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

April 24, 2000

Mr. Henry A. Sepp, Manager
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Westinghouse Electric Corporation
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355

SUBJECT: SAFETY EVALUATION RELATED TO TOPICAL REPORT WCAP-15063, REVISION 1, "WESTINGHOUSE IMPROVED PERFORMANCE ANALYSIS AND DESIGN MODEL (PAD 4.0)" (TAC NO. MA2086)

Dear Mr. Sepp:

By letter dated June 9, 1998, Westinghouse Electric Company LLC, submitted Topical Report WCAP-15063, "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)" for NRC staff review. This report describes the improved models for the Westinghouse fuel performance code PAD. In a letter dated November 18, 1999, Westinghouse submitted a revision to the subject topical report.

The Westinghouse PAD model is a best estimate fuel rod performance model used for both fuel rod performance analysis and safety analysis input. The PAD code consists of several fuel rod performance models integrated to predict fuel temperature, rod pressure, fission gas release, cladding elastic and plastic behavior, cladding growth, cladding corrosion, fuel densification, and fuel swelling as a function of linear power and time. Subsequent to the original model introduction, two specific revisions have been submitted for review and approval (PAD 3.3 and PAD 3.4). With respect to the creep model used in PAD, the original model form remains in effect except for a revision to the irradiation enhanced creep portion of the model in PAD 3.4. The thermal creep portion of the model has remained the same since the model's inception in 1972.

This topical report introduces a new creep model to be used in the overall PAD fuel rod performance model. The new creep model accounts for advances in the understanding of in-reactor creep that have occurred between 1972 and 1998, and represents a description of in-reactor creep relative to the information and data that are available in 1998. This model enhancement is projected to restore rod internal pressure limit margin to the fuel rod design criterion.

The NRC staff's review of the topical report was initiated by your letter dated June 9, 1998, followed by a September 15, 1998, meeting between the staff and representatives of Westinghouse to discuss the issues related to the revised PAD code. During the meeting, questions were raised that, along with a request for additional information from the NRC dated September 10, 1998, were answered in letters dated November 13, 1998, January 5, 1999, and

February 25, 2000. Westinghouse also submitted supplemental information in letters dated September 11 and 29, 1998, as well as an errata in a letter dated February 5, 1999. Westinghouse submitted WCAP-15063, Revision 1, by letter dated November 18, 1999. The staff has reviewed the topical report and the additional information provided, and finds that the topical report is acceptable for referencing. Our safety evaluation does not include any new staff positions and is provided as an enclosure to this letter.

The expected results from the improved PAD 4.0 model are more consistent with in-reactor experience using a mechanistic approach. Westinghouse states that for some fuel already in an operating reactor core or fuel that exists in the spent fuel pool that may be reinserted in later cycles, it may be possible that the new PAD 4.0 model might still predict some gap reopening. If analyses were to indicate that this situation could occur, Westinghouse would demonstrate that the affected fuel assemblies will continue to meet all safety limits as well as 10 CFR 50.46 oxidation limits for operating as well as future cycles, using the methodology that has already been presented to the NRC for gap reopening analysis. The staff agrees that this is an appropriate way to proceed.

Further, it is planned that the implementation of the new PAD 4.0 model will be made on a "forward-fit basis" (e.g., currently analyzed or operating cycles will not require reanalysis using the PAD 4.0 model). All plant specific reload analyses will be analyzed with the new PAD 4.0 in the year 2000 on a schedule consistent with an implementation plan being developed with the Westinghouse Owners Group. This implementation schedule is based on establishing appropriate documentation and training. The staff finds that this implementation schedule and analysis approach is acceptable.

Pursuant to 10 CFR 2.790, we have determined that the enclosed safety evaluation does not contain proprietary information. However, we will delay placing the safety evaluation in the public document room for a period of ten (10) working days from the date of this letter to provide you with the opportunity to comment on the proprietary aspects only. If you believe that any information in the enclosure is proprietary, please identify such information line by line and define the basis pursuant to the criteria of 10 CFR 2.790.

We do not intend to repeat our review of the matters described in the report and found acceptable when the report is referenced in licensing actions except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with procedures established in NUREG-0390, it is requested that Westinghouse publish accepted versions of this report, proprietary and non-proprietary, within three months of receipt of this letter. The accepted versions should incorporate this letter and the appropriate evaluation between the title page and the abstract. The accepted versions shall include an -A (designating accepted) following the report identification symbol.

Should our acceptance criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, Westinghouse and/or the applicant referencing the topical report will be expected to revise and resubmit its respective documentation, or submit justification for the continued applicability of the topical report without revision of the respective documentation.

Sincerely,

/***RA/***

Stuart Richards, Director
Project Directorate IV & Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 694

Enclosure: Safety Evaluation

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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT WCAP-15063-P, REVISION 1

"WESTINGHOUSE IMPROVED PERFORMANCE ANALYSIS AND DESIGN MODEL (PAD 4.0)"

WESTINGHOUSE ELECTRIC COMPANY LLC

1.0 INTRODUCTION

Westinghouse Electric Company (Westinghouse) has submitted to the U.S. Nuclear Regulatory Commission (NRC) Topical Report WCAP-15063-P (Reference 1) entitled, "Westinghouse In-Reactor Creep Model," for review and approval. This report documents changes to their Zr-4, improved Zr-4 and ZIRLO cladding creep models employed in the PAD fuel performance code. The creep model is also used to determine the internal rod pressure limits at extended burnups. An errata to this submittal was provided in Reference 2. Westinghouse informed the NRC in References 3 and 4 of their intent to change the original submittal and provided preliminary information on the changes that were to be incorporated in the topical report. As requested by NRC, a revision to Topical Report, WCAP-15063-P, Revision 1, was provided in Reference 5 that also changed the title to "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)." This revised submittal made five additional model changes to the PAD fuel performance code and these are discussed in Section 2.0 of this report along with the change in the creep model. Westinghouse responses to the last RAI (RAI # 9) were also provided in References 5 and 10.

Pacific Northwest National Laboratory (PNNL) has acted as a consultant to the NRC in this review. In a meeting on September 15, 1998 with PNNL and NRC, Westinghouse demonstrated the effects the creep model changes were going to have on the PAD code and also informed the NRC that they were going to make several other changes to the code at the same time and re-calibrate the code against thermal and fission gas release (FGR) data. The NRC staff informed Westinghouse that they would have to address several questions and issues before approval of the new revised PAD code and model changes could be granted. These issues were documented in the minutes of this meeting (Reference 6) and a follow-on meeting on June 23, 1999. Westinghouse provided partial responses to the questions and issues identified in the September 15, 1998, meeting in References 7, 8 and 9. The Westinghouse revised responses to RAI # 9 provided an example of PAD 4.0 licensing analyses for NRC audit comparisons as well as errata to their previous responses. These are provided in Reference 10.

As a result of several changes to PAD, Westinghouse has had to re-calibrate their thermal (gap conductance) and fission gas release models. The overall ability of the PAD 4.0 code to predict fuel temperatures, fission gas release, and rod pressures as well as the uncertainties in these predictions based on comparisons to data is discussed in Section 3.0 of this report.

The PAD 4.0 fuel performance code will be used by Westinghouse for stored energy and rod pressure inputs to LOCA, determining maximum rod internal pressures and rod pressure limits, and fuel melting analyses. Audit calculations have been made with the NRC developed FRAPCON-3 fuel performance code for comparison to PAD 4.0 calculations for maximum rod internal pressure, LOCA temperatures and pressures, and temperatures for the fuel melting analyses. These audit results will be discussed in Section 4.0. The conclusions are presented in Section 5.0.

2.0 PAD MODEL CHANGES

The original Westinghouse submittal (Reference 1) only applied to changes to the Zr-4, improved Zr-4, and ZIRLO cladding creep models. Westinghouse has made several model changes to the PAD 4.0 code (Reference 5) compared to the previous version, PAD 3.4 (Reference 11). These model changes are to the cladding creep, cladding irradiation growth, Zr-4 and ZIRLO clad thermal conductivity, Zr-oxide thermal conductivity, equation of state (EOS) gas pressure, the oxide-metal ratio, and Zr-4 clad gas absorption models. While the form of the gap conductance and fission gas release (FGR) models have not changed, the coefficients and uncertainties for these models have changed.

2.1 Cladding Creep Model

Westinghouse has made significant changes to their PAD 4.0 creep models for standard Zr-4, improved (low tin) Zr-4 and ZIRLO cladding materials. However, they have relied on essentially the same creep data base presented in their previously approved Westinghouse topical reports (References 11, 12 and 13) for previous creep models for these cladding materials. The amount of creep data for the standard Zr-4 is quite large with measurements from over 70 rods and 130 cycles of operation from 5 different plants. The improved Zr-4 data base is much smaller with measurements from fewer than 10 rods and the ZIRLO data base is even smaller. In order to accurately model cladding creep, creep data is needed from several different fuel batches and from different plants. These data are also needed to estimate the uncertainties in creep that are introduced from fabrication differences between different batches and from uncertainties in determining cladding temperatures for different plants. Westinghouse originally proposed to use only the improved Zr-4 data and only the ZIRLO data in determining improved Zr-4 creep and ZIRLO creep uncertainties, respectively. Westinghouse used nearly a hundred cladding diameter measurements per rod for the improved Zr-4 and ZIRLO cladding types to make their uncertainties appear low although they are only based on a very small number of rods. Use of this data suggested that the newer cladding types had much lower uncertainty than the standard Zr-4 creep. However, it was noted that the improved Zr-4 and ZIRLO data bases were much too small for a valid estimate of uncertainty. Westinghouse has revised their estimate of the improved Zr-4 and ZIRLO creep uncertainties (Reference 5) based on the standard Zr-4 data plus their respective data of Zr-4 and ZIRLO.

Westinghouse has assumed that the basic creep model is applicable for all three cladding types and has only adjusted the creep with a multiplication factor for each of the three types. Westinghouse assumes that the activation energy and stress dependencies in their creep model are applicable to all three cladding types. It is anticipated that the improved Zr-4 is most closely applicable because there was only a small change in tin content, but the ZIRLO cladding had larger changes in its metallurgy. These changes could introduce changes in the activation energy and stress dependencies different than for ZIRLO. Westinghouse intends to collect additional in-reactor creep data for ZIRLO to verify the activation energy and stress dependence for ZIRLO.

Westinghouse was also questioned about an apparent difference between tensile and compressive (stress state) creep rates for their cladding materials because different creep rates have been observed for zircaloy by other investigators (References 14 and 15) such that tensile creep rates are higher than compressive creep rates. An increase in tensile creep over compressive creep will reduce the margin to the rod pressure limit. Westinghouse responded (Reference 9) that the in-reactor experimental data from Reference 14 had several problems that made this data suspect. For example, Westinghouse claims that the reported steady state creep rates were unreasonably high compared to other in-reactor measurements of similar cladding, the creep measurements were not taken at steady-state creep because the time for the measurements was too short (still in transient or primary creep), and Zn crud formation from coolant chemistry could be altering the creep measurements. These are valid comments suggesting that this data may not be an accurate assessment of creep differences between tensile and compressive stress states.

Westinghouse has also reevaluated (Reference 9) the creep data in Reference 16 and claims that while there does appear to be a small difference in creep rate for the two stress states that it is within the uncertainty of this data and, therefore, there is little or no difference in creep rate between these two stress states. The staff has examined the Westinghouse reevaluation of the Reference 16 data and does not completely agree with Westinghouse's evaluation. One part of Westinghouse's re-analysis (Reference 9) is a linear fit to the compressive and tensile data as a function of hoop stress in the experimental samples to help substantiate the claim that there is little or no difference in the two creep states. The Westinghouse linear fit makes an implicit assumption in the analysis that there is no difference between tensile and compressive creep which does not appear to be valid proof that only small differences exist between the two stress states.

Westinghouse has also offered another alternative approach (Reference 9) to the analysis of the data by Garzarolli et al (Reference 15). Because there is a very small strain (creep) component in zircaloy cladding during irradiation at zero stress, Garzarolli has included a test capsule with zero stress to measure this component of strain. Garzarolli has subtracted this strain component from the compressive and tensile data in his analysis of this data as is appropriate for his analysis of creep differences. For Westinghouse's analysis of this same data, they have elected to average the zero stress data to Garzarolli data with a small level of tensile stress to estimate their zero stress component. The staff agrees that there is considerable scatter in creep data in general and that there is very little compressive to tensile data offered in either References 14 or

15 to accurately estimate the differences and uncertainty in creep rate for these two stress states. The staff contends that there may be a smaller difference between tensile versus compressive creep rates than previously estimated.
Westinghouse has initiated an experimental program to examine in-reactor creep for ZIRLO cladding and intends to measure creep under both compressive and tensile stresses to provide a more accurate estimate of creep differences in these two stress states. Westinghouse was requested to provide a list of the conservatisms in their rod pressure analyses to determine if there was ample conservatism in other parts of this analysis to compensate for the potential lack of conservatism in tensile creep in the revised Westinghouse creep model.

Westinghouse has provided the conservative margins used in their rod pressure analyses as contributed by each uncertainty component such as from creep, densification/swelling, fission gas release (FGR), and other uncertainties such as helium absorption/solubility, helium release, and fabrication. These uncertainties demonstrate that the fission gas release model contributes the greatest uncertainty. In addition, PAD 4.0 also provides a conservative prediction on rod pressures with their best estimate model (see Sections 3.2 and 4.1).

The staff has examined the impact of the possibility of tensile creep being greater than compressive creep on Westinghouse's rod pressure analysis. The staff has also examined the conservatism in the PAD 4.0 prediction of rod pressures as well as the FGR uncertainties to determine if there is adequate conservatism in this part of the Westinghouse rod pressure analysis to compensate for a possible lack in conservatism due to tensile creep. The staff has concluded that it appears that the conservatism in the PAD 4.0 predictions of rod pressure are adequate to compensate the decrease in rod pressure margin due to higher tensile creep.

Based on the adequate conservatism of rod pressure, the staff concludes that the PAD 4.0 creep models for Zr-4, improved Zr-4 and ZIRLO and associated uncertainties are acceptable.

2.2 Cladding Irradiation Growth Model

Westinghouse has retained the irradiation growth dependence for their Zr-4 and ZIRLO cladding but has also added a temperature dependence to these models above a particular temperature. This growth dependence has no impact on most of Westinghouse fuel licensing applications and only a very small impact on some rods in plants with high coolant outlet temperatures.

From an examination of the zircaloy growth data, the Westinghouse correlation of temperature dependence appears to be a best estimate representation of the temperature dependence in the growth data although there appears a large scatter in the data suggesting that there is considerable uncertainty in this temperature dependence.

Based on the results produced by the PAD model, the staff concludes that the Westinghouse modification of a temperature dependence to the Zr-4 and ZIRLO irradiation growth model is acceptable.

2.3 Zr-4 and ZIRLO Clad Thermal Conductivity Model

Westinghouse presents new correlations for Zr-4 and ZIRLO thermal conductivity based on ex-reactor measurements. The ZIRLO conductivity is slightly higher than the Zr-4, but the dependence (slope) versus temperature is identical. Based on the presentation and documentation of sufficient data, the staff has determined that these models are acceptable.

2.4 Zr-Oxide Thermal Conductivity Values

Westinghouse presents a range of oxide conductivity values derived from EPRI-sponsored Halden in-pile experiments. In these experiments, the oxide conductivity was deduced by comparison of cladding expansion between oxidized and non-oxidized fuel rodlets. The proprietary EPRI presentations on these measurements available to the NRC generally support Westinghouse's conclusions. Westinghouse proposes to increase their value for the oxide thermal conductivity based on the mean of this new data. The staff concludes that this change is appropriate for the best estimate PAD 4.0 code.

2.5 Equation of State Gas Pressure Model

PAD 4.0 uses an equation of state (EOS) that accounts for the non-ideal behavior of the gases found in the fuel rod internal void volume. It uses a modified version of the Peng-Robinson equation of state. In form, this EOS is similar to the more familiar Van der Waals EOS. Westinghouse has modified the Peng-Robinson calculated pressure values by a factor that adjusts the values upward slightly to match their data base of pressure-temperature data for a variety of gas mixtures.

To evaluate the PAD 4.0 EOS, the staff compared its pressure predictions to those of Van der Waals for pure gases at representative fuel rod operating gas temperatures and gas pressures. The modified Peng-Robinson model was found to predict lower pressures than the Van der Waals EOS slightly, but provided a better fit to the referenced data base used by Westinghouse. In order to verify that the relatively complex parameter and mixing rule equations used by Westinghouse, Westinghouse has supplied an example calculation with the Peng-Robinson EOS for a defined gas mixture and condition. An audit calculation was performed and agreed with the Westinghouse example. The staff concludes that the Westinghouse application of the Peng-Robinson EOS is acceptable because it correlates well with an extensive and applicable data base for gas mixtures at high pressures.

2.6 O-M Ratio Model

The oxygen-to-metal (O-M) ratio is often referred to as the Pilling-Bedworth ratio which is a measure of the volume of the oxide formed to the volume of the metal consumed during the ZrO_2 reaction. The theoretical ratio for zirconium oxide, ZrO_2, to zirconium is 1.56 which means that the oxide volume is a factor of 1.56 greater than the volume of the metal consumed. It is known that porosity, defects and cracks exist in the in-reactor zircaloy oxide layer such that the actual O-M ratio is sometimes greater than the theoretical value of 1.56. It is also observed that as the oxide thickness becomes larger in irradiated cladding, more cladding cracking is observed in the oxide layers and for some cladding with thick oxide layers the oxide begins to spall off the cladding. One of the uses of the O-M ratio for fuel performance calculations is in determining the cladding thinning due to oxide metal consumption for the calculation of cladding stresses. This generally only impacts high burnup cladding with oxide thicknesses between 3 to 4 mils. The other use is for determining the metal wastage factor due to cladding oxidation during a LOCA analysis for which 10 CFR 50.46 (Reference 16) imposes a limit on total calculated cladding oxidation not to consume more than 0.17 times the total cladding thickness before oxidation. Westinghouse has stated that the new best-estimate O-M ratio model will not be used for evaluating the 17 percent cladding wastage oxide limit used for LOCA in 10 CFR 50.46.

Westinghouse has metallographically measured the O-M ratio from several irradiated fuel rods by measuring the oxide thickness and the remaining metal thickness. The O-M ratios measured by Westinghouse are typical for high burnup cladding. Westinghouse has proposed a best estimate fit to this data that is a function of oxide thickness. The Westinghouse O-M ratio model does appear to go through the median of the data but there is a very large scatter in the data that is on the order of the difference between the theoretical value and that predicted with their model. The impact on cladding stress is small, however, and is much smaller than the uncertainty in the overall PAD 4.0 stress prediction.

Based on the sufficient data collected, the staff concludes that the Westinghouse O-M ratio model is acceptable for use in best estimate calculations for PAD 4.0.

2.7 Zr-4 Clad Gas Absorption Model

The Westinghouse application of the earlier PAD 3.4 code used ambient air in their fuel rods for their licensing analyses. The existence of ambient air in their rods had two impacts on fuel performance. It increased rod pressures slightly and increased fuel temperatures because nitrogen and oxygen have lower gas conductivities than the helium fill gas which decreases the fuel-cladding gap conductance. Westinghouse has proposed in their revised submittal (Reference 5) that while the air exists in their fuel rods following fabrication, it reacts quickly with the zircaloy and ZIRLO cladding when charged into the reactor and brought up to hot coolant conditions and operating powers. Based on the Westinghouse analyses the zircaloy has a strong affinity for oxygen and it will react first to form ZrO_2. According to Westinghouse the reaction of the nitrogen takes only a few hours to react with zircaloy. Therefore, Westinghouse proposes that the oxygen and nitrogen will have reacted with the cladding by the time the fuel rods achieve full power operation.

An independent analysis has been performed in Reference 17 on the reaction of gaseous impurities in fuel rods. Using these reaction rates it is calculated that it takes only a few minutes for the oxygen to react with zircaloy cladding but approximately 2 days for the nitrogen to react in a Westinghouse Zr-4 clad fuel rod. The reaction rates from Reference 17 were measured from zircaloy and Zirconium that had been abraded to reduce the oxide thickness. The Westinghouse coating will have a thicker oxide layer particularly after the oxygen reaction (from the air) is complete. Therefore, if we conservatively assume that the reaction rate decreases by a factor of 3 due to the extra oxide thickness it takes approximately 6 days for the nitrogen to react in a Westinghouse Zr-4 clad fuel rod. It is noted that the oxide reaction rates for ZIRLO in water and steam are approximately a factor of 2 less than for Zr-4. Assuming that the reaction rates of ZIRLO with nitrogen decrease a similar amount, the nitrogen will take up to 12 days to react with ZIRLO clad rods.

The Westinghouse PAD 4.0 analysis that is primarily impacted by the assumption of nitrogen in a fuel rod is in the initial conditions for LOCA and resulting PCT. For Westinghouse LOCA analyses the reaction of nitrogen decreases the initial rod internal pressures and decreases fuel average temperatures which have opposing effects on PCT. For example, lower rod pressures increase PCT while lower average fuel temperatures decrease PCTs. Westinghouse has performed a preliminary evaluation to determine the impact of nitrogen reacting immediately with the cladding on LOCA initial conditions and resulting PCT, i.e., the rod pressure and average fuel temperature decrease. This preliminary evaluation suggested that assuming the nitrogen reacts immediately in the rod (nitrogen does not exist during operation at full power) may result in slightly higher fuel PCTs for LOCA analyses than assuming the nitrogen exists in the fuel rod. This evaluation is based on previous Westinghouse sensitivity analyses of the impact of rod internal pressure and average fuel temperatures on PCT as well as the PAD 4.0 results on these two parameters.

Based on these conservative results, the staff concludes that the clad gas absorption model is acceptable for PAD 4.0.

3.0 PAD 4.0 COMPARISON TO THERMAL AND FISSION GAS RELEASE DATA

3.1 Comparison to Thermal Data

As noted in the Introduction (Section 1.0), the only thermal models in PAD 4.0 that have been changed are the Zr-4, ZIRLO cladding and ZrO_2 oxide thermal conductivities. However, the coefficients to the gap conductance model have also been changed. These changes in the cladding and oxide thermal conductivities reduce the predicted fuel temperatures in PAD compared to the previous results.

The primary licensing analyses that use PAD 4.0 thermal predictions are the loss-of-coolant accident (LOCA) and fuel melting analyses. The PAD 4.0 code is used to provide initial thermal conditions (fuel centerline and volume average temperatures) and rod pressures for the start of the LOCA analysis. The fuel volume average temperature is the primary PAD input that impacts the calculation of maximum peak cladding temperatures (PCTs) to verify that Westinghouse meets the 10 CFR 50.46 requirement of PCT not exceeding 2200°F. Traditionally, the NRC has required that a best estimate code such as PAD 4.0 maintain a 95 percent bounding estimate of centerline and volume average temperatures at a 95 percent confidence level for input to LOCA analyses.

The change in coefficient to the gap conductance model can make significant impact on thermal predictions. Therefore, it is important to evaluate the PAD 4.0 predictions against measured in-reactor temperatures. Westinghouse has elected to calibrate, validate and estimate code predictive uncertainties using the same experimental test rods from the Halden Reactor as used for PAD 3.4 even though there are a large number of additional rods at lower and higher burnups currently available (both from Halden and other experimental reactors) for code comparisons that were not available previously. In addition, the code uncertainties have been estimated from data at very low burnups because the LOCA and fuel melting analyses to which these thermal predictive uncertainties are applied are always limiting near beginning-of-life (BOL). From the example LOCA calculation provided by Westinghouse, the maximum fuel temperatures (generally corresponds to maximum PCTs) calculated by PAD 4.0 are consistent with the FRAPCON-3 code (Reference 18 and 19) results.

Westinghouse was questioned about the lower conservatism of PAD 4.0 compared to those data with a much more conservative 95 percent bounding at a 95 percent confidence level. Westinghouse responded that the initial conditions for their base (best estimate) PAD 4.0 calculation for LOCA are really not performed using best estimate input, but instead used conservative input values for fuel density, fuel sintering temperature, inlet coolant temperatures, coolant flow, and cladding creep. These additional conservatisms will further bound and remove the concern of the less conservatism in the uncertainty analysis.

PNNL has performed a calculation of the additional conservatism introduced in the Westinghouse PAD 4.0 best estimate input for LOCA on calculated fuel temperatures. Westinghouse has provided the uncertainty introduced by their root mean square (RMS) analysis of fabrication and additional model uncertainties not considered in PAD 4.0. Adding these uncertainties to those proposed by Westinghouse to bound fuel centerline temperatures for LOCA analyses results in an uncertainty value that appears to bound the data at a 95/95 level of conservatism.

Based on the conservative results produced by the PAD model, the staff concludes that the PAD 4.0 thermal predictions and uncertainties to thermal data are acceptable for PAD 4.0.

3.2 Comparison to FGR Data

The coefficients to the PAD low and high temperature FGR models as well as the transient FGR model have all been changed to provide a best estimate fit to their calibration data for these respective models. The PAD FGR models are also strongly temperature dependent such that the coefficients for the thermal and FGR modeling are interrelated.

The steady-state high temperature FGR data used by Westinghouse are from fuel with high burnups. A significant portion of this steady-state FGR data utilized by Westinghouse is primarily older FGR data from fuel manufactured by Westinghouse in the late 1960s to early 1970s, and typically has greater fuel densification than fuel fabricated today. The staff has observed that fuel with a greater degree of densification will show a larger amount of FGR and greater variation (uncertainty) among the data compared to fuel with a lesser degree of densification. Also, a significant amount of the transient FGR data used by Westinghouse is from another vendor that is also relatively older fuel with different fuel micro-structure and greater densification than fuel fabricated today. This fuel also tends to result in greater FGR than fuel fabricated today. Therefore, the use of this data to calibrate and verify the PAD 4.0 code should result in the code providing conservative predictions of FGR for today’s fabricated fuel.

Examination of the Westinghouse PAD 4.0 code comparisons to the high temperature steady-state and transient FGR data reveals a best-estimate prediction of this data with a large uncertainty. Because as noted above, Westinghouse has used FGR data from older fabricated fuel that the PAD 4.0 code would predict higher FGR than more state-of-the-art codes such as FRAPCON-3 (References 18 and 19). However, the FRAPCON-3 audit calculation of FGR and rod pressures shows similar results and uncertainties are generated between PAD and FRAPCON-3 codes. This is expected given that the FRAPCON-3 code has been calibrated against both steady-state and transient FGR data from modern fuel with several data points near rod average burnups of 62

GWd/MTU, and one data point at 74 GWd/MTU (Reference 19). Based on the acceptable similar results between PAD and FRAPCON-3 codes, the staff concludes that the FGR model and rod pressure analysis are thus acceptable for PAD 4.0.

4.0 PAD 4.0 LICENSING CALCULATIONS

The NRC requested that Westinghouse provide examples of licensing analyses for which the PAD 4.0 code will be applied, so that audit calculations could be performed with the NRC developed FRAPCON-3 code (References 18 and 19) for comparison to the examples provided in PAD 4.0 licensing analyses. Subsection 4.1 addresses the maximum rod pressure limit analysis, Subsection 4.2 addresses the temperature and rod pressure input supplied to LOCA analyses, and Subsection 4.3 addresses the centerline temperatures for the fuel melting analyses.

4.1 Audit of Rod Pressure Analysis

A maximum rod internal pressure limit is imposed on in-reactor operating fuel in order to prevent the rods from being over-pressurized to the point where the cladding swells or balloons due to normal operation and normal operating transients. Ballooning of the fuel rod could result in other adjacent rods going into departure from nucleate boiling (DNB) which could cause this rod to balloon and fail resulting in its neighboring rods to go through DNB. This could result in significant local flow blockages and further failures. Currently, NRC allows fuel rods to balloon during certain transients and accidents but requires vendors to account for and not underestimate the flow blockage and dose consequences. However, cladding ballooning and flow blockage is not allowed as a result of normal operation. In order to prevent this scenario the NRC Standard Review Plan, Section 4.2, (Reference 20) has conservatively limited rod pressures to below reactor system pressure. In the last 15 years vendors have requested and NRC has approved a rod pressure limit above system pressure such that the cladding creep rate does not exceed the fuel swelling during normal operation using the lower bound (95 percent) fuel swelling rate and the upper bound cladding creep rate. In addition, the NRC has required that vendor calculations of rod pressures be bounding at the 95 percent level. This approval of rod internal pressure above system pressure has been granted to Westinghouse (Reference 21).

As requested, Westinghouse provided an example of rod pressure (best estimate and bounding) analysis results using the PAD 4.0 code to calculate rod pressures for a UO_2 fuel rod near the Westinghouse pressure limit (Appendix A of Reference 10). The example rod pressure input and analysis provided by Westinghouse for the audit calculation was modified from a typical Westinghouse UO_2 fuel rod in order to calculate rod pressures that are typical of a peak integrated fuel burnable absorber (IFBA) rod. The IFBA rods almost always provide the more limiting rod pressures rather than UO_2 rods.

The FRAPCON-3 code was used to perform a rod pressure audit analysis using the same input as used for the PAD 4.0 code. The FRAPCON-3 code was developed to be a best estimate code similar to PAD 4.0 and has been compared to a large amount of high burnup data up to a rod average burnup of 62 GWd/MTU with a small amount of thermal data up to 100 GWd/MTU. The primary fuel performance parameter that impacts the internal rod pressure analysis is FGR. The FRAPCON-3 calculated results of rod pressure and FGR were similar to those calculated by Westinghouse PAD 4.0 taking into account the effects in different models. Based on the similar results produced by the PAD and FRAPCON-3 code, the staff concludes that the rod internal pressure prediction is acceptable for PAD 4.0 code.

4.2 Audit of LOCA Input

Westinghouse provided an example of PAD 4.0 analyses with best estimate fuel temperatures and rod pressures that are used for initialization of LOCA analyses (Appendix B of Reference 10). For Westinghouse analyses of LOCA, higher predicted fuel average temperatures and lower predicted rod internal pressures result in higher (more conservative) PCTs. Therefore, for LOCA analyses, Westinghouse uses PAD 4.0 best estimate predicted temperatures plus several uncertainties to provide upper bound initial fuel average temperatures. In order to provide a lower bound rod pressure for LOCA, Westinghouse uses PAD 4.0 best estimate rod pressures for the average operating (low power) rod in the core minus uncertainties in the rod pressure calculation.

FRAPCON-3 audit analyses were also performed using the same input used in PAD 4.0 to calculate best estimate fuel temperatures and rod pressures. A comparison of the FRAPCON-3 calculated centerline and average fuel temperatures to those from PAD 4.0 at LHGRs typical for LOCA initialization demonstrates that PAD 4.0 predicts higher temperatures very early in core life. This difference is reduced with increasing burnups such that the PAD 4.0 code prediction is similar at moderate burnups, and PAD predicts lower fuel temperatures than FRAPCON-3 at high burnups. The reason why the PAD 4.0 code thermal predictions are lower at high burnups is because the FRAPCON-3 code has a fuel thermal conductivity model that is burnup dependent (lower fuel conductivity with increasing burnup) while the PAD 4.0 code has a thermal conductivity model with no burnup dependence. A burnup dependence on thermal conductivity was first proposed by the Halden reactor staff (Reference 22) and has since been verified by several Halden experiments involving both in-reactor (Reference 23) and ex-reactor measurements of the thermal conductivity of high burnup fuel (References 24 and 25). The scatter in ex-reactor measurements have been proposed to be due to differences in irradiation temperatures of the ex-reactor samples (Reference 26).

Westinghouse was questioned about the lower conservatism in the PAD 4.0 thermal calculations at moderate to high burnup levels. Westinghouse responded that LOCA limiting conditions are currently limiting at early in life based on a recent Westinghouse justification for continued operation (JCO) analysis (Reference 27) that accounted for thermal conductivity degradation with burnups. This analysis also made some very conservative assumptions such as no burnout of the fissile material occurs in the fuel with burnup. The staff therefore believes that the PAD 4.0 prediction of LOCA temperatures are acceptable for licensing analysis.

The FRAPCON-3 predicted rod pressures for LOCA were slightly lower than those predicted with PAD 4.0. As noted above, the limiting rod pressure that results in the most conservative PCTs is a lower bound rod pressure. For this reason Westinghouse uses lower bound inputs and uncertainties for PAD 4.0 predictions of rod pressures for LOCA initial conditions. The difference between the FRAPCON-3 and PAD 4.0 code predictions of rod pressure is within the lower uncertainty bounds that Westinghouse applies to their PAD 4.0 predictions of rod pressure for LOCA. Therefore, the Westinghouse rod pressure input for LOCA are conservative and acceptable.

Based on the conservative results produced by the input described by Westinghouse, the staff concludes that the PAD 4.0 code is acceptable for LOCA analysis.

4.3 Audit of Fuel Melting Analysis

Westinghouse also provided an example of PAD 4.0 input and analysis results of best estimate fuel centerline temperatures that are used for the fuel melting analysis (Appendix B of Reference 10). FRAPCON-3 calculations were also made at various LHGRs to establish best estimate predicted fuel centerline temperatures near the fuel melting temperature using the same input as PAD 4.0. A comparison of the FRAPCON-3 and PAD 4.0 results demonstrated that PAD 4.0 predicted higher fuel centerline temperatures than FRAPCON-3 at BOL. Similar to the LOCA audit comparisons, the temperature differences decreased with increasing burnup such that PAD 4.0-predicted centerline temperatures became lower than those predicted by FRAPCON-3. Westinghouse has also claimed that the fuel melting analysis is limiting at BOL temperatures. PNNL analysis of fuel melting using FRAPCON-3 confirms that BOL predicted temperatures are limiting even with thermal conductivity degradation and the additional uncertainty in degradation considered.

Based on the conservative results produced by the PAD model, the staff concludes that the PAD 4.0 code is acceptable for fuel melting analysis.

5.0 CONCLUSIONS

The staff has reviewed the Westinghouse improved fuel performance code PAD 4.0 as described in WCAP-15063-P, Revision 1, and concludes that PAD 4.0 is acceptable for fuel licensing applications up to rod average burnup 62,000 MWd/MTU.

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