FINAL SAFETY EVALUATION BY THE OFFICE OF NEW REACTORS
TOPICAL REPORT MUAP-07008, REVISION 2
"FUEL SYSTEM DESIGN CRITERIA AND METHODOLOGY"
MITSUBISHI HEAVY INDUSTRIES, Ltd
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1.0 INTRODUCTION AND BACKGROUND

Mitsubishi Heavy Industries (MHI), hereinafter referred to as the applicant, has submitted to the U.S. Nuclear Regulatory Commission (NRC) staff, hereinafter referred to as the staff, Topical Report MUAP-07008-P & NP (Reference 1) entitled, “Mitsubishi Fuel Design Criteria and Methodology,” dated May 31, 2007, for review and approval. This report documents the methodology and computer code used to evaluate fuel rod performance. MHI has developed the Fuel Rod Integrity Evaluation (FINE) code for use in evaluating the United States - Advanced Pressurized Water Reactor (US-APWR) fuel rod performance. Earlier revisions of the FINE code have been applied to the Mitsubishi domestic plants.

The FINE code is used to evaluate the expected fuel rod behavior such as fission gas production and release; pellet and cladding temperatures; thermal expansion of the pellets and the cladding; pellet densification and swelling; cladding creep, growth, and deformation; pellet-cladding mechanical interaction in order to evaluate the fuel temperatures; rod internal pressure; cladding oxidation, hydriding, stress and strain.

The FINE code is used to predict the above parameters for the US-AWPR fuel and cladding design presented in References 26 and 30. The fuel pellet is sintered uranium dioxide and gadolinia-uranium dioxide produced by compression-molding powdered uranium dioxide and a powdered mixture of uranium dioxide and gadolinia, respectively. Maximum enrichment is limited to 5.0 weight percent U-235 without uncertainties with a theoretical density (TD) of 97 percent. The gadolinia doped fuel pellets can contain up to 10 weight percent gadolinia. The fuel cladding is ZIRLO^{TM} with a wall thickness similar to current standard designs. Helium is used as the gap gas with a typical backfill pressure.

Pacific Northwest National Laboratory (PNNL) was contracted as a consultant to the NRC for this review. PNNL compared FINE predictions to experimental data and confirmatory FRAPCON-3 analyses.

The staff’s review of MUAP-07008-P/NP and FINE code focused on the following major areas: thermal models, fission gas release, corrosion, fuel swelling and densification, mechanical properties, mechanical models and void volumes. Also reviewed was the FINE code’s ability to predict stored energy and maximum rod internal pressures used as inputs to the loss-of-coolant accident (LOCA) analyses. The maximum rod internal pressure review also addressed the effects of assumed normal operation and anticipated operational occurrences (AOOs) power distributions. The power distributions and the corresponding hold times are further discussed in Reference 26.

Topical Report MUAP-07008P/NP contains more information than is normally considered part of a fuel rod performance topical report. This information is redundant with that provided in Technical Report MUAP-07016 (Reference 26), “US-APWR Fuel System Design Evaluation,” or Topical Report MUAP-07034 (Reference 27), “FINDS: Mitsubishi Fuel Assemblies Seismic Analysis Code.” Therefore, this safety evaluation (SE) only addresses the fuel rod performance code FINE and its application to the US-APWR.

2.0 REGULATORY EVALUATION

Regulatory guidance for the review of fuel system designs and adherence to General Design Criteria (GDC) – 10, “Reactor Design,” GDC-27, “Combined Reactivity Control Systems Capability,” and GDC-35, “Emergency Core Cooling,” is provided in NUREG-0800, “Standard

Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants" (SRP), Section 4.2, "Fuel System Design" (Reference 32). 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 AOOs,

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

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

d. coolability is always maintained.

Topical Report MUAP-07008-P/NP describes the technical basis, qualification, and application methodology for the FINE thermal-mechanical fuel rod performance model. The staff's review of this report is to ensure that the FINE models are capable of accurately or conservatively predicting the in-reactor performance of fuel rods, to identify any limitations on the code's ability to perform this task, and ensure that the application methodology conservatively accounts for model uncertainties and is capable of ensuring compliance with the SRP 4.2 criteria.

3.0 SUMMARY OF APPLICATION

3.1 Radial Temperature Profile

In FINE, fuel and cladding temperatures are calculated assuming steady-state, radial-only heat transfer from the pellet across the pellet-cladding gap, through the cladding across the oxide and crud layers and across the water film to the coolant. The pellet is divided into [ ] annular rings with the temperature calculation in the radial direction only. The heat transfer solution for each fuel ring assumes uniform heat generation within the ring (which varies from ring to ring and varies with each time step). The boundary conditions for the calculation of fuel and cladding temperatures are zero heat flux at the pellet center and fixed surface temperature for a given axial node and time step. The heat transfer solution is accomplished by integration across the ring of the radial heat transfer equation with the inner-surface temperature solution from the next-outer ring forming the outer-surface boundary condition for the current ring being solved.

The FINE thermal conductivity model is based on recent Halden test data (Reference 33) and is a function of fuel centerline temperature and pellet burnup. For the same fuel pellet temperature thermal conductivity decreases with burnup.

3.2 Fuel Densification and Swelling Models

The densification model in FINE is a function of exposure and the measured density increase taken from the standard re-sinter test defined in Regulatory Guide (RG) 1.126, "An Acceptable Model and Related Statistical Methods for the Analysis of Fuel Densification."

There are two models for swelling, one for solid swelling, which is dependent on steady-state operation (burnup), and a second for gaseous swelling, which is typically only observed at high temperatures (i.e., overpower transients), and which becomes stronger at higher burnups. FINE uses a constant solid swelling rate per fission.

3.3 Fission Gas Release Model

The fission gas release fraction is calculated for each radial node due to diffusion and recoil and knockout. The fission gas release for an axial node is found by calculating the sum of the moles of fission gas released from each radial node and dividing by the moles of fission gas produced within the axial node. Then the fission gas release fraction from the rim is added to this fraction. The total fission gas release fraction for the rod is determined in a similar manner by calculating the sum of the moles of gas released from each axial node and dividing by the moles of gas produced within the rod. There are three fission gas release models in FINE: 1) release due to diffusion processes, 2) recoil and knockout, and 3) release from the high burnup rim region.

Because of helium's (He) importance in predicting gap conductance and rod internal pressure the FINE model has separate models for He generation, He release, and He absorption. The He generation model is a function of burnup and is based on an ORIGEN calculation of He produced in [ ] enriched UO_2 fuel. The He release model is also a function of burnup only and primarily impacts the rod pressure calculation. The fission gas release model in FINE is not modified for the effect of gadolinia.

3.4 Void Volume

The rod internal pressure in FINE is calculated in the typical manner of dividing the number of gas moles (multiplied by the gas constant) by the sum of the various volumes divided by temperature within the rod. In FINE the volumes used are the dish and chamfer volume, the volume in radial cracks, the volume of the fuel/cladding gap, the volume in the open porosity, the volume in the surface roughness and chip volume, and the upper and lower plenum volume, adjusted for differential fuel/cladding expansion.

3.5 Cladding Corrosion and Hydriding Models

The cladding corrosion (oxide) model is a function of the metal/oxide interface temperature and time. FINE contains models for both Zircaloy-4, low tin Zircaloy-4 and ZIRLO^{TM}. Different fitting coefficients (adjustment factors) are used for Zircaloy-4 and ZIRLO^{TM}. Also, each corrosion model has different coefficients for the pre- and post-transition region. The pre-transition model and corresponding coefficients are valid for lower oxide weights. The post-transition has two separate fits based on a second post-transition point. The post-transition coefficients increase the rate of oxide thickness gain due to the preexisting oxide thickness.

3.6 Mechanical Modeling

The mechanical modeling in FINE uses the thick-wall cylinder equations to calculate stress based on the rod internal and external pressures. For the open gap condition, the system pressure is used as the external pressure, and the gap gas pressure is used as the internal pressure. For the closed gap condition, the system pressure is used as the external pressure, and the internal pressure is set as the sum of the gap gas pressure and the contact pressure, which is calculated using a pellet-clad elastic interference model.

The strain in the cladding is calculated from the stress using a modified version of Hooke's law. The ratio of stress to strain is given by Young's modulus up to the elastic limit, which is defined as [ ]. The correlation for stress as a function of strain above the elastic limit is a linear interpolation between the point at the elastic limit and a point at the yield stress with a strain value of 0.002+YS/E. This linear interpolation is also used to calculate plastic strain beyond the yield stress.

The following Requests for Additional Information (RAIs) are referenced throughout this SE:

- RAI First set Response dated December 19, 2008 (Reference 2).
- RAI First set Second Response dated January 30, 2009 (Reference 3).
- RAI Second Set Response dated July 7, 2009 (Reference 4).
- RAI Second Set Amended Response dated November 30, 2009 (Reference 5).
- Revised information for RAI Questions 39a, 40, 43, 44, 45, 47 and 48 dated March 31, 2010 (Reference 6).
- Revised information for RAI Question 43 dated June 22, 2010 (Reference 7).

4.0 TECHNICAL EVALUATION

The NRC audit code, FRAPCON-3 (References 8, 9, and 10), has been used as an aid in this review to assess the models and calculation results from FINE. This code was originally assessed against a large volume of low and high burnup fuel performance data (Reference 11) and has been continually assessed against newer high burnup data (References 12 and 13) as it becomes available.

4.1 THERMAL MODELING

4.1.1 Radial Fuel Pellet Power Distribution

A 4.8 weight percent enriched UO_2 sample radial power distribution for rod average burnups of [ ] gigawatt days per metric ton uranium (GWd/MTU) was provided in Topical Report MUAP-07008 P/NP (Reference 1). This radial power distribution was compared to the equivalent FRAPCON-3 radial power calculations at the same rod average burnups. The radial power profiles in FINE were in good agreement with FRAPCON-3 at 3 GWd/MTU and slightly less edge-peaked in FINE than FRAPCON-3 for burnups ≥ 18 GWd/MTU. A less edge-peaked power profile, results in higher fuel centerline temperatures; which is generally more conservative in relation to cladding strain, rod pressure, fuel melting, cladding fatigue and stored energy analyses. The exception is for reactivity-initiated accidents. Therefore, the radial fuel pellet power distribution is acceptable except for reactivity initiated accidents

The applicant has requested that gadolinia doped fuel pellets be approved for use in the US-APWR. As no radial power distribution sample was provided for UO_2-Gd_2O_3 the staff asked in RAI Question 27 (Reference 2) that the applicant provide sample radial power profiles for 2.95 weight percent ^{235}U with 6 weight percent and 10 weight percent Gd_2O_3. A comparison of the power distributions showed that FINE compared well with FRAPCON-3. Therefore, the radial fuel pellet power distribution for UO_2-Gd_2O_3 is acceptable except for reactivity initiated accidents.

4.1.2 Fuel Thermal Conductivity

FINE uses a degraded UO_2 thermal conductivity model versus fuel centerline temperature and burnup based on recent Halden Boiling Water Reactor measurements (Reference 33). The FINE thermal conductivity model was compared to the FRAPCON-3 model, which is based on Reference 14 and modified in Reference 15, for burnups of [ ] GWd/MTU.

The modification is based on recent high burnup and high temperature thermal conductivity data and provides a good comparison to both in-reactor fuel temperature and ex-reactor diffusivity data at high burnup (References 16 and 17). The FINE and FRAPCON-3 are in good agreement but FINE predicts slightly higher conductivities as a function of temperature and burnup.

The applicant has requested application of FINE for gadolinia additions up to 10 weight percent. The FINE pellet thermal conductivity model contains a degradation function that is proportional to the weight fraction of gadolinia (Gd_2O_3) contained in urania-gadolinia pellets. To assess the thermal conductivity degradation applied in FINE for gadolinia additions, FINE was compared to the FRAPCON-3 model for 10 weight percent gadolinia. FINE calculates a thermal conductivity greater than FRAPCON-3 for UO_2-Gd_2O_3 at the 10 weight percent level. This over-prediction may lead to under-prediction of fuel temperatures. In MUAP-07008- P/NP Appendix B, the applicant provided comparisons of the FINE model predictions to unirradiated experimental data from urania-gadolinia showing reasonable agreement.

The FINE over-prediction of thermal conductivity (relative to FRAPCON-3) may lead to an under-prediction of fuel temperature but other factors such as radial power profile, gap conductance, rim effect and fuel relocation model may compensate for the slightly higher FINE thermal conductivities. The overall effect on FINE-predicted centerline temperatures will be discussed in Section 4.1.9 of this SE.

4.1.3 Fuel Thermal Expansion

The model used in FINE to calculate the fuel thermal expansion as a function of temperature was compared to FRAPCON-3. The two models predicted virtually the same thermal expansions. Therefore, the staff finds the FINE thermal expansion model acceptable.

4.1.4 Fuel Relocation Model

There is no fuel relocation model due to fuel cracking in FINE. A lack of a relocation model in FINE will cause the fuel-cladding gap to be larger and to contact the cladding at a higher burnup than in FRAPCON-3. The larger FINE fuel-cladding gap will result in higher fuel temperatures if other models are similar. However, the lack of a FINE relocation model could cause strain during a transient to be lower than FRAPCON-3 for low to moderate burnup levels where FRAPCON-3 predicts a closed gap.

The staff concludes that the lack of a relocation model in FINE is acceptable if the FINE prediction of cladding strain accounts for the additional uncertainty introduced by the lack of this model. As described in Section 4.9.4 of this SE, "Clad Strain Overpower Analysis," an additional uncertainty has been added to account for the lack of a fuel relocation model.

4.1.5 Gap Conductance

The FINE model has two gap conductance models. The first is for the open gap condition with no pellet-cladding contact. The second is for the closed gap condition. Each of these models was compared to the model in FRAPCON-3. FINE and FRAPCON-3 are similar for large open gaps (~75 microns and above), but FINE gap conductivity increases rapidly for smaller gaps while FRAPCON predicts a much smaller increase for smaller gaps.

For the closed gap case, FRAPCON-3 is continuous from the open to closed gap case. FINE appears to be discontinuous between open to closed gaps. For closed gaps FINE starts at higher contact conductance but does not increase as rapidly as the FRAPCON-3 model.

The staff notes that the gap conductance primarily impacts the fuel temperature prediction and the validation of the gap conductance model is tied in with the other models that impact the temperature prediction, such as pellet and cladding thermal conductivity and fuel relocation. Therefore, the gap conductance model in FINE is acceptable if the overall assessment of fuel temperature predictions is acceptable based on comparisons to measured in-reactor fuel temperatures discussed in Sections 4.1.9 and 4.9.3.

4.1.6 Gas Conduction Model

The difference in open gap conductivity may be due to individual gas conductance differences. FINE can calculate gas conductance for a mixture of up to [ ] as a function of gap temperature. The FINE gas conductances were compared to FRAPCON-3 and the MATPRO database. The FINE model gas thermal conductivity compares very well with both FRAPCON-3 and the MATPRO database. Therefore, it appears that the gas conductance values used are not the reason for the difference in gap conductivity. Based on these comparisons the staff finds the FINE gas individual gas conductance models acceptable.

4.1.7 Cladding Thermal Expansion

FINE contains correlations for thermal expansion in Zircaloy and zirconium in the circumferential and axial directions. Between [ ] thermal expansion in circumferential and axial directions shows good agreement between FINE and FRAPCON-3. Above [ ] there is an 8 percent difference between FINE and FRAPCON-3, which is believed to be due to the lack of FINE modeling of the decrease in thermal expansion, which occurs in the alpha+beta phase region (806°C - 982°C) (1483°F - 1800°F), or the correct thermal expansion in the beta phase. The thermal expansion models in both FINE and FRAPCON-3 assume the same Zircaloy and ZIRLO^{TM} thermal expansion, which has been validated based on proprietary information.

Based on the good agreement between FINE and FRAPCON-3, the staff finds the cladding thermal expansion between [ ] to be acceptable. The staff does not find the FINE thermal expansion model to be acceptable above (greater than) [ ] (see Conclusions and Limitations, Section 5).

4.1.8 Cladding Surface Temperature Modeling

The FINE subcooled cladding surface temperature is a sum of the bulk coolant plus the change due to film heat transfer, crud and oxide layers. For subcooled boiling the Dittus-Boelter correlation is used in both FINE and FRAPCON-3. For water temperature above the saturation temperature (nucleate boiling) FINE and FRAPCON-3 use similar correlations, except FRAPCON-3 uses the Jens-Lottes formula to calculate the temperature increase while FINE uses the maximum of the Thom and the Tong correlations to calculate temperature increase. Both the Thom and Tong correlations have previously been evaluated and the Thom correlation has demonstrated excellent prediction of cladding surface temperature during nucleate boiling. By using the maximum of Thom and Tong for nucleate boiling conditions the maximum cladding surface temperature will be predicted. Therefore, the staff concludes that both the subcooled and nucleate boiling models are acceptable.

Cladding waterside corrosion results in a thin coating of zirconium oxide that offers a lower thermal conductivity than the zirconium alloy. In FINE a constant value of [ ] is used for the zirconium oxide conductivity. The FINE oxide conductivity was compared to the FRAPCON-3 model oxide conductivity as a function of temperature. The FINE oxide thermal conductivity is always lower than the FRAPCON-3 value. A lower oxide thermal conductivity increases clad and fuel temperatures; hence the staff finds the FINE is conservative and acceptable.

In both FINE and FRAPCON-3, the crud conductivity under single-phase forced convection is a constant value of [ ]. Under nucleate boiling, FINE uses a crud conductivity of [ ]. The FRAPCON-3 code does not account for crud conductivity (i.e., crud conductivity is infinite) during nucleate boiling. Therefore, the staff finds the FINE crud conductivity acceptable as it is more conservative than FRAPCON-3.

FINE uses the same clad thermal conductivity model for Zircaloy and ZIRLO™. This model is based on two linear functions of temperature within two temperature ranges [ ]. The model for Zircaloy and ZIRLO™ conductivity in FINE was compared to the FRAPCON-3 cladding conductivity model, which is also only a function of temperature. FRAPCON-3 also uses the same thermal conductivity model for Zircaloy-4 and ZIRLO™ but a different model than the FINE conductivity model. Over the range of [ ] FINE and FRAPCON-3 predict almost the same thermal conductivity. Therefore, the staff finds the FINE fuel cladding conductivity model valid from [ ] (see Conclusions and Limitations, Section 5).

4.1.9 Integral Centerline Fuel Temperature Assessment

The integral centerline fuel temperature assessment compared the FINE predicted values to both measured and FRAPCON-3 predicted values. In Reference 1 MHI provided FINE temperature predictions with 10 Halden instrumented fuel assemblies (IFAs). MHI assigned an upper bound (95/95) uncertainty of [ ] absolute to the temperature predictions in FINE.

The staff noted that most of the rods in the temperature assessment database were irradiated between 30 and 40 years ago with few recent experimental temperature data comparisons. The staff requested in RAI Question 33 that the applicant compare the FINE code to selected recent Halden experiments to expand the validation in the following areas: high power and lower burnup, high burnup, and UO_2-Gd_2O_3 fuel.

In its response to the staff's RAI (Refence 2 and 3) regarding validation at high powers and low burnup the applicant provided measured and predicted fuel centerline temperatures versus burnup for recent Halden UO_2 IFA-677.1, Rods 2 and 6 (References 34 and 35), IFA-681.1, Rods 1 and 5 (Reference 36). MHI demonstrated that FINE compares well with the measured and in general slightly over-predicts fuel centerline temperature, which is conservative and therefore acceptable.

In its response to the staff's request for additional validation at high burnup, the applicant provided measured and predicted fuel centerline temperatures versus burnup for recent Halden UO_2 IFA-515 Rod A1 (Reference 37) and IFA-597, Rod 8 (Reference 38). Rod burnups extended to approximately 85,000 MWd/MTU. MHI demonstrated that FINE compares well with the measured data and in general slightly over-predicts fuel centerline temperature, which is conservative and therefore acceptable.

The applicant also provided additional validation data for IFA-681 Rods 2, 4 and 6 and for IFA-636, Rod 2. IFA-681 Rods 2 and 4 have 2 weight percent $Gd_2O_{3,}$ while IFA-681, Rod 6 and IFA-636, Rod 2 contain 8 weight percent Gd_2O. As with the UO_2 comparison, FINE compares well with the measured data and in general slightly over-predicts fuel centerline temperature which is conservative and therefore acceptable.

As part of RAI Question 33, the staff requested that the applicant recalculate the standard deviation and mean of all the predicted minus measured temperature comparisons including those requested by the staff. Finally, the staff requested that MHI calculate a mean and standard deviation only for those data where the temperature is greater than 1300°C (2372°F). MHI provided (Reference 3) the requested data comparisons and analyses. In general the FINE code provides a small over-predictive bias of [ ] when compared to all the measured data evaluated. Using all the data comparisons, including the original and new data, MHI calculated an absolute upper bound (95/95) uncertainty of [ ]. Using only the data with temperature greater than 1300°C (2372°F), MHI calculated an upper bound (95/95) uncertainty of [ ], which is less than the original upper bound of [ ]. Therefore, the staff finds using an upper bound of [ ] acceptable.

In addition to measured data, RAI Question 12 requested that the applicant provide data used to compare to FRAPCON-3 on a best estimate basis. FINE data was provided and compared to FRAPCON-3 for rod average burnups of [ ]. As shown in Figures 3, 4 and 5 of Section 4.9.3 of this SE; "Comparison of FINE and FRAPCON-3 Predicted Centerline temperatures vs. LHGR at 10 GWd/MTU," "Comparison of FINE and FRAPCON-3 Predicted Centerline temperatures vs. LHGR at 30 GWd/MTU," and "Comparison of FINE and FRAPCON-3 Predicted Centerline temperatures vs. LHGR at 50 GWd/MTU;" FINE either over-predicts fuel centerline temperatures versus local kW/ft, which is conservative, or compares very well with the FRAPCON-3 predictions.

Based on FINE comparisons to measured centerline temperature data from 22 UO_2 fuel rods and 8 UO_2-Gd_2O_3 rods (Section 3.2.1 in Reference 1 and response to RAI Question 33 in Reference 3) and comparisons to FRAPCON-3, the staff concludes that the FINE centerline temperature predictions are acceptable for UO_2 and UO_2-Gd_2O_3 fuel up to a rod average burnup of 62 GWd/MTU.

4.2 FISSION GAS MODEL ASSESSMENT

FINE models the release of fission gases Xe and Krypton, and He. The fission gas release (FGR) model in FINE considers three fission gas release mechanisms. These mechanisms are: release due to diffusion processes, recoil and knockout, and release from the high burnup rim region. For release due to diffusion processes, the FINE model uses a model proposed by Speight (Reference 39). In RAI Question 46 the applicant was requested to provide more details and derivations for some of the terms in the diffusion process equation. In its response (Reference 4), the applicant provided these details confirming that the diffusion processes equations in FINE are empirical rate equations rather than diffusional release equations.

To model recoil and knockout, the FINE model uses the recoil and knockout term from the ANS 5.4 model. This model is a function of burnup and temperature difference across the pellet radius. This equation was modified from that in ANS 5.4 to take out the effect of diffusional release. To model the release from the high burnup rim structure, FINE uses a modified version of the Barner et al (Reference 18) model. Since the empirical rate equations already capture the diffusional release, the staff finds the modifications to the recoil and knockout model acceptable.

4.2.1 He Release Models

FINE has separate models for He generation, He release and He absorption. The He generation model is a function of burnup and is based on an ORIGEN calculation of helium produced in [ ] U-235 enriched UO_2 fuel pellet.

The He release model is a function of burnup only and primarily impacts the rod internal pressure calculation. Figure 4.3.4-1 of Reference 1, "M/P of Helium Mol versus Burnup," shows a comparison of measured and predicted He release rates. Figure 4.3.4-1 demonstrates that FINE slightly over-predicts He release above a rod average burnup of 35 GWd/MTU with a relatively small standard deviation. The small over-prediction in He release has little impact on fuel temperatures because it changes the initial He fill amount by less than [ ] such that a [ ] over-prediction in release results in less than a [ ] change in He total rod void volume. This is further illustrated by the FINE small over-prediction in fuel temperatures discussed in Section 4.1.9 of this SE, "Integral Centerline Fuel Temperature Assessment." Therefore, the staff concludes that the FINE He release model is acceptable.

Since FRAPCON-3 does not contain a He absorption model the staff requested in RAI Question 31 (Reference 2) that the applicant describe how the He absorption model is applied. The applicant stated that after the He pressure in the gap is calculated in each time step, the pressure is reduced by the amount predicted to be soluble in the fuel. The He absorption model is acceptable based on the FINE validation against [ ] He measurements given in Section 4.3.4 of Reference 1, “Helium.”

4.2.2 Integral Fission Gas Assessment

The qualification of the FINE (Reference 1) fission gas release model consists of about [ ] UO_2 and UO_2-Gd_2O_3 fuel rods from commercial and test reactors.

The data show that, in general, FINE over-predicts fission gas release for steady state UO_2 and UO_2-Gd_2O_3 fuel rods up to 62 GWd/MTU. The cases that FINE under-predicts are almost all [ ] cases. For the power ramped rods, FINE over-predicts the measured FGR for all the cases with burnups up to [ ] and ramp terminal levels between [ ]. MHI calculated a relative (95/95) measured-to-predicted ratio upper bound uncertainty of [ ] on model predictions using the [ ] UO_2 steady state cases with [ ].

In RAI Question 34 the staff requested that the applicant provide FINE comparisons to additional selected fission gas release measurements and re-calculate the upper bound model uncertainty including these cases as well. In its response (Reference 3) the applicant provided the requested code comparisons and uncertainty analyses. The results of these comparisons are discussed below.

Two high burnup (62 GWd/MTU) Babcock and Wilcox Co. (B&W) rods ramped at Studsvik (B&W rod 1 and rod 3) were modeled with FINE. The comparisons show that FINE over-predicts the measured fission gas release, similar to all the other power-ramped rods in the database.

The Halden rod, IFA-597.3 rod 8 irradiated to 70 GWd/MTU was modeled with FINE. The comparisons show that FINE under-predicts the measured gas release. The applicant stated that this under-prediction may be due to uncertainty in the provided power as noted by Halden. MHI performed an analysis that demonstrated that [ ] would cause FINE to predict the measured FGR. The staff notes that FRAPCON-3 predicted close to the measured gas release without [ ]. The under-prediction in FINE may be due to error in the reported power or due to a model deficiency at high burnup. It is noted that the burnup for this rod is greater than the requested burnup limit of 62 GWd/MTU and therefore is acceptable.

The staff requested that the applicant model the Halden rods IFA-534 rods 18 and 19 irradiated to 63 GWd/MTU with varying initial grain size. MHI modeled rod 19 with a grain size of 8.5 microns as determined by mean linear intercept (MLI). MHI declined to model rod 18 with a grain size of 22.1 microns (MLI) stating that the large grain size is not applicable to US-APWR. A large grain size sometimes reduces the fission gas release relative to fuel with a small grain size but the dependence with grain size appears to be small, based on the IFA-534 data. The FINE FGR model is not a function of grain size and has been calibrated based on fuel with grain sizes between [ ]. Based on this, it is expected that FINE may over-predict gas release from fuel with grain sizes greater than [ ]. For rod 19, FINE over-predicted the gas release in a manner similar to other rods in the database.

The Halden rod IFA-429 rod DH irradiated to 99 GWd/MTU was modeled with FINE. The comparisons show that FINE under-predicts the measured gas release and hence may under-predict for very high burnup rods. The staff notes that FRAPCON-3 predicted close to the measured gas release for this case. As the 99 GWd/MTU rod average burnup is much greater than the 62 GWd/MTU licensing limit (see Conclusion and Limitations, Section 5.0) the staff finds this under-prediction to be acceptable.

As part of the applicant's response to RAI Question 34 (Reference 3) the applicant provided a re-evaluation of the upper bound uncertainty using the additional cases. It was demonstrated that [ ] is still a valid upper bound (95/95) model uncertainty.

The staff concludes that FINE is acceptable for calculating fission gas release in UO_2 and UO_2-Gd_2O_3 fuel under steady state and power ramp conditions with grain size less than [ ] (MLI) up to a rod average burnup of 62 GWd/MTU. The staff also concludes that the model uncertainty calculated for FINE is acceptable.

4.3 CLADDING CORROSION AND HYDRIDING MODELS

4.3.1 Cladding Corrosion Model

The cladding corrosion model in FINE is a function of metal/oxide interface temperature and time. This model has three different correlations that are applicable for different oxide thickness ranges. No corrosion thickness limit was specified for FINE.

Rather, cladding oxide-metal temperature limits of [ ] for steady state operation and [ ] for AOOs were given.

As suggested by SRP Section 4.2, RAI Question 5a requested that the applicant propose an oxide thickness limit. In Reference 2 MHI proposed a [ ] limit. This corrosion limit is consistent with ZIRLO^{TM} cladding used by other vendors. Therefore, the staff finds the [ ] oxide thickness limit acceptable.

Since metal/oxide temperature is a function of the bulk coolant temperature, the applicant was requested in RAI Question 24 to demonstrate that the US-APWR has coolant temperatures consistent with or bound by the ZIRLO^{TM} corrosion data temperatures given in Reference 1. The applicant presented data (Reference 2) that demonstrated that US-APWR coolant conditions and core average kW/ft (which also affect the metal/oxide temperature) are consistent with or are bounded by the existing ZIRLO^{TM} corrosion database coolant temperature conditions and core average powers. Therefore, the staff finds that the data used to develop the corrosion models are applicable to US-APWR operating conditions.

In Topical Report MUAP-07008 (Reference 1), the applicant provided plots of measured minus predicted oxide thickness for [ ] measurements from Zircaloy-4 and ZIRLO rods. In general these comparisons show a best estimate comparison to measured corrosion with a maximum under-prediction of [ ]. The staff noted that the cladding corrosion verification only included rods irradiated up to about [ ] (rod average), which does not bound the requested licensing limit. Therefore the staff requested in RAI Question 38 that the applicant provides comparisons to the Vandellos ZIRLO™ cladding high burnup corrosion data. In its response (Reference 2) the applicant provided Vandallos data from the ZIRLO™ high burnup extension program. After correcting for crud thickness the measured corrosion levels (oxide thicknesses) were well predicted at high burnups.

In RAI Question 48 the staff requested that MHI address concerns that the rod power histories of the high burnup extension program were not typical for two duty cycle (24 month cycles) high burnup US-APWR fuel rods. In its response (References 4 and 5) by showing comparisons of rod power histories from these programs to expected US-APWR rod power histories. MHI demonstrated that the high burnup extension program power histories were not prototypical for the US-APWR. Therefore, the applicant committed (Reference 5) to implementing an oxide measurement fuel surveillance program for US-APWR assemblies to confirm the measured corrosion performance is consistent or conservative relative to the FINE predicted ZIRLO™ corrosion model (oxide thickness). A revised oxide inspection plan submitted in response to Design Control Document (DCD) Section 4.2, "Fuel System design," and can be found in the response to RAI 129-1673, Question 4.2-19, Table 4.2-19-1, "Surveillance Program (Minimum Scope) Measurements and Inspections for Fuel Assemblies loaded into the initial Core (Close examination)." The staff agreed that only peripheral rods could be examined on re-inserted assemblies as the potential violating the [ ] limit during the first cycle of operation of a re-inserted assembly was not likely to be based on the initial low power densities and industry observed ZIRLO oxide behavior. Both peripheral and interior fuel rods will be examined upon final discharge of the fuel assemblies. The response to RAI 129-1673, Question 4.2-19, included development of an interim report for the first fuel inspections which will be available for possible NRC review before the start of the next operating cycle. A complete report, including the relevant portions of the interim report, will be made available for a possible NRC review, 90 days following the off-load of the last fuel assemblies following Cycle 2 for a 24-month fuel cycle, or Cycle 3 for 18-month fuel cycle. The commitment to measure oxide thickness was made by modifying DCD Section 4.2.4.5.3, "Cladding Oxide Thickness Inspections for Additional Design-Basis Verification," to be a Tier 2* item.

4.3.2 Hydriding and Hydrogen Pickup Models

The hydrogen pickup model in FINE assigns a specified fraction of the hydrogen liberated from the metal-water reaction for absorption by the cladding. This is similar to the Pressurized-Water Reactor (PWR) hydrogen uptake model in FRAPCON-3. In FINE a pickup fraction of [ ] is used for low tin Zircaloy-4 and for ZIRLO™. In its response to RAI Question 5b (Reference 2), the applicant presented data which seems to indicate that FINE under-predicted hydrogen content (ppm) for oxide thicknesses greater than [ ]. Therefore, in RAI Question 41 the staff requested the applicant to justify the use of a [ ] pickup fraction when it appears to not bound all the hydrogen content data. In its response, (Reference 4), the applicant responded that the comparison shown used measured oxide thickness values. When updated to use predicted oxide thickness values, the [ ] hydrogen pickup fraction over-predicted almost all low and mid-hydrogen content values. For very high hydrogen content values FINE tends to under-predict, but only one data point at highest hydrogen content [ ] was outside the uncertainty band. The one point outside the uncertainty band was for a hydrogen content well above the [ ] licensing limit (see Conclusions and Limitations, Section 5.0). For hydrogen contents equal to or below [ ] the FINE model is conservative and therefore acceptable.

In Reference 1, the applicant proposed a ZIRLO hydrogen content limit of [ ] to maintain adequate cladding ductility based on total plastic elongation (TE) data that demonstrates TE values greater than one percent plastic strain. In RAI Question 5b (Reference 2) the staff requested that uniform plastic elongation (UE) be provided up to the requested maximum burnup level rather than TE data, because brittle failure has been observed in zirconium alloys with measured TE greater than one percent (References 19 and 20). These TE data (References 19 and 20) suggest that TE is not a valid measure of ductility and UE may be a better ductility measure. In addition, RAI Question 40 (References 4, 5 and 6) noted UE data (References 19 and 20) suggesting that Zr-4 can produce a brittle failure with average hydrogen levels between [ ]. Therefore, RAI Question 40 requested further justification for the [ ] limit or to provide a lower hydrogen limit based on further data.

In its response to RAI Question 40 (Reference 4), the applicant provided a small amount of UE data from ZIRLO burst tests suggesting that UE plastic strains were near [ ] of hydrogen; this results in an elastic + plastic UE of [ ] strain. Simulated reactivity initiated accident (RIA) tests in the nuclear safety research reactor with ZIRLO™ cladding and hydrogen levels of ~ 660 ppm demonstrated an elastic + UE plastic deformation of 1.0 to 1.2 percent strain at temperatures of 285°C (545°F) and 0.9 to 1.1 percent at temperatures below 100°C (212°F) (Reference 21).

In its revised response to RAI Question 40 (Reference 6), the applicant stated that it will limit hydrogen to [ ]. The staff concludes that the hydrogen limit of [ ] will provide a reasonable assurance that a strain capability above the required elastic + UE plastic strain limit of 1.0 percent will be maintained for ZIRLO™ cladding.

The staff concludes that the hydrogen pickup model in FINE is acceptable and also concludes that the revised hydrogen content limit for ZIRLO™ of [ ] is acceptable.

4.4 FUEL DENSIFICATION AND SWELLING MODELS

There are two models for swelling, one for solid swelling, which is dependent on steady-state operation (burnup) and a second for gaseous swelling, which is typically only observed at high temperatures (only important during overpower transients) and which becomes more important at higher burnups.

4.4.1 Fuel Densification and Solid Swelling Models

MHI provided comparisons that showed measured and predicted pellet density as a function of burnup to verify the FINE fuel densification and solid swelling models predictive capabilities. In general, FINE slightly over-predicts the measured density [ ]. In RAI Question 36 the staff requested that the applicant discuss how the fuel density measurements were made and discuss the impact of over-predicting fuel density. In its response, (Reference 2), the applicant discussed how the density measurements were made and concluded that some of the variability in the density comparisons may be due to measurement technique. In order to address the impact of an over-prediction in pellet density, the applicant ran sample cases with the initial pellet density biased down by [ ]. These analyses showed that the impact is less than one percent on strain and fatigue analyses and negligible impact on rod internal pressure and stress analyses. These analyses also showed that the impact on centerline temperature was less than [ ].

The solid swelling model in FINE uses a constant swelling rate of [ ]. This corresponds to a rate of [ ], which is slightly lower than the rate of 0.62 percent delta V/V per 10 GWd/MTU that is used in FRAPCON-3 below 85 GWd/MTU (Reference 24). This difference is considered to be well within the standard deviation of 0.08 percent delta V/V per 10 GWd/MTU in solid swelling data (Reference 22). The lower solid swelling rate in FINE relative to FRAPCON-3 will result in a slightly larger gap and a lower gap conductance value at low burnup and a higher fuel temperature, which is conservative for fuel centerline and fuel melt temperatures.

The staff concludes that the FINE fuel densification and solid swelling models are acceptable for thermal analyses and acceptable for evaluating the relative mechanical performance of different fuel designs and operational modes.

4.4.2 Gaseous Swelling Models

The FINE gaseous swelling model increases with increasing burnup and fuel temperature. The model decreases both the initial temperature at which gaseous swelling starts and maximum fuel temperature at which the maximum swelling is experienced with increasing burnup. The gaseous swelling model purpose is to correctly predict cladding strains during AOO overpower transients. It was unclear from Reference 1, as to how the FINE gaseous model worked. Therefore, the staff requested in RAI Question 39b that the gaseous swelling model be explained in further detail. In its response (Reference 4) the applicant provided sufficient detail for the swelling model to be understood and for the staff to independently predict gaseous swelling for a given fuel pellet radial temperature profile (Reference 31).

[ ] power ramp tests were provided in the Reference 1 to verify the FINE predictive capabilities for overpower transients. The staff requested in RAI Question 36 (Reference 2) that the FINE code be compared to [ ] rods that were ramped in power and significant cladding plastic strains were measured.

In its response the applicant provided a comparison of measured and FINE predicted strain (Reference 2) for the [ ] fuel rods. The comparison shows that FINE code generally over-predicted cladding strains when rod average burnups exceeded [ ] and the fuel-clad gap was closed. This suggests that the FINE gaseous swelling model is conservative in relation to calculating plastic strain for AOO overpower events. The staff concludes that the gaseous swelling model provides a conservative prediction of plastic strain during an AOO overpower event when the fuel-clad gap is closed and, therefore, is acceptable.

4.5 MECHANICAL MODELING AND PROPERTIES

The Zircaloy-4 and ZIRLO™ mechanical properties include cladding creep, yield strength, Young's modulus, and Poisson's ratio. Cladding creep is the most important of these properties because predicted cladding creepdown significantly affects the fuel-cladding gap and therefore the thermal and strain analyses. The creep model in FINE is a function of three components, 1) irradiation 2) thermal and 3) axial growth.

4.5.1 Irradiation Induced Creep

In Reference 1 the applicant provided a limited profilometry database from [ ] to evaluate the ZIRLO™ creep model performance. No validation of the Zircaloy-4 creep model was provided. As no Zircaloy-4 creep model was provided in Topical Report MUAP-07008, the staff requested in RAI Question 29 additional validation of the FINE Zircaloy-4 creep model. In its response (Reference 2) the applicant stated that only ZIRLO™ cladding would be licensed in the United States. Based on this response, FINE will not be approved for application to Zircaloy-4 clad fuel rods. Also in RAI Question 29 the staff requested the applicant to provide more details of the ZIRLO™ validations that were performed and to justify the exclusion of creep data from the top and bottom of rods. In its response (Reference 2) the applicant demonstrated that there was no bias with respect to local fluence or measured diameter decrease. In addition the data set used to validate the model comes from three different fuel batches. [ ].

The staff also compared the creep models in FINE to those in FRAPCON-3 for Zircaloy-4 and ZIRLO™ for a case with cladding temperature of 625K (1125R) and fast neutron flux of 1.0×10^{14} n/cm²/s. Calculations were performed for three effective stress levels. At low effective stress levels, the FINE model predicts less creep than FRAPCON-3 (Reference 31). At moderate effective stress levels, the two models predict similar results. At high effective stress levels, the FINE model predicts more creep than FRAPCON-3.

For the higher and lower stresses, the FINE creep strain predictions are different due to the much larger exponent [ ] on stress than in the FRAPCON model (stress exponent for thermal creep is 2 and exponent for irradiation creep is 1.0). The FINE creep model has been assessed against a limited amount of in-reactor creep data. The applicant has stated that a lower bound uncertainty multiplier of [ ] and upper bound uncertainty multiplier of [ ] will be applied to the creep model uncertainty analyses. This uncertainty is adequate to cover differences between FINE and FRAPCON-3 and to bound the assessment data. [ ]. The creep model is limited to mid-wall temperatures of [ ] or less because the irradiation creep database does not extend beyond this temperature.

Based on these comparisons and the large assumed uncertainties, the staff concludes that the creep model in FINE is acceptable for calculating ZIRLO™ irradiation creep. FINE will not be used for licensing calculations on rods with Zircaloy-4 cladding.

4.5.2 Young's Modulus

FINE uses Hooke's Law to relate stress and strain in the elastic region. This approach is identical to the approach used in FRAPCON-3. However, the equations for Young's modulus are different from those used in FRAPCON-3.

The model in FRAPCON-3 is a function of temperature, cold work and fast neutron fluence. The FINE model is only applicable to cold work stress relief annealed cladding and therefore does not require a cold work dependency. The model for Young's modulus in FINE was compared to the Young's modulus model in FRAPCON-3 for irradiated Zircaloy-4 and ZIRLO™. The two models are in close agreement between [ ]. The staff concludes that the Young's modulus model of Zircaloy-4 and ZIRLO™ cladding in FINE is acceptable within a temperature range of [ ].

4.5.3 Yield Strength

FINE uses a yield strength formula, which is a function of temperature only. However, there are separate formulas for unirradiated and irradiated cladding. The formula in FRAPCON-3 is a function of temperature, cold work, strain rate and fast neutron fluence. For US-APWR, the ZIRLO cladding will always be stress relief annealed; therefore the FRAPCON-3 formula for 50 percent cold work will be used to compare with FINE.

The FINE model compares well with the unirradiated FRAPCON-3 model and with the FRAPCON irradiated model at [ ]. However, the FINE model predicts instantaneous hardening (increase in yield) with fluence below [ ] while FRAPCON-3 has a more gradual increase with fluence. A higher predicted yield strength at these low fluences will result in less cladding permanent (plastic) strain at low burnups than calculated with FRAPCON-3. For fluence values greater than [ ] FINE predicts a lower yield stress, which is conservative. The over-prediction of yield strength below a fluence of [ ] is acceptable for calculating cladding strain for two reasons: 1) maximum predicted strain is at fluences > $5x10^{21}$ n/cm^2, and 2) the one percent strain limit for the cladding strain analysis is based on the total of elastic + UE plastic strain such that the prediction of yield strength does not impact this analysis of total elastic + plastic strain.

4.6 COMPARISON OF FINE PREDICTIONS TO POWER RAMPED STRAIN DATA

In Reference 1, FINE was assessed against [ ] power ramped rods. The staff judged that [ ] power ramps were not an adequate validation of the FINE code to predict cladding strains during an AOO overpower event. These [ ] assessments were performed on rods with a rod average burnup of around 30 GWd/MTU. These comparisons show that FINE predicts permanent hoop strain well for one rod and [ ] for the other rod. Because of the extremely limited database of ramped rods, RAI Question 35 requested MHI to provide comparisons to more ramp test data from the RISO FGP3 ANF rods, Studsvik B&W ramps, Super-Ramp, and Over-Ramp. In its response the applicant provided (Reference 3) FINE comparisons for [ ] power ramped rods from these power ramp tests. In general these comparisons show that FINE over-predicts strain during power ramps. However, there are two cases that FINE under-predicts by up to [ ] strain which is greater than the [ ] uncertainty assumed at low-to-moderate rod average burnups.

FINE was also compared to the FRAPCON-3 predicted strains. The staff requested in RAI Question 1b and 1c (Reference 2) that the applicant provide a sample strain calculation that could be compared to FRAPCON-3. The results of this comparison show that FINE may under-predict cladding strain at low burnups [ ] by up to [ ] strain. When comparing FINE to both experimental and FRAPCON-3 predictions at low-to-moderate burnups the staff concludes that the FINE permanent strain prediction uncertainty may be as large as [ ] below [ ]. Therefore, MHI has agreed to use a [ ] strain uncertainty for rod average burnup below [ ] (see Conclusions and Limitations, Section 5). The staff finds the [ ] strain uncertainty for rod burnups below [ ] is acceptable.

4.7 VOID VOLUME MODEL AND ASSESSMENT

The rod internal pressure in FINE is calculated in the typical manner of dividing the number of gas moles (multiplied by the gas constant) by the sum of the various volumes divided by temperature within the rod. In FINE the volumes used are the dish and chamfer volume, the volume in radial cracks, the volume of the fuel/cladding gap, the volume in the open porosity, the volume in the surface roughness and chip volume, and the upper and lower plenum volume, adjusted for differential fuel/cladding expansion.

The staff requested in RAI Question 32 for MHI to discuss how the volume attributed to pellet chips is determined. In its response (Reference 2) the applicant provided discussion that pellet chip volume is inferred from the differences between calculated densities from weight and pellet dimensions and from immersion density measurements. The staff notes that there is considerable scatter (uncertainty) and bias in immersion density measurements such that it is difficult to infer the very small effects of chips from these measurements.

The applicant provided plots showing comparisons of measured and predicted void volume. In RAI Question 37 (Reference 2) the staff requested MHI to provide the data from these plots of measured void volumes from commercial rods. The data indicates that FINE over-predicts the measured void volume by about [ ].

The staff noted that the amount of over-prediction in void volume is similar to the amount of volume attributed to chips and surface roughness. Since FINE over-predicts void volume, the staff submitted RAI Question 47 requesting the applicant to provide additional justification for using pellet chips and surface roughness volumes. In its response (Reference 4) the applicant stated that this is justified as the rod internal pressures are not under-predicted.

The over-prediction of FINE rod internal void volume by approximately [ ] is non-conservative when calculating rod internal pressure. Because of this non-conservatism, the staff did not agree that pellet chips and surface roughness volumes should be used in determining the rod internal pressure. The applicant revised its response to RAI Question 47 (Reference 6), that chips and surface roughness will not be included in the void volume calculation for rod internal pressure and the nominal fabrication values will be used.

The staff concludes that the FINE void volume model is acceptable based on the measured versus predicted rod internal volume agreement provided in response to RAI

Question 37 without the inclusion of the volume due to chips and surface roughness as described in response to RAI Question 47.

4.8 ROD AXIAL GROWTH

FINE contains irradiation axial growth models for stress-relief annealed Zircaloy-4 and ZIRLO™. The models for Zircaloy-4 and ZIRLO™ in FINE have been compared against the models in FRAPCON-3 for these alloys. Both the FINE models and the FRAPCON-3 models are a function of fast neutron fluence only. The two models are in close agreement [ ] up to fast fluences (one > MeV) of 13×10^{21} n/cm^2, which exceeds the requested burnup level of 62 GWd/MTU. The staff concludes that the FINE irradiation axial growth models are acceptable for SRA Zircaloy-4 and ZIRLO™.

4.9 FINE LICENSING APPLICATIONS

The applicant has provided methodologies for each application of the FINE code to design analyses to satisfy specified acceptable fuel design limits (SAFDLs) identified in Section 4.2 of the SRP and Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50.46 Emergency Core Cooling System (ECCS) criteria are met. The code applications to these analyses include:

- Cladding liftoff analysis (rod internal pressure).
- Fuel melt overpower analysis.
- Cladding stress and strain overpower analysis.
- Cladding fatigue.
- Cladding corrosion and hydriding.
- Thermal-mechanical inputs to other analyses (LOCA).

The scope of this SE is to assess the ability of FINE to predict fuel rod performance in a best estimate or conservative manner.

4.9.1 Cladding Liftoff Analysis (Rod Internal Pressure)

For the design basis dealing with excessive rod internal pressure during normal operations and AOOs, MHI has identified two limits that must be met to ensure no fuel damage. These limits are:

- No cladding liftoff during normal operation.
- No reorientation of the hydride in the cladding radial direction.

In order to ensure that no cladding liftoff is experienced during normal operation there are two parts to this analysis. The first is the determination of the internal rod pressure limit that prevents cladding liftoff, [

]. The rod pressure limit analysis includes [ ] uncertainties. The second part of this analysis is to perform a FINE calculation for the rods in the core that achieve the highest pressures to verify the limit is not exceeded.

The FINE analysis of the highest rod internal pressures must account for uncertainties in the FINE models, rod fabrication and rod power histories that impact predicted rod pressures.

In RAI Question 9a, the staff requested that the applicant describe how FINE determines the pressure limit at which liftoff occurs. In its response (Reference 2), the applicant stated that a conservative analysis [ ] is used to determine the rod internal pressure limit. The applicant's conservative methodology is to vary [ ] over a wide conservative range of values to determine a range of rod internal pressures that causes lift-off. From this conservative range the lowest internal pressure with lift-off is selected. The liftoff pressure is defined as when the gap re-opens or, in the case of no gap closure, when the gap size begins to increase.

The staff concludes that the applicant's rod internal pressure limit based on varying [ ] is indeed conservative when compared to Halden data and staff analyses. Therefore the staff finds this method of determining the rod lift-off pressure limit acceptable.

The following will discuss the analysis of maximum rod internal pressure to demonstrate that the conservative rod pressure limit is met. Since rod power histories significantly impact the maximum rod internal pressure calculation, the staff requested in RAI Question 9b (Reference 2), that the applicant describe how power histories are selected for peak operating rods and what transients and AOO events are included. In RAI Question 9e, the staff requested that the applicant describe how rod power uncertainties are applied in FINE rod internal pressure analysis. In RAI Question 9c, the staff asked what assumptions are being made for the F_Q and $F_{\Delta H}$ limits as these determine the maximum local and integrated, steady state rod powers. In order to perform a FRAPCON-3 audit calculation, the staff requested in RAI Question 9d, that MHI provide sample FINE calculations of the maximum pressure.

In its response to RAI Question 1b (Reference 2) the applicant applied to RAI Question 9b, where the following power histories are used to determine which will give the maximum rod internal pressure:

- [ ]
- [ ]
- [ ]
- [ ]

The power history of those above that gives the maximum rod internal pressure is used to compare to the limit. The applicant further stated (Reference 2) that [

] are generally the most limiting for rod internal pressure. The staff modeled the maximum pressure cases provided using FRAPCON-3 for the UO_2 and the UO_2-Gd_2O_3 cases (Reference 31). These comparisons are shown below in Figure 1, “Calculated US-APWR Maximum Pressure Case.” Figure 1 shows that FINE and FRAPCON-3 predict similar pressures and FINE predicts the same or greater maximum pressure at end-of-life (EOL).

The staff examined the applicant power histories used in the rod pressure analysis and notes that they are considerably less than the F_Q and $F_{\Delta H}$ assumed Core Operating Limit Report (COLR) values (Reference 26). The applicant has stated that it utilizes best estimate calculated power histories for a given core to determine whether they meet their rod internal pressure limit. The staff notes that the applicant does not include uncertainties from the nuclear analysis code (e.g., Advanced Nodal Code), an uncertainty between planned or actual operation, or uncertainties in measuring the rod powers during actual operation. The staff notes that conservative rod power histories are important in determining a conservative rod internal pressure value. The lack of uncertainties will be discussed below with a discussion of the application of fabrication and code model uncertainties.

In its response to RAI Question 9e, the applicant provided the list of fabrication and model uncertainties that are considered in the rod pressure analysis. The nominal (best estimate) maximum pressure is increased by determining the impact (delta change) on pressure of each of the following parameters to their tolerance limits for manufacturing parameters or to their upper 95/95 values for model parameters.

- [ ]
- [ ]

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

The impact of each parameter is combined in a square root of the sum of squares method, and this uncertainty is added to the calculated nominal maximum pressure. [ ].

It is the staff's position that, regardless of the impact of AOOs on rod internal pressure for the sample US-APWR core loading scheme, its impact should be accounted for in the rod internal pressure evaluation because some fuel management schemes can result in AOOs having a more significant impact on rod pressure. As a follow-up to RAI Question 9b, RAI Question 42 requested that MHI describe the AOOs and Xe transients (part of normal operation) that were used to determine the minimal effect of AOOs on rod internal pressure and to describe a methodology that would include the effect of AOOs and Xe transients in the calculation of maximum rod internal pressure. In its response to RAI Question 42 (Reference 4), the applicant provided a description of the normal operational (xenon) transients and AOOs; the discussion of how they are applied in the maximum rod internal pressure analysis was given in response to RAI Question 43.

To address the issue of what type of normal operation and AOO transients would be analyzed, the applicant responded to RAI Question 43 (Reference 6) that in the rod pressure analysis it would use either a xenon transient [ ] or an AOO transient [ ]. In addition, the rod average power for the xenon transient would be increased by [ ] to account for the change [ ]. The transient (either the Xe or limiting AOO) with the maximum rod internal pressure would be compared to the rod internal pressure limit. As a Xe transient, within the COLR Axial Offset (A.O.) limits, is considered normal operation, the staff's position was that a combination of a Xe transient and the limiting AOO should be considered together. Based on the staff's concern, the applicant revised the response to RAI Question 43 (Reference 7) to explicitly include the limiting AOO event superimposed on the limiting Xe transient for A.O.s within the COLR limits. The staff finds the MHI methodology of combining the limiting AOO and Xe transient acceptable.

As noted above, the applicant does not include rod power uncertainties for steady-state (normal) operation in the determination of an upper bound rod internal pressure. As a follow-up to RAI Question 9e, RAI Question 43 requested that the applicant propose estimated uncertainties on the power history and propose a methodology for including these uncertainties in the determination of a maximum rod internal pressure per SRP 4.2. In its response (Reference 4), the applicant stated that [ ]. The staff does not agree that [ ] is enough uncertainty to apply to a realistic power history to account for all the possible variations from the following sources:

- [ ]
- [ ]
- [ ]

A typical nuclear analysis code calculational uncertainty alone can be up to [ ]. The staff also had concerns that selecting only the power history with [ ] may not provide the maximum pressure power history. For example, a higher power at beginning-of-cycle (BOC) may result in lower rod pressures than a lower power at end of cycle because fission gas release increases with increasing burnup. It is the staff's position that more power histories need to be selected from smaller (multiple) burnup intervals within a cycle to ensure that the maximum (conservative) pressure case is identified.

In a revised response to RAI Question 43 (Reference 7) the applicant addressed the staff's concern of insufficient rod power uncertainties and number of analyzed power histories to determine the maximum rod internal pressure. The applicant responded that [ ]. In addition, [ ]. Therefore, a total rod power uncertainty of [ ] will be used for FINE internal pressure calculations. Also, if actual operation exceeds these assumed uncertainties the FINE rod internal pressure analyses must be reanalyzed to take into account actual rod powers with measurement uncertainties to verify that the rod internal pressure limit is not exceeded.

4.9.2 No Radial Reorientation of Hydrides

To ensure that hydrides are not reoriented in the radial direction due to high rod internal pressure, the applicant uses FINE to calculate the stress in the fuel cladding. The applicant has found that hydride reorientation in cold worked, stress relived annealed (CWSRA) material begins at 110 MPa (15950 psi) in Zircaloy-4 and at 80 MPa (11600 psi) in Zr-2.5Nb. Since ZIRLO™ is a CWSRA material and contains one percent niobium (Nb), any impact of Nb additions or reorientation stress is bounded by the Zircaloy-4 (0.1 percent Nb) and the Zr-2.5Nb (2.5 percent Nb). The applicant selected 80 MPa as the critical hoop stress to avoid hydride reorientation. For typical system pressure, this corresponds to an internal pressure of 27 MPa (3900 psi). The staff concludes that using the lower bound stress from the Zircaloy-4 and Zr-2.5Nb for ZIRLO™ is acceptable since these alloys bound the Nb content in ZIRLO™ and all these alloys have a similar heat treatment. The calculated upper bound pressure is checked each reload to make sure that it does not exceed 80 MPa.

4.9.3 Fuel Melt Overpower Analysis

The applicant uses FINE to evaluate that the calculated fuel centerline temperature will not exceed the no melt SAFDL during normal operation and AOOs. The fuel melting criteria (SAFDL) applied by the applicant is that "…there shall be at least a 95-percent probability at a 95-percent confidence level that the fuel rod with the most limiting linear heat rate (kW/ft) does not cause the fuel pellet to melt during normal operation and AOOs." An AOO event bounds normal operation in regard to this analysis; therefore, MHI examines all AOO events to determine which is the most limiting in terms of fuel melting.

The best estimate fuel melting temperature limits in FINE for UO_2 and for UO_2-Gd_2O_3 with 10 weight percent Gd_2O_3 are shown in Figure 2 below, versus burnup with the FRAPCON-3 best estimate melting temperature limit. It can be seen from this figure that the FINE best estimate melting temperature limits are less than those predicted by FRAPCON-3. This is conservative for the fuel melt analysis and therefore is acceptable.

The FINE analysis applies the model and fabrication uncertainties to the fuel melting limit rather than to the FINE calculated fuel temperatures. The 95/95 uncertainty penalty on (subtracted from) the fuel melting temperature is determined by perturbing the model and fabrication uncertainties at their 95/95 level to determine a delta temperature response (with respect to no uncertainty, i.e., best estimate). These 95/95 delta responses (due to uncertainties) on fuel temperature plus [ ] (95/95) uncertainty in FINE temperature predictions are then combined using the square root of the sum-of-squares of these responses such that a 95/95 bounding value of [ ] is determined. MHI has added an additional conservatism of [ ] on this uncertainty analysis to obtain a conservative bounding value of [ ] (Figure 3.3.4-1 of Reference 1) which is subtracted from the fuel melting limit for a given burnup. The fuel melting limit used by the applicant for determining the Linear Heat Generation Rate (LHGR) limit to prevent fuel melting as a function of burnup is [ ] lower than the best estimate values provided in Figure 2 above.

The following parameters are those uncertainties included in the square root sum-of-squares analysis as per Reference 26:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

The staff has examined these uncertainties and believes the uncertainty on FINE calculated temperatures in terms of an absolute value of [ ] may be underestimated at the LHGRs where melting is experienced (see Section 4.1.9 of this SE). This is because the true temperature uncertainty is typically a constant percentage of the prediction such that at high LHGRs where fuel melting is calculated the absolute temperature uncertainty is greater than at low LHGRs where the FINE verification temperature data exist. Therefore, the uncertainty on predicted fuel temperatures should be based on a relative uncertainty (percent uncertainty) rather than the [ ] absolute temperature used by MHI. For example, the FINE temperature comparisons to measured data are typically at LHGRs of [ ]or less while the LHGR limits for fuel melting near beginning-of-life are greater than [ ]. The staff has performed an independent uncertainty analysis (Reference 31) using a more conservative temperature uncertainty of [ ] for FINE temperature predictions and concluded that this will result in a slightly lower square root sum-of-squares uncertainty at a 95/95 level than that used by the applicant [

]. Therefore, the staff concludes that the [ ] uncertainty is conservative such that the MHI fuel melting limit is conservative and therefore is acceptable.

The FINE code is used to calculate the LHGR limit where fuel melting is prevented based on the conservative melting temperature limit discussed above. The staff requested in RAI Question 12 (Reference 2) for MHI to provide sample best estimate calculations of fuel melting at various burnup levels. The applicant provided these sample calculations, and the staff performed audit calculations using FRAPCON-3 (Reference 31). The FINE and FRAPCON-3 predicted centerline temperature as a function of local linear power are shown in Figures 3, 4, and 5 for rod average burnups of 10, 30, and 50 GWd/MTU, respectively. It can be seen from these figures that FINE predicts temperatures similar to FRAPCON-3 near the LHGR limits for fuel melting at rod average burnups ≤ 30 GWd/MTU but predicts higher temperatures at a rod average burnup of 50 GWd/MTU. MHI verifies that the local linear power meets the fuel melt LHGR limit for each reload cycle for the most limiting AOO event.

The staff concludes that the FINE code and the proposed methodology are acceptable for calculating fuel melt margin because they adequately account for uncertainties, providing a conservatively bounding calculation of fuel melting.

4.9.4 Clad Strain Overpower Analysis

The applicant uses FINE for evaluating strain for both normal operation and AOO events but the criteria for delta strain are different for these two operating conditions. The applicant uses FINE to evaluate the strain criterion that the total cladding strain change during normal operation shall be less than one percent relative of the unirradiated (as-fabricated) condition. In RAI Question 1a the staff asked if the applicant takes the one percent strain to be elastic plus plastic strain, or just plastic strain. In its response (Reference 2) the applicant assumes the one percent strain limit is elastic plus plastic for normal operation. [ ] are examined to determine the rod with the maximum strain during steady state. The applicant noted that for US-APWR the maximum cladding strain is compressive due to creepdown, while the one percent cladding strain limit is applied in tension. MHI does not apply any uncertainties to the strain analysis for normal operation because it considers the one percent strain criterion to be conservative for normal operation.

The staff agrees that the one percent cladding strain limit is conservative for normal operation because power changes are relatively slow compared to an AOO event such that cladding stresses generally remain below the elastic limit and fuel and cladding creep dominate the plastic deformation. The cladding can generally accept more plastic deformation due to creep than plastic deformation due to stresses exceeding the elastic limit as in an AOO overpower event.

For an AOO event, MHI uses FINE to evaluate the design criterion that the total cladding strain change, elastic plus plastic, shall be less than one percent from the pre-transient (AOO) condition. The AOO strain criterion is much more limiting than that for normal operation. In RAI Question 1b the staff requested the applicant to provide a sample calculation showing the calculation of maximum strain increment during a limiting AOO overpower event. In its response (Reference 2) the applicant provided an example as well as a description of how the limiting power histories are selected and what uncertainties are applied.

The applicant takes the following power histories to determine which one will give the maximum strain increment:

- [ ]
- [ ]
- [ ]
- [ ]

At each time step in these histories, a power ramp of [ ] of the steady state power is applied and the maximum strain increment is recorded. The hold time of [ ] for an AOO event is assumed based on typical operator response times to an AOO event. However, the hold time for determining cladding strain for an AOO event is not critical because of the short times for these events such that cladding creep is minimal and the fuel expansion and gaseous swelling models in FINE that drive the strain are not time dependent. An uncertainty is applied to the maximum calculated strain increment by determining the impact (delta change) on predicted strain from varying the following parameters to their tolerance limits for manufacturing parameters or to their upper 95/95 values for model parameters:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

The delta strain response of each parameter at the upper limit is combined in a square root of the sum of squares method, and this uncertainty is added to the maximum best estimate calculated strain increment. The applicant stated that the uncertainty for UO_2 is [ ] strain and the uncertainty for UO_2-Gd_2O_3 is [ ] strain (Reference 1).

To evaluate the [ ] and [ ] strain uncertainties, the staff requested in RAI Question 1c that the applicant provide best estimate predicted cladding strain results for the limiting UO_2 and UO_2-Gd_2O_3 rods for the limiting AOO event as a function of burnup. This request was made because it was suspected that the FINE-predicted maximum cladding strains could be lower than the FRAPCON-3 values at lower rod average burnups due to the lack of a FINE fuel relocation model. The lack of a relocation model is conservative for temperature calculations but may not be conservative for cladding strain predictions at lower burnups as the fuel relocation model causes earlier pellet-clad interaction.

The staff used the FINE inputs in FRAPCON-3 to compare nominal strain values (Reference 31). Table 1 below shows the comparison of the two models.

It can be seen from this table that the FINE maximum strain prediction is greater than the FRAPCON-3 maximum strain prediction. However, the staff noted that FINE predicts gap closure to occur at a significantly higher burnup than FRAPCON-3 due to the assumption of no fuel relocation in FINE. The staff has concerns that FINE may under-predict cladding strain at lower burnups. The staff noted that at lower burnups, FINE predicts less strain than FRAPCON-3 as seen in the above table. This is a concern because different fuel management schemes or changes in design can result in peak strains occurring at lower burnups. In fact FRAPCON-3 predicts peak strains to occur at a lower burnup than FINE for the current US-APWR design. In addition, the FINE UO_2 uncertainty of[ ] is barely enough to cover this under-prediction at 25 GWd/MTU. Also, as noted in Section 4.6, FINE under-predicted the strain of two power ramped rods by [ ] at burnups less than 33 GWd/MTU, which is greater than the MHI [ ].

Because of the staff's concerns of using a [ ] uncertainty at lower burnups RAI Question 39a (References 4, 5 and 6) requested MHI to propose a new strain uncertainty below 33 GWd/MTU. In its response (Reference 6) the applicant has proposed an additional uncertainty of [ ] to the upper bound cladding strain when the burnup is less than [ ]. This brings the total uncertainty for cladding strain to [ ] for rod average burnups less than or equal to [ ] and retains the uncertainty of [ ] for burnups greater than [ ].

The staff concludes that the FINE code, the proposed methodology, and updated uncertainties are acceptable for cladding strain for the AOO overpower analysis.

4.9.5 Cladding Fatigue

The applicant uses the FINE code to obtain the cladding stress for each specified operational condition for the cladding fatigue analysis. These include reactor startup/shutdown operation, AOOs, and other power changing operation. MHI then uses the fatigue damage curve in Figure 3.2.4-1 of Reference 1 to determine the damage fraction that each operational condition causes. The damage fraction for each operational condition is determined by taking the reciprocal of the number of allowable cycles predicted for the stress amplitude. The applicant then adds up the damage fraction from each operational condition and ensures that the total is less than 1.0. This methodology is industry standard practice for calculating fatigue damage due to cycles at different stress intensities from a fatigue curve derived from fatigue tests at the same stress intensity.

The staff noted that Figure 3.2.4-1, “Fatigue Design Curve,” of Reference 1 had two design curves. In RAI Question 3 the staff requested the applicant to provide, which of these curves would be used for fatigue cladding analyses. In its response (Reference 2) the applicant stated that the design curve corrected by maximum mean stress is the curve that would be used in cladding fatigue analyses.

A reduction of cladding thickness caused by grid-to-rod fretting would increase clad stress causing clad fatigue to occur earlier. The staff requested in RAI Question 4a if fretting wear is included when determining cladding stress. In its response (Reference 2) the applicant stated that the design limit on fretting wear is subtracted from the cladding thickness in the stress calculation and therefore is included.

The staff concludes that the FINE code and the proposed methodology are acceptable for cladding fatigue analysis based on the ability of the FINE code to calculate stress and the use of an industry standard methodology for calculating fatigue damage from multiple cycles at different stress intensities.

4.9.6 Cladding Corrosion and Hydriding

The FINE code is used to calculate the corrosion and hydriding of the cladding. As noted in Section 4.3 the models for oxidation and hydrides limits are acceptable. For the fuel cladding oxide thicknesses above [ ], the FINE analysis uses an upper bound 95/95 uncertainty of [ ]. After review of the data provided in Reference 1, the staff finds the provided oxide thickness uncertainty acceptable. As stated in Section 4.9.1 of this SE, the rod power histories used for the oxide thickness calculation are not representative of that expected from the US-APWR fuel managements. Therefore, MHI has agreed to a fuel inspection campaign to confirm the FINE oxide model. A Combined License item will be included in DCD Section 4.2, “Fuel System design,” (Reference 30) to ensure that fuel inspections are performed. Based on future confirmation of the oxide model the staff finds the current oxide methodology and uncertainty acceptable.

FINE code analysis of cladding hydriding is based on a best estimate analysis, i.e., there is no uncertainty evaluation to demonstrate that the hydride limit is met. This is consistent with other approved hydrogen pickup models for ZIRLO^{TM} cladding. As noted in Section 4.3.2 of this SE, the best estimate FINE hydride model over-predicts all but one of the hydride data demonstrating conservatism in this model. The staff concludes that the FINE code and the proposed analysis methodology for predicting hydrogen content is acceptable.

4.9.7 FINE Calculational Inputs to LOCA and AOO Analyses

Reference 1 did not discuss the application of FINE to other analyses such as for LOCA initialization.

RAI Question 18 asked if the FINE code will be used to determine initial conditions for LOCA analyses and if so to provide a sample calculation of limiting rod initial LOCA conditions for US-APWR. In its response (Reference 2) the applicant stated that the FINE code will be used to determine the initial conditions for LOCA analyses.

The applicant provided (Reference 2) a sample calculation of centerline temperature as a function of LHGR at a burnup of [ ]. A burnup of [ ] was chosen, as this is used for all the rod burnups in the Large Break LOCA model (Reference 29). The applicant also provided (Reference 2) calculations at other burnup levels to demonstrate maximum centerline temperatures were at the burnup of [ ].

A FRAPCON-3 calculation of this same case was also performed. The centerline temperature predictions from each code are shown below in Figure 6. It can be seen that for all power levels FINE predicts higher temperatures than FRAPCON-3. It should be noted, however, that FRAPCON-3 predicts maximum temperature at which the LHGR limit is established, i.e., 25 GWd/MTU as shown in Figure 6. This is because the FRAPCON-3 fuel relocation model reduces the gap at low burnups up to 10 GWd/MTU, and burnup degradation of the fuel thermal conductivity increases fuel centerline temperatures at a constant LHGR limit beyond 10 GWd/MTU up to its maximum burnup of 25 GWd/MTU. Beyond 25 GWd/MTU the LHGR limit decreases with increasing burnup at a faster rate than the burnup degradation on thermal conductivity increases fuel temperatures. FINE calculates maximum fuel temperature at a lower burnup because the gap is at its maximum due to lack of a relocation model, and gap size dominates the temperature predictions rather than the increased fuel thermal conductivity. As shown in Figure 7, below, the maximum fuel temperatures calculated with FRAPCON-3 at all burnup levels were less than those maximum temperatures calculated by FINE at [ ] burnup. Therefore, the FINE fuel temperature predictions are conservative. This conservatism is further confirmed by FINE comparisons to measured fuel temperature data from instrumented fuel rods (see Section 4.1.9 of this SE).

An uncertainty is calculated for the nominal centerline temperature by determining the impact (delta change) on predicted temperature from varying the following parameters to their tolerance limits for manufacturing parameters or to their upper 95/95 values for each model parameter:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

The impact (delta change) of each parameter on fuel temperature is combined in a square root of the sum of squares method. The nominal temperature and the 95/95 uncertainty are provided to the LOCA analysis.

An uncertainty is calculated for the nominal rod internal pressure by determining the impact on (delta change) pressure of each of the following parameters to their tolerance limits for manufacturing parameters or to their upper 95/95 values for each model parameter:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

The impact (delta change) of each parameter on rod pressure is combined in a square root of the sum of squares method. The nominal rod internal pressure and the 95/95 uncertainty are provided to the LOCA analysis.

The staff concludes that the FINE code is acceptable for calculating initial conditions for LOCA analyses based on the conservative FINE fuel centerline temperature results.

4.9.8 LHGR Limits

This section addresses the US-APWR LHGR limits that result in fuel melt as a function of burnup and whether the FINE code has been validated over this range. In RAI Question 9c, the staff requested the applicant to provide the US-APWR $F_{\Delta H}$ and F_Q limits. In its response (Reference 2) the applicant stated that the best estimate peaking factor values of $F_{\Delta H}$ = 1.52 and F_Q = 1.82 (core average power of 4.65 kW/ft, (15870 Btu/hr-ft) were given in Reference 26 for a typical equilibrium cycle. Therefore, the best estimate $F_{\Delta H}$ and F_Q LHGRs are 7.07 kW/ft and 8.46 kW/ft (24130 Btu/hr-ft and 28870 Btu/hr-ft), respectively. The steady state, COLR LHGR limits for $F_{\Delta H}$ and F_Q are 8.04 kW/ft and 12.1 kW/ft (27440 Btu/hr-ft and 41,290 Btu/hr-ft) (up to 25 GWd/MTU) per Table A-1 of Reference 26 and response to RAI Question 18 of Reference 2. As demonstrated by the applicant's response to RAI Question 19, FINE is well validated to 62 GWd/MTU with a [ ], which covers the US-APWR operating range. Therefore, the staff concludes that the FINE code has been adequately verified for the US-APWR LHGR versus burnup operating ranges.

The applicant has also constructed a LHGR limit for AOOs based on their conservative fuel melting temperature limit (reduced by [ ]). Slightly lower powers are selected than those powers that will cause incipient fuel melting. These limits are shown in Figure 8 for UO_2 fuel and for UO_2-Gd_2O_3 fuel. Also shown in this figure is a calculation of power to melt using FRAPCON-3 with uncertainties applied. As the FINE LHGR limits for fuel melting are lower than those calculated with FRAPCON-3 the staff concludes that the LHGR limits for fuel melting are acceptable.

4.10 Analysis Methodologies in MUAP-07008 other than those Evaluated in the FINE Code

As noted in Section 1, the FINE topical report includes information additional to that in the FINE code and its use in determining fuel rod performance. This information is redundant to that provided in report MUAP-07016 (Reference 26), “US-APWR Fuel System Design Evaluation,” or report MUAP-07034 (Reference 27), “FINDS: Mitsubishi Fuel Assemblies Seismic Analysis Code.” Review of this material will be addressed in other SEs. Therefore, this SE only addresses the fuel rod performance code FINE and its application to the US-APWR.

5.0 CONCLUSIONS and LIMITATIONS

The staff recommends that FINE be approved for licensing applications for US-APWR up to a rod-average burnup of 62 GWd/MTU with the following limitations. These limitations should only apply for licensing applications and the staff acknowledges that some of the models in FINE may be used for model verification activities beyond the boundaries of the following limitations.

1. Applicability limited to US-APWR fuel rod designs and materials as presented.

2. Fuel pellet.

    a. UO_2 (No additive other than Gd_2O_3 and sintering aids).

    b. Gadolinia concentration less or equal to 10 weight percent.

    c. Grain size greater than [ ] and less than or equal to [ ] (MLI).

    d. Predicted fuel temperature less than the conservative melting temperature limit.

    e. Nominal pellet density between 90 and 97 percent TD.

    f. Steady state LHGR limit of [ ].

    g. Rod average fuel burnups less than or equal to 62 GWd/MTU.

    h. Pellet chips and surface roughness assumptions should not be included for rod internal pressure calculations.

    i. Radial power predictions not approved for fast transients, e.g., RIA.

3. Fuel rod cladding.

    a. Only cold worked, stress relief annealed ZIRLO™.

    b. Hydrogen content limit of less than or equal to [ ].

    c. Oxide thickness limit of less than or equal to [ ].

    d. Cladding metal-oxide interface temperature of less than or equal to [ ] for steady state and [ ] for AOOs.

    e. Cladding thermal conductivity is limited to a range between [ ].

    f. Young’s modulus is limited to a range between [ ].

   g. Cladding thermal expansion is limited to a range between [ ].

   h. Cladding mid-wall temperature equal to or less than [ ] based on the limitations of creep model.

4. Analyses.

   a. For the cladding strain overpower analysis, MHI will use an uncertainty of [ ] strain for burnup below [. For higher burnup, MHI may use the calculated uncertainty for the error propagation analysis.

   b. To ensure that the power history providing the limiting rod internal pressure is evaluated for transient conditions, the steady state power history that contains [ ] will be selected. In addition, the power histories with the cycle maximum and minimum discharge rod-average burnups shall also be selected. All of these power histories will be evaluated to ensure the transient rod internal pressure limit criteria is met.

In addition to these limitations, the empirical nature of the FINE calibration and validation process, the specific values of the equation constants and tuning parameters documented in MUAP-07008-P/NP (as updated by RAIs) are inherently part of the approved models. Thus, these values will not be updated without further NRC review. In addition, the uncertainties documented in MUAP-07008-P (as updated by RAIs) will be used in the applicable licensing calculations.

The approval of MUAP-07008-P/NP is based on completion of a fuel surveillance program, as described in Section 4.3.1 of this SE, which demonstrates that FINE predicts conservative oxide thicknesses. In MHI's response to the DCD RAI 893-6232, dated February 23, 2012, the applicant agreed to a Tier 2* DCD wording modification stating that an oxide fuel inspection will occur for the first US-APWR to reach the end of Cycle 1, for a 24 month fuel cycle, or Cycle 2, for an 18 month fuel cycle. After the first oxide fuel inspection, the applicant will compare predicted and measured oxide thicknesses and determine if the [ ] limit could be violated in the next fuel cycle (assuming re-insertion). Fuel inspections after the first 24 month fuel cycle or second 18 month fuel cycle are acceptable, as current, higher kW/ft PWR plants with the same fuel cladding material have not challenged the [ ] limit. After the first oxide fuel inspections, an interim report, generated during the refueling outage, will compare the measured and predicted oxide thicknesses and will predict the follow-on fuel cycle oxide thickness addition. The interim report shall be made available for possible NRC review prior to the start of the next operating cycle. The predicted (total) maximum oxide thickness shall not exceed the [ ] limit.

Furthermore, the response to RAI 893-6232 commits to fuel inspections of discharged fuel assemblies that are predicted to be the highest oxide thickness fuel rods. The choice of which discharged fuel rods to inspect shall use information obtained during the first oxide inspection campaign and the as operated in-core power distributions. The details of the oxide thickness inspections can be found in the response to DCD Chapter 4.2 RAI 129-1673, Question 4.2-19, Revision 1, Table 4.2-19-1, "Surveillance Program (Minimum Scope) Measurements and Inspections for Fuel Assemblies loaded into the initial Core (Close examination)." In its response to RAI 893-6232 the applicant committed to revising DCD Section 4.2.4.5.3, "Cladding Oxide Thickness Inspections for Additional Design-Basis Verification," to identify the oxide inspection commitment as a Tier 2* item. A final report will be prepared including the results of the first cycle interim report and a comparison of the measured and predicted oxide thicknesses of the discharged fuel rods. The report should be available for possible NRC review within 90 days following the off-load of the last fuel assemblies inspected. If the current FINE oxide prediction model is non-conservative the applicant must resubmit a revised, conservative oxide model for NRC approval. A non-conservative oxide model may create the possibility of a malfunction of a structure system and component (the fuel cladding) important to safety with a different result than previously evaluated in the DCD and would be a departure from a method of evaluation used in establishing the design bases or in the safety analyses.

6.0 REFERENCES

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7.0 LIST OF ACRONYMS

AOO	Anticipated Operational Occurrences
BOC	Beginning of Cycle
CFR	Code of Federal Regulations
COL	Combined Operating License
COLR	Core Operating Limit Report
CWSRA	Cold Worked, Stress Relived Annealed
DCD	Design Control Document
ECCS	Emergency Core Cooling System
EOL	End of Life
FGR	Fission Gas Release
FINE	Fuel Rod Integrity Evaluation
GDC	General Design Criteria
He	Helium
LHGR	Linear Heat Generation Rate
LOCA	Loss of Coolant Accident
MHI	Mitsubishi Heavy Industries, LTD
MLI	Mean Linear Intercept
NRC	U. S. Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
PWR	Pressurized water reactor
RAI	Request for additional information
RIA	Reactivity Initiated Accident
SAFDL	Specified Acceptable Fuel Design Limits
SE	Safety Evaluation
SER	Safety Evaluation Report
SRP	Standard Review Plan
TD	Theoretical Density
TE	Plastic Elongation
UE	Uniform Plastic Elongation
US-APWR	United States Advanced Pressurized Water Reactor