradiated in commercial reactors for base steady-state power operation to accumulate burnup and then transported to the Halden or R2 test reactors for the power ramping and then punctured to measure the FGR following the ramp test. The power ramp tests were performed at relatively low to moderate burnups between [ ] some of which (Duane Arnold/Halden data) were ramped to relatively low powers resulting in low FGR. The power ramp tests were identified as the Duane Arnold/Halden, [ ]/Halden, and Segmented Rod Program tests with FGR values in the range [ ]. GNF has provided PRIME predictions of these [ ] FGR power ramped data using the previously approved UO_2 FGR model.

The steady-state power tests were from 5 different irradiation tests identified as IFA-537, IFA-538, [ ]. These steady-state power tests ranged in burnup from [ ] with FGR values between [ ]. GNF has provided PRIME predictions of these [ ] steady-state FGR data from additive fuel using the previously approved UO_2 FGR model. PNNL's evaluation of this data noted that the PRIME code under predicted all [

].

This was of concern because the GNF rod pressure analyses assumes that the fuel rod runs at the TMOL for steady-state power operation out to the burnup limit to demonstrate that the SAFDL for rod pressure is met for a given reactor core, this usually results in FGR values above 9 percent at end-of-life (EOL) rod average burnups (≥ 55 GWd/MTU). In addition, GNF also performed rod pressure analyses with power ramps above the TMOL. Therefore, it is important to be able to adequately predict data at high rod powers (near or above the TMOL) and high release values up to the approved GNF burnup limit of **[ ]**. As a result, past NRC reviews of FGR models within the last 15 years have concentrated on verifying that the proposed vendor FGR models adequately predict data with measured values greater than 5 percent FGR. This was also the focus by NRC (model verification against FGR values greater than 5%) in the previous review and approval of the UO_2 FGR model in PRIME.

An RAI (RAI 20, Reference 3) requested more background information on those fuel rods with high release values that included information on the terminal peak rod powers achieved in the ramped power tests and the power histories of the steady-state tests. This rod power information was needed to verify that GNF had FGR data that operated near or at their TMOL power limit for steady-state power operation used in their rod pressure analyses. In addition, AOO events are evaluated by GNF above the TMOL powers such that power ramp data above the TMOL are needed to verify FGR predictions for AOO events. The first GNF response provided addition FGR data at low burnups between **[ ]** from power ramped rods (identified as SRP ramped rods).

GNF initially did not provide the rod powers for either the ramped nor steady-state power tests, such that a follow up request was made to obtain this information.

GNF provided the rod power histories in follow up responses. In these follow up responses GNF suggested that certain data from **[**

] GNF based the suggestion on the fact that the **[**

] Staff noted that if the **[**
] data were eliminated from Figure 5, there would only be **[**
] at a burnup of 53 GWd/MTU that operated near or above the GNF TMOL. GNF recognized the staff concern about lack of data in the power/exposure range where rod internal pressure is limiting and accepted the staff position that the **[ ]** data be considered in the evaluation of the acceptability of the proposed additive fuel FGR model.

The staff evaluated the rod powers supplied by GNF and made a plot of predicted-minus-measured FGR versus fuel burnup for those data with greater than 5 percent FGR in Figure 5. The data is differentiated on whether rod powers were near or above the GNF TMOL powers and those significantly below the TMOL. Examination of this figure demonstrates that the PRIME code provides a relatively good prediction (even distribution of under predictions and over predictions) of FGR at burnups below **[ ]** that operated near the TMOL but at burnups above **[**

].

GNF proposed to include all of the additive FGR data including those at low FGR and low rod powers (significantly below the TMOL). GNF has noted that when all of the data is used, the mean predicted-minus-measured of all the data is nearly zero suggesting no bias in the predictions. However, as noted earlier when additive data at high FGR values are examined there appears to be a [

]can be explained in Figure 6. Figure 6 is a copy of Figure 4.3 from the submittal with trend lines drawn by the staff. This plot demonstrates that the additive FGR model [

].

In order to concentrate on those additive FGR data applicable to the rod pressure analyses performed at their TMOL at higher burnups where rod pressure becomes limiting, staff has selected only those FGR data that operated ≥ 0.85 TMOL and burnups ≥ 40 GWd/MTU based on the power histories supplied to PNNL/staff in RAI 20 (S02). This has resulted in [ ] additive fuel FGR data that meet this criterion. The [ ] FGR data points selected from additive fuel rods are the following: [

].

There are three primary reasons why the staff used only these [ ] data:

1) From examination of Figure 4-3 (see Figure 6 below) of submittal it is obvious that the FGR model over predicts the FGR additive fuel at low LHGRs and/or low burnup.

2) Low power and/or low burnup (< 40 GWd/MTU) conditions are not within the operating range where rod pressures are limiting.

3) From Figure 6 it is obvious that the FGR model [

]. The red line in Figure 6 is the trend in additive fuel predictions of additive data while the dark dashed line is the trend in the predictions of UO_2 data. The solid dark line is the 2σ upper bound of the predictions of the [ ] additive fuel FGR data at ≥ 0.85*TMOL and burnups > 40 GWd/MTU.

GNF has proposed to use the same bounding analysis methodology used for UO_2 fuel to bound the additive fuel FGR data for rod pressure analyses. This bounding analysis includes using a bounding power perturbation of [ ] and a bias to the FGR model (lowers the temperature-exposure dependent term for earlier grain boundary gas interlinkage and release). A follow up RAI to RAI 20 of Reference 3 requested that GNF provide a prediction of the [ ] additive FGR data using this bounding analysis methodology to demonstrate that this bounds the additive fuel FGR data applicable to rod pressure analyses at a 2σ level. GNF provided a prediction using a power perturbation of [ ], rather than the [ ] power perturbation used for licensing, and the FGR model bias used for UO_2 licensing. The results indicated that [ ] of the [ ] data points were under predicted ([ ]) and [ ] data point ([ ]) was on the bounding line. All of these additive FGR data should have been bounded in order to provide a 2σ bounding prediction.

As a follow up to RAI 20, the staff requested GNF to provide FGR predictions of the [ ] selected additive FGR data using a [ ] power perturbation and the FGR model bias used for UO_2 fuel to determine if this would bound this additive FGR data. Using this increased power perturbation, the predictions bounded the [ ] but the [ ] datum remained under predicted.

Examination of the power history of the [ ] experimental fuel rod revealed that the LHGRs of this rod remained significantly higher over the entire exposure range of this rod ([ ]) than the TMOL versus exposure used by GNF. In addition, the measured value of FGR for this rod is much higher than what would be expected in a commercial fuel rod. Therefore, the staff concludes that this rod operated outside of the rod power range of interest for GNF fuel and this fuel rod FGR datum does not need to be bounded. Therefore, the staff concludes that the bounding prediction of the [ ] remaining additive fuel FGR data using a [ ] bounding power perturbation is acceptable.

As an alternative, GNF has proposed that instead of using the [ ] bounding power perturbation that they continue using the [ ] power perturbation used for UO_2 licensing analyses [ ] to achieve the same or more bounding predictions as those using a [ ] bounding power perturbation for the [ ] additive FGR data identified above. The staff concludes that this is also acceptable.

[

]

Figure 5. Predicted-Minus-Measured Fission Gas Release by PRIME Code of Additive Data with Measured Releases Greater Than 5%, Data is Differentiated in Terms of Rod Powers Near or Above the GNF Thermal-Mechanical Operating Limit (TMOL and Those with Rod Powers Less Than the TMOL.

[

]

Figure 6. GNF Predicted versus Measured for UO_2 and Additive Fuel with Trend Lines Drawn by PNNL.

3.3.3 *Cladding Deformation (Strain)*

GNF performed cladding strain analyses with the PRIME code to establish a MOP limit for AOO events (involving power transients). GNF initially provided very little measured cladding strain data from power ramping of additive fuel to validate the PRIME code strain predictions for AOO events with additive fuel and the various additive fuel models in PRIME used to predict cladding strain. As a result, RAI 21 of Reference 3 requested additional information on the power ramp testing that was performed on additive fuel to assess the applicability to PRIME and the MOP limits.

GNF responded with cladding strain data from **[ ]** power ramps, however, two of these power ramps were at very low burnups (**[ ]**) where cladding strains were negligible because the fuel cladding gap was relatively large at this burnup. The other

[ ] power ramp data were from rods with burnups between [ ] (close to the burnup at which margin to MOP limit is the smallest) with PRIME under predicting cladding strains for [ ] rods. In addition, the power ramps of this data were below the rod powers of the MOP limit. The NRC staff's evaluation concluded that the PRIME code appeared to have an [ ] in cladding strain for additive fuel based on the small amount of cladding data near the burnup and rod power where margin to the MOP limit is minimum. The NRC staff further recommended that [

]. The NRC staff concludes that this is acceptable and notes it is very conservative because GNF has provided data (Section 6.3 of Reference 1 and Figure RAI 21-3 of Reference 3) to show that the failure limit during a power transient for additive fuel is noticeably [ ] than for UO_2 fuel at equivalent burnup levels.

3.4 Impact of Additive Fuel on Licensing Criteria

This section will address the review results of the effect of additive on the design bases for each of the fuel system damage, failure, and coolability criteria established in Section 4.2 of NUREG-0800 relative to standard fuel. Specifically, this section addresses the impact of the additive fuel on the following fuel licensing criteria for fuel melting, rod internal pressure, cladding strain, cladding fatigue, cladding creep collapse, and LOCA/stability/core transients.

3.4.1 *Fuel Melting*

The impact of additive on fuel melting limit is addressed in Sections 3.1.2 and 3.2.2 of this evaluation.

3.4.2 *Rod Internal Pressure (RIP)*

Fuel RIP is limited by the licensing requirement that there is [ ] due to high fuel RIP at operating power levels. The RIP limit is dependent on cladding creep and fuel swelling.

The cladding type has not been altered in this submittal and the cladding creep model was previously found to be acceptable in PRIME. The effect of additive in the PRIME calculation of fuel RIP is demonstrated by analyzing the GNF2 fuel design with and without additive. The fuel swelling model for additive fuel was found to be acceptable in Section 3.2.4. The staff concludes that the RIP limit for additive fuel is acceptable.

The RIP calculation is used to demonstrate that the peak operating rod in a core will remain below RIP limit. RIP is dependent on FGR (addressed in Section 3.3.2) and internal void volume calculations. FGR has the largest impact on RIP calculations; the FGR model is discussed in Section 3.3.2. The internal void volume calculation is dependent on cladding creep, fuel thermal expansion, and fuel swelling. As noted above the cladding type has not been altered in this submittal and the cladding creep model was previously found to be acceptable in PRIME. The thermal expansion model for additive fuel was found to be acceptable in Section 3.1.4. As noted above, the fuel swelling model for additive fuel was found to be acceptable in Section 3.2.4.

In addition, GNF has presented predicted versus measured rod internal pressures that demonstrated a best estimate prediction of rod internal pressures. However, it should be noted that experimental rods have a much larger internal void volume to fuel volume than commercial fuel rods such that these comparisons are not prototypical of commercial rods. In addition, lead test assembly (LTA) rods do not operate at limiting power conditions and, therefore, typically have low FGR such that these rods are not prototypical of peak power rods in the core that will be limiting in terms of rod internal pressure.

The NRC staff concludes that the RIP calculation is acceptable based on the acceptability of those models in PRIME used in this analysis.

3.4.3 Cladding Plastic Strain

GNF performed analyses for each rod type to determine the maximum overpower magnitudes for which the cladding circumferential strain does not exceed 1 percent cladding **[ ]** strain limit. Analyses to determine the **[ ]** circumferential strain were performed at several exposure points during the fuel rod lifetime. The MOP is determined as the maximum permissible overpower for which the cladding circumferential strain does not exceed the limit. For the cladding strain analysis, GNF considered the **[ ]** that produces the most severe result.

Figure 5-3 of the submittal (Reference 1) indicates that the presence of additive greatly increases the margin to **[ ]** strain for same overpower (**[ ]** in the limiting exposure range). An RAI (RAI 21(g), Reference 3) noted that the submittal did not include the **[ ]** for MOP events, as approved in the PRIME review. GNF responded and showed that additive fuel met the **[ ]** strain limits at high burnup approved in the PRIME code review. These strain limits are only dependent on the cladding and not the fuel type. Therefore, these strain limits at low and high burnup are found to be applicable to additive fuel. The prediction of cladding strain is addressed in Section 3.3.3 above.

3.4.4 *Cladding Fatigue plus Creep Rupture Limit*

GNF demonstrated the effect additive on the fatigue life by performing PRIME analyses of additive and standard fuels. The analysis by GNF included creep rupture damage added to the fatigue damage which applies conservatism to the results.

The limit on cladding fatigue is only dependent on the cladding type, and the amount of cladding oxidation and irradiation damage. The additive fuel does not impact any of these cladding properties. Therefore, the cladding fatigue limits are found to be applicable to additive fuel. The higher creep rate (discussed in Section 3.1.8 above) in additive fuel as compared to UO_2 fuel will result in lower cladding stresses and strains that should result in more margin to cladding fatigue. However, GNF will continue to use UO_2 properties for bounding cladding fatigue analyses.

3.4.5 *Cladding Creep Collapse*

The only fuel property that impact cladding creep collapse is densification, e.g., higher densification may result in a higher probability for collapse. As noted in Section 3.2.4 above, the use of the UO_2 fuel densification model for additive fuel may be conservative because the small amount of data on densification of additive fuel suggests that [ ]. Lower FGR could potentially impact cladding creep collapse because RIPs are lower, however, past GNF creep collapse analyses for UO_2 fuel have conservatively assumed no FGR or only athermal FGR, this removes the concern of lower FGR for additive fuel. Previous creep collapse analyses for UO_2 fuel are found to be applicable to additive fuel.

3.4.6 *LOCA/Stability/Core Transients*

The LOCA limits of PCT and cladding oxidation are not impacted by the additive fuel. An RAI (RAI 18 (c), Reference 3) requested that GNF provide example stored energy analyses for additive and non-additive (UO_2) fuel for a PCT limited plant. This comparison demonstrated that additive fuel made little difference in stored energy as compared to non-additive fuel. This is because the change in specific heat and thermal conductivity from UO_2 fuel are negligible. The LOCA limits on PCT and cladding oxidation are found to be applicable to additive fuel.

The LOCA, transient, and stability analyses use gap conductance for both a high power and lower power case. The gap conductance for the high power case is significantly lower early in exposure due to decrease in thermal conductivity of additive fuel. The impact of additive fuel on fuel rod failure during a RIA event is addressed in Section 3.2.3 above.

3.4.7 *Impact of Nuclear Design Requirements*

To confirm compliance with GDC 11, GNF analyzed the impact of introducing additive fuel on the key reactivity coefficients; results of the evaluation confirmed that the introduction of additive at the planned concentration does not impact the nuclear dynamic parameters/reactivity coefficients. For BWR fuel, the key reactivity coefficients are: 1) the moderator void coefficient, 2) the moderator temperature coefficient, 3) the Doppler coefficient, and 4) the prompt power coefficient. Since the neutron absorption cross section of aluminosilicate is very small relative to the fuel, the additive does not make the reactivity coefficients less negative.

GDC 26 requires that the reactivity control system shall be capable of maintaining the reactor subcritical under cold conditions with sufficient margin to account for equipment malfunctions such as stuck control rods. GNF's 3D analysis assures adequate cold shutdown margin.

In summary, the staff concludes that the impact of additive fuel on licensing analysis for the

GNF fuel designs are negligible and do not significantly impact the fuel behavior or characteristics.

3.5 Operating Experience

GNF has been irradiating additive fuel in power reactors starting with segmented rod bundle (SRB) with up to **[ ]** additive and up to approximately **[ ]** exposure. The irradiated fuel segmented rods were retrieved for hot cell examination and further ramp testing. Restricted LTAs were inserted into US commercial reactor core and achieved up to **[ ]** exposure. These LTAs consisted of segmented and full-length rods. LUAs with segmented and full-length rods were irradiated in European reactors and achieved approximately **[ ]** exposure. The rods were retrieved for hot cell examination and further ramp testing and followed by re-insertion in reactors.

Section 3.2 of this safety evaluation provides detailed discussion of the specific in-reactor operating experience related to measured fuel temperatures, fission gas release, and cladding deformation.

Several rod segments, both standard and additive and without an inner zirconium liner or barrier, were ramped and few of them re-ramped in test reactors with a range of additive concentrations **[ ]** with peak power of **[ ].** GNF reports that the standard rods failed and none of the additive rods failed during testing. Tests have shown that the additive fuel provided additional margin to pellet-cladding-interaction (PCI) failure compared to barrier alone. The staff requested information (RAI 21(c), Reference 3) on whether additive fuel with and without barrier cladding have different LHGR operating limits than non-additive fuel with and without barrier cladding to prevent PCI failures. GNF responded that even though currently, LHGR operating limits for non-additive fuel are identical for barrier and non-barrier cladding, due to the susceptibility of fuel with non-barrier to PCI failures during rapid power increases, GNF provides **[ ]** for fuel with non-barrier cladding to minimize the risk of PCI failures. GNF stated that based upon currently available test results **[ ]** may be offered for additive fuel with barrier cladding relative to non-additive fuel with barrier cladding.

The ramp test program of additive rods base irradiated in **[ ]** provided a valid assessment of PCI performance. GNF reports that the principal factor in PCI resistance appears to be a **[ ].** The NRC staff has determined that GNF has demonstrated there is adequate margin for additive fuel with respect to PCI failure compared with non-additive fuel.

The staff concludes that GNF has provided sufficient operating experience for additive fuel.

4.0 CONCLUSIONS, LIMITATIONS, AND CONDITIONS

4.1 Conclusions

GNF has tested additive fuel (aluminosilicate in UO_2) over a wide range of concentrations and compositions. GNF used the NRC-approved PRIME fuel performance code to evaluate the key material properties of the additive fuel. The impact of additive fuel on in-reactor fuel performances such as washout characteristics, RIA behavior, FGR, RIP, and fuel melting have been adequately analyzed. The licensing criteria assessment per SRP 4.2 (NUREG-0800) of additive fuel relative to standard fuel with respect to fuel melting, fuel RIP, cladding strain, and cladding creep has been adequately addressed.

The NRC staff concludes that thermal-mechanical performance of the proposed additive fuel design is adequately addressed in the GNF submittal with the application of the PRIME fuel performance code. Fuel melting and fuel creep rate are found to have significant effects from addition of aluminosilicate. Theoretical density is deemed to have been affected only slightly. Fuel properties such as thermal conductivity, FGR, and fuel washout have been insignificantly impacted.

The staff's safety evaluation of the additive fuel is subject to the limitations and conditions listed in Section 4.2.

4.2 Limitations and Conditions

1. Ratio of silica-to-alumina shall be within the range **[ ]**. (Section 1.0)
2. The maximum concentration of aluminosilicate shall be **[ ] ([ ]**). (Section 1.0)
3. The time for AOO events with fuel near the **[ ]** criterion shall be limited to less than or equal to **[ ]**. (Section 3.1.2)
4. Steady-state power operation shall be limited to less **[ ]** of liquid unless further testing at long time periods typical for steady-state operation or analysis are provided. (Section 3.1.2)
5. For licensing analyses, the initial grain size for additive fuel shall be no greater than **[ ]**, based on 3-D dimensions. (Section 3.1.7)
6. The rim thickness model for additive fuel shall be the same used for UO_2 fuel. (Section 3.1.13)
7. For the additive fuel the currently approved peak pellet burnup limit of **[ ]** shall be applied.

8. Until sufficient cladding strain data from power ramps can be used to determine a higher limit, the MOP limits for UO_2 fuel shall be applied to additive fuel. (Section 3.3.3)

9. The FGR model uncertainty for UO_2 with additives as proposed in NEDE-33406P shall be modified for additive fuel licensing analyses by biasing the rod power by **[ ]** in order to bound the limited additive fuel FGR data that operated near the thermal mechanical operating limit (TMOL). This limitation is imposed due to the fact that the 2σ upper bound determined using a power perturbation of **[ ]** under predicts **[ ]** out of **[ ]** FGR data from additive fuel (data that operated greater than 0.85% TMOL). This limitation can be removed or modified based on additional data analysis that satisfies the concern that the limited amount of additive fuel FGR data is not bounded for licensing analyses. The uncertainty used for licensing analyses for UO_2 without additives is unchanged with a **[ ]** model uncertainty and a **[ ]** power perturbation (Section 3.3.2).

   OR

   The interlinkage temperature threshold for additive fuel **[ ]** to achieve the same or more bounding predictions as those using a **[ ]** bounding power perturbation for the **[ ]** additive fuel data discussed in Section 3.4.2 above. (Section 3.3.2)

   The staff is providing the above option for Limitation number 9 to the applicant since the revised interlinkage temperature will achieve the same or more bounding predictions as those using a **[ ]** power perturbation for the **[ ]** additive FGR data identified in Section 3.3.2 of the safety evaluation.

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Attachment: Resolution of Comments

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Date: November 9, 2015