FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT WCAP-12610-P-A & CENPD-404-P-A, ADDENDUM 2/WCAP-14342-A

& CENPD-404-NP-A, ADDENDUM 2, "WESTINGHOUSE CLAD CORROSION

MODEL FOR ZIRLO^{TM} AND OPTIMIZED ZIRLO^{TM}"

WESTINGHOUSE ELECTRIC COMPANY

PROJECT NO. 700

1.0 INTRODUCTION

On November 24, 2008, Westinghouse Electric Company (Westinghouse) submitted a Topical Report (TR), WCAP-12610-P-A & CENPD-404-P-A, Addendum 2/WCAP-14342-A & CENPD-404-NP-A, Addendum 2, "Westinghouse Clad Corrosion Model for ZIRLO^{TM} and Optimized ZIRLO^{TM}," for the U.S. Nuclear Regulatory Commission (NRC) staff review (Reference 1). The report summarizes the Westinghouse fuel rod cladding corrosion model that will replace the existing ZIRLO^{TM} corrosion model developed when ZIRLO^{TM} was first licensed. The new corrosion model will apply to fuel rod designs of ZIRLO^{TM} and Optimized ZIRLO^{TM} cladding. During the review, the NRC staff issued requests for additional information (RAIs) and Westinghouse provided responses to the RAIs in References 2 and 3 including supporting information of References 6 and 8.

The current ZIRLO^{TM} corrosion model is based on a model originally developed for zircaloy-4 cladding. As utilities moved to increased fuel thermal duty associated with higher peaking factor, uprated core power, and longer cycle length, cladding corrosion becomes one of the important factors in assessing the potential to achieve these goals.

Cladding corrosion is a phenomenon where the cladding metal reacts with the reactor coolant resulting in oxide buildup on the cladding surface which can partially wear away cladding material. Cladding corrosion is a damaging mechanism which could affect the cladding integrity. Corrosion leads to pilfering and spalling of the metal surface and causes hydrogen absorption in the metal. Cladding would become brittle resulting in premature failure due to high corrosion and hydrogen absorption. The rate of corrosion could eventually determine the fuel rod lifetime. It is desirable in the nuclear industry to control and minimize the corrosion effect. With the contemporary operating schemes at higher temperature and for longer cycles, corrosion, in addition to the rod internal pressure, becomes a key factor in determining fuel rod capability being able to withstand harsh environment and survive for the designed lifetime.

The Westinghouse corrosion model was developed to predict best-estimate values for the observed data of ZIRLO™ and Optimized ZIRLO™ cladding over a large range of operating conditions. The data base includes the cladding corrosion data from Westinghouse and Combustion Engineering (CE) Nuclear Steam Supply System (NSSS) plants. The new corrosion model is intended for use in Westinghouse pressurized water reactor (PWR) design methodologies using ZIRLO™ and Optimized ZIRLO™ cladding for Westinghouse and CE NSSS plants.

2.0 REGULATORY EVALUATION

Regulatory guidance for the review of fuel system designs and adherence to applicable General Design Criteria (GDC) is provided in NUREG-0800, "Standard Review Plan (SRP)," Section 4.2, "Fuel System Design." In accordance with SRP Section 4.2, the objectives of the fuel system safety review are to provide assurance that: (1) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs), (2) fuel system damage is never so severe as to prevent control rod insertion when it is required, (3) the number of fuel rod failures is not underestimated for postulated accidents, and (4) coolability is always maintained. A fuel system that is "not damaged" is defined as fuel rods do not fail, fuel system dimensions remain within operational tolerances, and functional capabilities are not reduced below those assumed in the safety analysis. The first objective is consistent with GDC 10 of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, Appendix A, and the design limits that accomplish this are called specified acceptable fuel design limits (SAFDLs). Fuel rod failure means that the fuel rod leaks and the first fission product barrier (the cladding) has been breached. Fuel rod failures must be accounted for in the dose analysis required by 10 CFR Part 100 for postulated accidents. "Coolable geometry" means, in general, that the fuel assembly retains its rod-bundle geometrical configuration with adequate coolant channels to permit removal of residual heat following a design-basis accident. The general requirements to maintain control rod insertability and core coolability appear repeatedly in the GDC (e.g., GDC 27 and 35). Specific coolability requirements for the loss-of-coolant accident (LOCA) are given in 10 CFR 50.46.

The rate of corrosion could eventually determine the fuel rod lifetime. It is desirable in the nuclear industry to control and minimize the corrosion effect, thereby reducing the fuel rod failures. The Westinghouse corrosion model was developed to predict best-estimate values for the observed data of ZIRLO™ and Optimized ZIRLO™ cladding over a large range of operating conditions. This safety evaluation (SE) discusses the corrosion model developed by Westinghouse to demonstrate that the intent and objectives of the SRP Section 4.2 are met.

3.0 MODEL EVALUATION

3.1 Heat Transfer Correlations and the Proprietary Claim

Westinghouse stated that the corrosion model was developed based on the Dittus-Boelter and Thom correlations taking into account the effect of the flowing fluid between fuel rods. Both correlations are typical heat transfer correlations, and can be found in textbooks and open literatures. Citing it might result in the loss of an existing or potential competitive advantage, Westinghouse claimed both correlations were proprietary and to be withheld from public disclosure.

The NRC staff researched the correlations in open sources and found abundant technical information. For example, detailed descriptions and applications of both correlations in PWRs can be found in Reference 4. In another example, the NRC staff found through internet search engines like Google that the Dittus-Boelter heat transfer correlation is used for fluids in turbulent flow and the Thom correlation is used for boiling water flow under conditions where the nucleate boiling contribution predominates over forced convection. The internet search essentially revealed that anyone as well as Westinghouse could use these correlations to simulate the boiling and turbulent flow phenomena. The NRC staff notices that the final formulation of the corrosion model has significantly deviated from either equation form of the heat transfer correlations. The NRC staff does not believe that any scientific or engineering correlation in public domain may constitute a trade secret, privileged, or as confidential commercial or financial information. The NRC staff thus determines that the claim of proprietary information of the Dittus-Boelter and Thom correlations, which can be acquired through open sources, is baseless.

Based on the 10 CFR 2.390(b)(4)(iv), the NRC staff concludes that Westinghouse provided no reasonable basis for the proprietary claim of the public sources on the Dittus-Boelter and Thom correlations. Therefore, the NRC staff rejects the Westinghouse proprietary claim of the Dittus-Boelter and Thom correlations.

3.2 Data Base and Crud Treatment

The Westinghouse ZIRLO™ cladding corrosion model was developed based on rod oxide measurements collected from post irradiation examinations (PIEs) of ZIRLO™ and Optimized ZIRLO™ cladding. The PIEs were conducted in 16 plants for ZIRLO™ data, and 8 plants for Optimized ZIRLO™ data, which comprised several thousand individual measured data points. In responding to the NRC staff RAI, Westinghouse stated that there was no difference between Westinghouse and formerly CE techniques for corrosion measurement and data analysis. For both systems, a contact eddy current probe was calibrated first against standards of known oxide thickness, and then scanned axially along the fuel rod surface. The measurements were averaged and included in the data base. The two averaged methods provided essentially the same results. The NRC staff reviewed the results and agrees with the Westinghouse assessment.

The crud or building up of the corrosion products was frequently observed to be present on the oxide thickness during PIEs. The crud in general consists of two components, fluffy and tenacious crud. The tenacious crud would tend to stick on the cladding surface while the fluffy crud would not when a crud removing device was used. During PIEs, it is likely the measurements could not distinguish between oxide and crud even with removing crud prior to the measurements. Therefore, the oxide thickness would include partial crud, which is mostly tenacious crud, in the measured values. Westinghouse stated that no explicit crud model was used with the corrosion model, and the effect of partial crud was implicitly accounted for in the use of a **[ ]** in the model. The approach of implicitly considering the crud effect is typical in the industry. However, the NRC staff notices that this approach does not necessarily take into account all of the crud deposited on the cladding surface. Therefore, the NRC staff determines that the Westinghouse approach only considers partial crud effect. The NRC staff reserves the right to challenge Westinghouse for claiming that the crud effect was accounted for in the model.

3.3 Model Formulation

The Westinghouse corrosion model consists of two terms of thermal reaction energy (TRE) and thermal reaction accumulated duty (TRD). TRE has an exponential form involving an oxide and **[ ]** The oxide-coolant interface temperature has a **[ ]** The adjusted coefficient is an empirical fitting constant. TRD is an **[ ]** of TRE with power histories. The final fit in the corrosion model is also an exponential form involving TRD for ZIRLO™ cladding. Westinghouse attached an **[ ]** coefficient to the ZIRLO™ corrosion model for Optimized ZIRLO™ cladding to account for the fact that the Optimized ZIRLO™ oxide thickness is a **[ ]** of the ZIRLO™ oxide thickness. Westinghouse stated that the corrosion model was based on the **[ ]** and the integration of thermal duty according to operating power conditions.

The subcooled boiling, or nucleate boiling, is a boiling phenomenon, in general, consisting of two regimes, partial and fully developed nucleate boiling. The critical heat flux correlations and the departure from nucleate boiling criterion are developed based on the fully developed nucleate boiling regime. Boiling phenomenon is an extremely complicated phenomenon. Despite derived intricate equations, Westinghouse still relied on empirical fitting of coefficients for best predicting the data base. Westinghouse stated that the coefficients in Equations 2-1, 2-2, 2-5, and 2-6 (Reference 1) need to be adjusted in order to predict best-estimate results. Westinghouse will rely on the fuel criteria evaluation process (FCEP) described in WCAP-12488-A (Reference 5) for coefficient adjustment.

In responding to the NRC staff RAI, Westinghouse provided a plot of cladding local boiling rate versus burnup to explain the boiling effect (Reference 2). The selected fuel rod was from a lead test assembly operating at high coolant outlet temperature, high duty, and high burnup conditions. However, the NRC staff could not interpret the significance of the plot. The NRC staff requested a plot of cladding surface temperature versus burnup for the identical fuel rod. Westinghouse provided the plot which showed substantial cladding temperature increase from non-boiling regime to the subcooled boiling regime (Reference 3). Although the plot is meaningful in terms of a physical parameter (i.e., the cladding surface temperature) (the interface temperature between cladding oxide surface and coolant), it is very difficult to verify the cladding surface temperature in the reactor environment. In most cases, the cladding surface temperatures are derived from analytical means using thermal-hydraulic tools simulating the boiling phenomenon. Since the NRC staff could not verify the cladding temperature, which could lead to non-conservative results in the corrosion prediction, the NRC staff requested additional information.

Westinghouse provided additional information to support the use of the cladding surface temperature (Reference 6). Autoclave testing results showed that there were no accelerated corrosion for ZIRLO™ and Optimized ZIRLO™ cladding in high temperature steam environment for a long period of time. Although the testing material would not exhibit accelerated corrosion at these conditions, the corrosion model did predict rapid corrosion rates for such high values of cladding surface temperature. Consequently, the model would predict the corrosion to reach the 100 micron design limit (Section 3.6) in short periods of time for such high temperature reactor operations. Westinghouse contended that this type of operation was undesirable and should be precluded. Thus, Westinghouse concluded that the corrosion limit of 100 microns provides adequate protection against unrealistic high cladding temperature operations.

Based on the supporting results in Reference 6, the NRC staff concludes that the cladding surface temperature is restricted through the means of corrosion design limit of 100 microns in the model.

3.4 Model Uncertainty and Validation

Westinghouse divided the database into two different groups: the calibration group and the validation group. The calibration group is for model development, while the validation group is for model verification and validation. Westinghouse presented plots of measured versus predicted values, prediction residuals (measured-predicted) versus predicted values, and prediction residuals versus TRD values for the validation data for ZIRLO™ cladding. The results showed that the model predictions were conservative, and observed no significant biases. Based on the calibration data, Westinghouse derived an upper 95 percent bound curve. The results showed that the upper bound (UB) uncertainty curves bounded over 95 percent of the data.

Westinghouse developed a similar process for the Optimized ZIRLO™ in model uncertainty and validation. The same and consistent results were obtained for the Optimized ZIRLO™ corrosion model (i.e., the model predictions were conservative and no observed significant biases), and the UB uncertainty curves bounded over 95 percent of the data.

Based on the acceptable uncertainty analysis and validation, the NRC staff concludes that the ZIRLO™ and Optimized ZIRLO™ corrosion models have adequate conservatism. However, the NRC staff notes that the best – estimate rather than conservative results are used in the design analyses.

3.5 Zinc and Lithium Addition Effect

Reactor water chemistry plays an important role in the degradation of component material such as steam generators, piping, and fuel cladding. The chemicals injected into the coolant for water chemistry control in PWRs may contain lithium and zinc. Elevated lithium is required to maintain pH in the presence of high boric acid concentrations at the start of the cycle. Zinc is added at low concentrations to reduce radiation dose rates and primary water stress corrosion cracking.

During the development of the corrosion model, Westinghouse obtained data containing zinc and lithium concentrations. These data were used in the model calibration and validation. There are no specific terms in the model for the addition of zinc or lithium. Westinghouse indicated that there were no observed biases or trends due to zinc or lithium injection during the model validation. Westinghouse will continue to monitor plants using high lithium concentrations and zinc addition in high boiling duty cycles with fuel surveillance programs to provide guidance and recommendations for future model improvement.

In responding to the NRC staff RAI, Westinghouse provided plots of two cycle fuel rod operating under high duty with zinc addition (Reference 2). The results showed that the predicted oxide thickness bounded the measured data for the rod.

Based on the Westinghouse initiative in continued fuel surveillance, the NRC staff concludes that the corrosion model with no specific terms for lithium or zinc addition is acceptable for

ZIRLO™ and Optimized ZIRLO™ cladding. The NRC staff may require Westinghouse to submit the model for review if a significant bias or trend detected due to zinc or lithium addition.

3.6 Design Limit

Based on the SRP, the NRC staff established an oxide thickness of 100 microns limit to ensure the cladding integrity during normal operations and AOOs. Westinghouse has an oxide limit in fuel design identical to the NRC staff requirement. Westinghouse predicted best estimate oxide thickness will remain below 100 microns. The Westinghouse approach is consistent with the NRC staff requirement, and thus is acceptable.

Westinghouse considered that the oxide limit of 100 microns was proprietary and to be withheld from public disclosure. However, Westinghouse published a paper in 2009 (Reference 7) which indicated the 100 microns oxide thickness limit for the ZIRLO™ cladding. Based on the fact that Westinghouse published the information in the open literature, the NRC staff concludes that Westinghouse cannot continue claiming the 100 micron oxide limit as proprietary information. Thus, the NRC staff rejects the Westinghouse proprietary claim of the 100 micron oxide limit.

In responding to the NRC staff RAI, Westinghouse provided applicable ranges of TRD for the corrosion limit of 100 microns (Reference 3). The results showed that the calculated TRDs are **[ ]** for ZIRLO™ cladding and **[ ]** for Optimized ZIRLO™ cladding in the best estimate calculations. None of these TRDs were reached in the current operating Westinghouse fuel designs. However, Westinghouse indicated that the ranges of TRD data base were **[ ]** for ZIRLO™ cladding and **[ ]** for Optimized ZIRLO™ cladding. The results show that there is not sufficient data to support the predicted TRD at 100 microns for Optimized ZIRLO™ cladding because the predicted value exceeds the TRD data base.

Westinghouse provided additional information to show corrosion data of Optimized ZIRLO™ cladding at higher TRDs than the TRDs reported in the original submittal (Reference 6). Westinghouse showed a plot of measured versus predicted oxide thickness from a high burnup LTA which experienced a TRD of **[ ]**. The corrosion model presented conservative results of higher predictions than measurements in most cases.

Westinghouse will continue to gather surveillance data for cladding corrosion at elevated levels of TRD. Westinghouse indicated that the TRD range will continue to enlarge as more data are collected. Since the TRD is a fictitious number with no real physical meaning, although TRD was derived from the concept of boiling phenomenon, the NRC staff questioned its use.

Westinghouse explained that the maximum TRDs achieved could be varied depending on core loading, power history, and fuel design. While arguing that the 100 micron design limit is the ultimate TRD-based corrosion model limit, Westinghouse was reluctant to provide any definitive maximum TRDs. Therefore, the NRC staff requires that a condition be imposed that the maximum TRDs are restricted to numbers corresponding to a corrosion amount of 100 microns.

3.7 Model Revision

Westinghouse intends to maintain flexibility to adjust the model as new data are obtained to ensure the accuracy of the predictions. If revisions to the model coefficients are warranted, Westinghouse will follow the process and limits specified in WCAP-12488-A (Reference 5).

WCAP-12488-A describes a process, FCEP, to allow Westinghouse to make necessary changes or revisions to improve the prediction capability for the approved fuel performance codes or models without specific NRC staff reviews as long as Westinghouse meets the criteria and limits specified in WCAP-12488-A.

During the development of the best-estimate corrosion model, Westinghouse has a mean bias of measured-predicted (M-P) value, **[ ]** microns, as opposed to an unbiased model of M-P close to 0.0. However, the allowable change for the corrosion is **[ ]** microns according to FCEP in WCAP-12488-A. In responding to the NRC staff RAI, Westinghouse indicated that any new data must be analyzed using the licensed model to calculate M-P (Reference 3). The M-P for the new data must be within the FCEP limit of licensed **[ ]** microns (i.e., **[ ]** microns). Under FCEP, the **[ ]** the data base. Data that do not meet the FCEP criterion cannot be used in a model that is to be implemented under FCEP. The NRC staff may require Westinghouse submit the model for review in the event that new data show significant under-prediction or unusual trends which could not meet the FCEP criterion.

Based on the Westinghouse commitment to the FCEP, the NRC staff agrees with the Westinghouse approach for the model revisions.

3.8 <u>Model Sensitivity</u>

Concerned with the model sensitivity to changes, the NRC staff requested a sensitivity study with variations in different parameters. Westinghouse provided plots of maximum predicted oxide thickness versus burnup with varied rod average power, coolant inlet temperature, and coolant flow (Reference 2). The results showed that the variations in rod power, inlet temperature, or coolant flow did not result in drastic changes in the predictions, which indicated the model stability and consistency.

Based on the model stability and consistency, the NRC staff considers that the sensitivity study is acceptable for the corrosion model.

3.9 <u>Hydrogen Absorption</u>

During the corrosion process, the cladding reacts with the coolant to form oxide layer on the cladding surface, and releases hydrogen. The oxide layer would gradually reduce the cladding wall thickness. A fraction of the released hydrogen is absorbed by oxide layer and the base cladding metal. The remaining unabsorbed hydrogen goes into the coolant. Hydrogen absorbed by the base metal can impact cladding material properties and strength. Excessive hydrogen absorption could lead to reduced ductility and premature brittle fracture of the cladding.

The current hydrogen pickup is limited to **[ ]** for ZIRLO™ and Optimized ZIRLO™ cladding in the Westinghouse design. Westinghouse intends to demonstrate a best estimate relationship between cladding hydrogen content and oxide thickness of **[ ]** (Reference 6). The hydrogen absorption in the oxide layer was described in Equation 3-2 of Reference 1. Westinghouse showed several figures of hydrogen absorption in cladding and oxide layer versus oxide thickness (Reference 1). The data showed large scattering around the best fit curves. Westinghouse stated that the current best estimate limit of 100 microns in cladding oxidation may result in hydrogen pickup of up to **[ ]**. The NRC staff notices that there is a large uncertainty of **[ ]** involved in the predicted **[ ]** hydrogen absorption.

Assuming a critical crack size and known fracture toughness, Westinghouse analyzed the crack propagation mechanism through the cladding wall using fracture mechanics analysis for irradiated hydrogen charged fuel rods. Westinghouse concluded that the corrosion criterion of 100 micron oxide thickness ensured cladding integrity such that there was no need to have a separate hydrogen limit for the ZIRLO™ cladding (References 1 and 7). Lacking independent verification of the critical crack size and fracture toughness, the NRC staff determines that the Westinghouse finding is inconclusive. Due to the fact that the hydrogen is **[ ]**, the hydrogen distribution would have higher concentration in the outer cladding surface which could significantly exceed the hydrogen design limit. Westinghouse will have to ensure that the hydrogen absorption would not have adverse effects on the cladding ductility as TRDs grow larger. Therefore, the NRC staff disagrees with Westinghouse assertion that there is no need to have a separate hydrogen limit in addition to the 100 micron corrosion limit.

Westinghouse provided additional information to address the NRC staff concern (References 6 and 8). Westinghouse initially stated in the submittal that Optimized ZIRLO™ cladding would have similar hydrogen pickup fraction as ZIRLO™ cladding based on autoclave tests. Westinghouse obtained additional data on Low Tin ZIRLO™ cladding and Optimized ZIRLO™ cladding from different reactors. The hydrogen pickup data are within the scatter band for ZIRLO™ and Optimized ZIRLO™ cladding data base. The plot of measured versus predicted hydrogen pickup for these cladding showed that the hydrogen pickup model predicted higher results than measurements for most cases. Westinghouse demonstrated that the hydrogen pickup model is conservative. In addition, Westinghouse presented a figure of high burnup cladding ductility as a function of hydrogen. Westinghouse claimed that cladding ductility is adequately maintained for hydrogen pickup up to **[ ]**. Due to the scarcity of the data, the NRC staff cannot come to definitive conclusion. The NRC staff recognizes that the current approved hydrogen limit is **[ ]** for Westinghouse fuel design.

Based on prediction conservatism and demonstration of cladding ductility, the NRC staff concludes that the hydrogen pickup model for cladding and oxide layer described in References 1 and 6 is acceptable for licensing applications. However, the NRC staff disagrees with the Westinghouse assertion that the corrosion limit of 100 microns would be able to forgo the hydrogen pickup limit for the cladding design. A hydrogen pickup limitation is imposed as described in Section 5.0 of this SE.

4.0 MODEL APPLICATIONS

Westinghouse intends to use the new corrosion model on a forward fit basis in design analyses subsequent to the NRC staff approval. The new corrosion model will replace the current corrosion models one-for-one in the corrosion model applications. The new corrosion model will be used according to the currently licensed methodologies for Westinghouse NSSS plants and CE NSSS plants (Reference 6).

4.1 Westinghouse Methodology Application

Westinghouse stated that fuel rod analyses performed using the PAD code typically addressed the fuel rod design criteria of clad stress and strain, rod internal pressure, and fuel centerline temperature in fuel melting and safety assessments (Reference 3). Depending on analyses, the analytical approach could be a best estimate plus uncertainties or a bounding calculation. In either case, all significant model uncertainties were accounted for including the corrosion model uncertainty. The oxide layer thermal feedback and wall thinning were considered in the PAD code. For the evaluation of the 100 micron design limit in cladding corrosion, the best estimate calculation was performed. Westinghouse further provided a definition of corrosion design limit in Reference 8.

It is the NRC staff understanding that the current Westinghouse corrosion model is an independent model. The corrosion model can provide thermal feedback to the PAD.

Westinghouse intends to replace the current existing corrosion criteria with the TRD-based corrosion model (Reference 1) for ZIRLO™ and Optimized ZIRLO™ cladding on a forward fit basis in fuel rod design analyses subsequent to the NRC approval. The NRC staff accepts this approach.

Westinghouse provided a list of current explicit cladding corrosion criteria for Westinghouse NSSS plant applications (Reference 6). These corrosion criteria include cladding metal-oxide interface temperature limits (Reference 9), cladding oxide thickness limit (Reference 10), and hydrogen pickup limit for ZIRLO™ and Optimized ZIRLO™ material (References 9 and 10). The NRC staff agrees with Westinghouse approach to replace cladding metal-oxide interface temperature limits and cladding oxide thickness limit with the TRD-based corrosion model. However, the NRC staff disagrees with Westinghouse intent to eliminate the hydrogen pickup limit with the argument that the corrosion limit of 100 microns would be able to ensure the cladding ductility as discussed in Section 3.9.

Based on the NRC staff evaluation, the NRC staff concludes that Westinghouse approach of replacing the current existing corrosion criteria with the TRD-based corrosion model for ZIRLO™ and Optimized ZIRLO™ cladding on a forward fit basis in fuel rod design analyses is acceptable with condition. The condition specifies that Westinghouse cannot eliminate or replace the hydrogen pickup limits in the current existing topical reports including References 9 and 10 for ZIRLO™ and Optimized ZIRLO™ cladding.

4.2 Combustion Engineering Methodology Application

Westinghouse intends to apply the same approach of the TRD-based corrosion model for CE licensed methodologies.

Westinghouse provided a list of current explicit cladding corrosion criteria for CE NSSS plant applications (Reference 6). These corrosion criteria include cladding corrosion limit of 100 microns (Reference 11) and fuel duty (Reference 11) for ZIRLO™ cladding, cladding oxide thickness limit (Reference 10), and hydrogen pickup limit for Optimized ZIRLO™ cladding (Reference 10). The cladding corrosion limit of 100 microns is consistent with the NRC staff position. The fuel duty is discussed in the following Section 4.3. Except for the 100 micron corrosion limit and fuel duty, the NRC staff agrees with Westinghouse approach to replace cladding oxide thickness limit with the TRD-based corrosion model. However, the NRC staff disagrees with Westinghouse intent to eliminate the hydrogen pickup limit with the argument that the corrosion limit of 100 microns would be able to ensure the cladding ductility as discussed in Section 3.9. The NRC staff also notices that the ZIRLO™ cladding does not have a hydrogen pickup limit as required by Optimized ZIRLO™ cladding.

The NRC staff expressed a concern of applying the corrosion model in the CE FATES code (Reference 12) which lacks many contemporary features. In responding to the NRC staff concern, Westinghouse indicated that the TRD-based corrosion model was not incorporated into the FATES code (References 3 and 8).

Instead, the TRD-based corrosion model will be applied in connection with the thermal-hydraulic and cladding temperature modeling methodology which was described in the implementation of ZIRLO™ cladding in CENPD-404-P-A, Revision 0, "Implementation of ZIRLO Cladding Material in CE Nuclear Power Fuel Assembly Designs," (Reference 11) for CE NSSS plant applications. Since CENPD-404-P-A, Revision 0, was approved, the NRC staff agrees with the Westinghouse approach of applying the corrosion model for CE NSSS plant applications.

Based on the NRC staff evaluation, the NRC staff concludes that the Westinghouse approach of replacing the current existing corrosion criteria with the TRD-based corrosion model for ZIRLO™ and Optimized ZIRLO™ cladding on a forward fit basis in fuel rod design analyses is acceptable with two conditions. The first condition requires that a hydrogen pickup limit of **[** **]** be implemented for ZIRLO™ cladding. The second condition specifies that Westinghouse cannot eliminate or replace the hydrogen pickup limits in the current existing TRs including Reference 10 for Optimized ZIRLO™ cladding.

4.3 <u>CENPD-404 Safety Evaluation Condition 4</u>

The NRC staff issued a safety evaluation of CENPD-404-P, Revision 0, on September 12, 2001 (Reference 11). The SE approved the use of Westinghouse designed ZIRLO™ cladding for CE fuel assemblies. However, there were five conditions attached to the SE. Condition 4 states:

> Until data is available demonstrating the performance of ZIRLO™ cladding in CENP designed plants, the fuel duty will be limited for each CENP designed plant with some provision for adequate margin to account for variations in core design (e.g., cycle length, plant operating conditions, etc.). Details of this condition will be addressed on a plant specific basis during the approval to use ZIRLO™ in a specific plant.

On May 1, 2009, Westinghouse submitted a letter, "Data Satisfying CENPD-404-P-A SER Condition 4," for the NRC staff review in conjunction of the corrosion model review (Reference 13). Specifically, Westinghouse requested that Condition 4 be removed on the basis of the use of the TRD-based corrosion model. Westinghouse intended to use the TRD-based rather than the fuel-duty-index (FDI)-based corrosion model for licensing applications for CE fuel designs. Westinghouse presented a plot of measured oxide thickness versus TRD, which showed CE plant data following closely with the trend of Westinghouse plant data although CE data base significantly lagged behind Westinghouse data base.

In responding to the NRC staff RAIs (References 2 and 3), Westinghouse confirmed that TRD-based corrosion model will be applicable to all CE designed ZIRLO™ and Optimized ZIRLO™ fuel assemblies, and FDI will not be used for licensing applications.

Based on the TRD-based data confirmation, the NRC staff concludes that the Condition 4 in the CENPD-404-P-A SE can be removed. The NRC staff disapproves the use of the FDI-based corrosion model for any future licensing applications.

5.0 LIMITATIONS AND CONDITIONS

The following limitations and conditions apply to the use of TR WCAP-12610-P-A & CENPD-404-P-A, Addendum 2, "Westinghouse Clad Corrosion Model for ZIRLO™ and Optimized ZIRLO™:"

1. The maximum TRDs are restricted to numbers corresponding to a cladding corrosion amount of 100 microns for licensing applications. The corrosion is defined as **[** **]**

2. The NRC staff requires that a hydrogen pickup limit of **[** **]** be implemented for ZIRLO™ and Optimized ZIRLO™ cladding.

3. The NRC staff disapproves the Westinghouse assertion that a single corrosion limit could ensure cladding integrity without a separate hydrogen pickup limit. The hydrogen pickup limit in the current existing topical reports including References 9 and 10 for ZIRLO™ and Optimized ZIRLO™ cladding shall not be eliminated or replaced.

4. Condition 4 in CENPD-404-P-A SE can be removed. And, the NRC staff disapproves the use of the FDI-based corrosion model for any future licensing applications.

6.0 CONCLUSION

The NRC staff has reviewed the Westinghouse TR WCAP-12610-P-A & CENPD-404-P-A, Addendum 2, "Westinghouse Clad Corrosion Model for ZIRLO™ and Optimized ZIRLO™." Based on the technical evaluation, the NRC staff concludes that the TRD-based corrosion model, as described in WCAP-12610-P-A & CENPD-404-P-A, Addendum 2, is acceptable for ZIRLO™ and Optimized ZIRLO™ cladding licensing applications with the limitations and conditions stated in Section 5.0 of this SE.

7.0 REFERENCES

1. Letter from Westinghouse Electric Company to NRC, "Submittal of WCAP-12610-P-A & CENPD-404-P-A/WCAP-14342-A & CENPD-404-NP-A, Addendum 2, "Westinghouse Clad Corrosion Model for ZIRLO™ and Optimized ZIRLO™," LTR-NRC-08-58, November 24, 2008.

2. Letter from Westinghouse Electric Company to NRC, "Response to the NRC's Request for Additional Information RE: Westinghouse Electric Company Topical Report WCAP-12610-P-A & CENPD-404-P-A/WCAP-14342-A & CENPD-404-NP-A,

Addendum 2, “Westinghouse Clad Corrosion Model for ZIRLO™ and Optimized ZIRLO™," LTR-NRC-10-27, April 30, 2010.

3. Letter from Westinghouse Electric Company to NRC, "Response to the NRC Request for Additional Information on WCAP-12610-P-A & CENPD-404-P-A/WCAP-14342-A & CENPD-404-NP-A, Addendum 2, “Westinghouse Clad Corrosion Model for ZIRLO™ and Optimized ZIRLO™," LTR-NRC-11-48, September 19, 2011.

4. L. S. Tong and Joel Weisman, “Thermal Analysis of Pressurized Water Reactors,” Third Edition, American Nuclear Society, La Grange Park, Illinois USA.

5. WCAP-12488-A, “Westinghouse Fuel Criteria Evaluation Process,” October 1994.

6. Letter from Westinghouse Electric Company to NRC, "Additional Information to Support NRC Review of WCAP-12610-P-A & CENPD-404-P-A/WCAP-14342-A & CENPD-404-NP-A, Addendum 2, “Westinghouse Clad Corrosion Model for ZIRLO™ and Optimized ZIRLO™,” LTR-NRC-12-40, April 26, 2012.

7. Anand M. Garde, William H. Slagle, and David Mitchell, Westinghouse Electric Company, LLC, “Hydrogen Pick-Up Fraction for ZIRLO® Cladding Corrosion and Resulting Impact on the Cladding Integrity,” Proceedings of Top Fuel 2009, Paris, France, September 6–10, 2009.

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Attachment: Resolution of Draft SE Comments

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