SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

ADDENDUM 1 TO WCAP-12610-P-A AND CENPD-404-P-A, "OPTIMIZED ZIRLO™"

WESTINGHOUSE ELECTRIC COMPANY

PROJECT NO. 700

1.0 INTRODUCTION

By letter dated February 14, 2003 (Reference 1), as supplemented by letters dated February 3 (Reference 2), August 4 (Reference 3), and October 29, 2004 (Reference 4), and April 19, 2005 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML051150303), Westinghouse Electric Company (Westinghouse or W) requested review and approval of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, "Optimized ZIRLO™." The stated purpose of Addendum 1 is to obtain NRC staff approval of an extension to the regulatory definition of ZIRLO™ as approved in WCAP-12610-P-A and CENPD-404-P-A. This extension would expand the allowable material composition of ZIRLO™. The zirconium-based alloy with the extended composition is referred to as "Optimized ZIRLO™."

The NRC staff's review was assisted by Pacific Northwest National Laboratory (PNNL). The NRC staff's conclusions on the acceptability of Optimized ZIRLO™ are supported by PNNL's Technical Evaluation Report which is referred to in italics within this safety evaluation (SE). The NRC staff's approval is contingent on meeting the conditions and commitments in Section 5.0 of this SE. PNNL refers to this as "conditional approval."

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 for the Review of Safety Analysis Reports for Nuclear Power Plants" (SRP), Section 4.2, "Fuel System Design" (Reference 5). In accordance with SRP Section 4.2, the objectives of the fuel system safety review are to provide assurance that:

- The fuel system is not damaged as a result of normal operation and anticipated operational occurrences (AOOs),
- Fuel system damage is never so severe as to prevent control rod insertion when it is required,
- The number of fuel rod failures is not underestimated for postulated accidents, and
- Coolability is always maintained.

A fuel system that is "not damaged" is defined as fuel rods that do not fail, fuel system dimensions that remain within operational tolerances, and functional capabilities that are not reduced below those assumed in the safety analysis. The first objective above 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 that the first fission product barrier (the cladding) has, therefore, been breached. Fuel rod failures must be accounted for in the dose analysis required by 10 CFR Part 100 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.

In order to assure that the above stated objectives are met and follow the format of Section 4.2 of the SRP, Sections 3.3, 3.4 and 3.5 of this SE covers the following three major categories: (1) fuel system damage mechanisms, which are most applicable to normal operation and AOOs; (2) fuel rod failure mechanisms, which apply to normal operation, AOOs, and postulated accidents; and (3) fuel coolability, which are applied to postulated accidents. Specific fuel damage or failure mechanisms are identified under each of these categories in Section 4.2 of the SRP. This SE discusses the analysis methods and data used by Westinghouse to demonstrate that the objectives of SRP Section 4.2 are met up to the currently approved rod-average burnup levels for Westinghouse and Combustion Engineering (CE) plant fuel designs with Optimized ZIRLO™.

The Westinghouse and CE fuel assembly design criteria previously approved for each individual fuel assembly design do not change with the implementation of Optimized ZIRLO™ fuel cladding material.

3.0 TECHNICAL EVALUATION

3.1 Regulatory Definition of Optimized ZIRLO™

The stated purpose of Addendum 1 is to obtain NRC staff approval of an extension to the regulatory definition of ZIRLO™ as approved in WCAP-12610-P-A and CENPD-404-P-A. This extension would expand the allowable material composition of ZIRLO™. However, due to the inclusion of ZIRLO™ in 10 CFR 50.46, any alteration to its regulatory definition necessitates rulemaking and may not be accomplished with an addendum to the previously approved topical reports (TRs). As such, the NRC staff does not approve the proposed extension to the regulatory definition of ZIRLO™. The NRC staff's review instead focused on the acceptability of Optimized ZIRLO™'s material properties and performance as well as Westinghouse's ability to accurately model its in-reactor behavior.

The NRC staff recognizes the material referred to in Addendum 1 as Optimized ZIRLO™ based upon the following definition and anticipated performance.

Regulatory Definition of Optimized ZIRLO™:

Optimized ZIRLO™ is defined as a niobium-tin-iron zirconium-based alloy with a microstructure comprised of a body-centered cubic (BCC) ZrNb phase and a close-packed hexagonal (CPH) ZrNbFe phase homogeneously distributed throughout the zirconium matrix. The nominal composition for Optimized ZIRLO™ is listed in the August 4, 2004 letter, responding to a request for additional information (RAI) #2d. The final **[ ]** microstructure of Optimized ZIRLO™ fuel clad material is discussed in response to RAI #3 of the October 29, 2004 letter. The allowable composition for Optimized ZIRLO™ is limited to the following:

Element	Allowable Range (wt%)
Niobium	0.8 - 1.2
Tin	0.6 - 0.79
Iron	0.09 - 0.13
Oxygen	0.09 - 0.16
Zirconium	Balance

Regulatory Performance:

Based upon demonstrated material performance in Addendum 1 and in response to RAIs (References 2, 3, and 4) and the irradiated database, the NRC staff has approved Optimized ZIRLO™ for full batch implementation. Optimized ZIRLO™ has undergone a series of physical and mechanical testing. Test procedures and results are specified in Appendices A and B of Addendum 1, respectively. Along with lead test assembly (LTA) irradiation experience, this documented material performance forms the basis of the NRC staff's acceptance of Optimized ZIRLO™.

In general, test specimens and LTA components are based on a target or nominal composition. As such, the composition of the test specimens and LTA components does not encompass the full range of compositions available within the allowable range. The effect of a slight variation in tin content is described in this Addendum (e.g., standard ZIRLO™ versus Optimized ZIRLO™). Similarly, adjustments to the remaining alloying composition within the allowable range and/or variations of certain trace elements within the material specification may lead to changes in physical and mechanical performance.

Variances in manufacturing process (e.g., heat treatments, surface finish, etc.) may also impact the material's performance.

In response to RAI #2 of Reference 3 concerning manufacturing process control, Westinghouse stated that material specifications and quality control (e.g., chemical analysis of each ingot) are used to control the material's composition and microstructure. Furthermore, product specifications and quality control (e.g., periodic mechanical and corrosion testing) are used to verify material performance. The NRC staff relies upon Westinghouse's process and product specifications and quality controls to ensure that the performance of future batches of Optimized ZIRLO™ material is consistent with the material's performance presented in Addendum 1.

On September 2, 2004, the NRC staff visited Westinghouse Commercial Nuclear Fuel Division at Western Zirconium near Ogden, Utah to tour the facility and review the material and product specifications. The NRC staff found that the quality control steps defined within these specifications are adequate to ensure that the material's performance is maintained.

3.2 Material Properties

In support of the NRC staff's review, PNNL evaluated the material properties of Optimized ZIRLO™ documented in Addendum 1. The NRC staff has reviewed and concurs with PNNL's assessment provided below. Reference and section numbers within the PNNL text have been changed in order to integrate it into this SE.

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

*Optimized ZIRLO™ fuel cladding is different from standard ZIRLO™ cladding in two respects; 1) the tin (Sn) content is lower, and 2) the microstructure is **[** **]**. This difference in tin content and microstructure can lead to differences in some material properties. Guide tube applications of Optimized ZIRLO™ have only one difference from standard ZIRLO™ guide tubes and that is in tin content. The microstructure of both Optimized ZIRLO™ and standard ZIRLO™ guide tubes is similar such that both are **[** **]**. Because the microstructure is similar between Optimized ZIRLO™ and standard ZIRLO™ guide tubes the material property differences will not be as different for some properties as for the two materials when applied to fuel cladding with different microstructures.*

For most of these material properties W claims that the properties of Optimized ZIRLO™ and standard ZIRLO™ for both cladding and structural applications are the same within the uncertainty of the data and, therefore, use of standard ZIRLO™ or Zr-4 properties for safety analyses is acceptable. It is true when comparing the latest property measurements made by W for both Optimized ZIRLO™ and standard ZIRLO™ in many cases the data are similar. However, the major issue is that this is not true of the standard ZIRLO™ or Zr-4 property models that are used in their codes to perform safety analyses of fuel designs using Optimized ZIRLO™. This is because some of the property models used in their codes do not compare well to the latest data Optimized ZIRLO™ and standard ZIRLO™ (see Sections 3.2.2, 3.2.3 and 3.2.4 below). For example, a comparison of the W and CE specific heat models used for LOCA and other analyses to the Optimized ZIRLO™ and standard ZIRLO™ data show that there are *differences of **[ ]** than the scatter in the measurement data in the **[ ]** between the models used and the data.*

Another issue is that W has claimed that the irradiation creep of Optimized ZIRLO™ is virtually the same as for standard ZIRLO™ but there currently is no irradiation creep data from Optimized ZIRLO™ cladding to verify this claim (see discussion in Section 3.2.10 below). Irradiation creep is an important property in nearly all analyses with the greatest impact on cladding collapse, rod pressure, and departure from nucleate boiling (DNB) propagation analyses.

*A third issue is that W has claimed that there is no difference in yield strength (YS) between Optimized ZIRLO™ and standard ZIRLO™ once irradiation begins even though the unirradiated YS of Optimized ZIRLO™ is **[ ]** than that of standard ZIRLO™. The **[ ]** in Optimized ZIRLO™ that results in **[ ]** regions while the standard ZIRLO™ is **[ ]**.*

3.2.1 Specific Gravity (Density)

*W has measured the specific gravity of Optimized ZIRLO™ and standard ZIRLO™ resulting in very close measured values between the two materials, i.e., **[ ]**. However, there was a **[ ]** between the values measured previously and those presented in this submittal but these are considered to be relatively small differences with a small impact on analyses. The PNNL staff concludes that the W value for specific gravity is acceptable for Optimized ZIRLO™ licensing applications up to currently approved burnup levels.*

3.2.2 Coefficient of Thermal Expansion

*W has measured the diametral thermal expansion of Optimized ZIRLO™ and standard ZIRLO™ that show differences on the order of **[ ]** between these two materials up to the maximum measured temperature of 1100ΕF. W also measured axial thermal expansion in both these materials but the differences were not as great; **[ ]**. Thermal expansion is used in stored energy estimates, LOCA, rod pressure, fuel temperatures and cladding stress/strain analyses.*

W has performed sensitivity LOCA analyses for both W and CE plants to determine the impact of thermal expansion changes on the order of those observed in the diametral expansion differences between Optimized ZIRLO™ and standard ZIRLO™. These analyses demonstrated only small changes in calculated peak clad temperatures (PCTs) for LOCA analyses, but this did not include the impact on stored energy and PCTs nor did it examine the impact on other analyses, e.g., rod pressure and cladding stress/strain. The higher diametral expansion for Optimized ZIRLO™ should result in decreased fuel-clad gap conductance and increased fuel temperatures for a given linear heat generation rate (LHGR), but stresses and strains should be lower.

An RAI question also asked about the synergistic impact of significant differences in the Optimized ZIRLO™ material properties of thermal expansion, thermal conductivity and specific heat on their accident analyses. The synergistic effects of changes in these three properties from those currently used by W will be discussed in Sections 3.2.4 and 3.5.

3.2.3 Thermal Conductivity

W has measured the thermal conductivity of Optimized ZIRLO™ and standard ZIRLO™ up to 2200°F that demonstrate small differences less than **[ ]***. In addition, the current data has been compared against the thermal conductivity models proposed for licensing analyses (Appendix K and Best-Estimate) of W and CE fuel designs with Optimized ZIRLO™ that show that both the W and CE models are a reasonable representation of the data* **[ ]***. For example, at temperatures between* **[ ]** *the differences are less than* **[ ]***, but at temperatures above* **[ ]** *the differences are on the order of* **[ ]** *between the data from these two materials and both the W and CE models. W has stated in their submittal that the differences between the models and the data have been evaluated in sensitivity analyses that demonstrate an insignificant impact on large and small-break LOCAs.*

An RAI question also asked about the synergistic impact of significant differences in the Optimized ZIRLO™ material property models and the data of thermal expansion, thermal conductivity and specific heat on their accident analyses. The synergistic effects of changes in these three properties from those models currently used by W will be discussed in Sections 3.2.4 and 3.5.

3.2.4 Specific Heat

W has measured specific heat for both standard ZIRLO™ and Optimized ZIRLO™ and found that the two are very similar; however, there are considerable differences between the measured values for Optimized ZIRLO™ and the specific heat model currently being used in safety analyses for W and CE designed plants. These differences are greatest in the **[ ]** *such that W and CE evaluation models are* **[ ]** *than the scatter in the measurement data for specific heat of Optimized ZIRLO™.*

W was questioned on what effect this has on several accident analyses where heat transfer is important in determining the outcome of the accident. The question also asked what the combined effect of three material properties (specific heat, thermal conductivity and thermal expansion) that showed differences between the evaluation models used on these analyses and the Optimized ZIRLO™ data presented in the submittal. W responded with some examples of results from large-break and small-break LOCAs for both W- and CE-designed plants with only the specific heat changed to closely match the Optimized ZIRLO™ data. These results demonstrated that for those analyses where the changes (utilized specific heat model based on Optimized ZIRLO™ data) were greatest in PCTs occurred early in the accident such as in blowdown or early in reflood. W also provided two analysis examples of large-break LOCAs, one with maximum PCTs achieved during early reflood and a second with late reflood taking into account the combined effects of specific heat, thermal conductivity and thermal expansion for properties based on Optimized ZIRLO™ data. The maximum PCT changes with late reflood or for a small-break LOCA were minimal, but for a plant with a large-break LOCA and early reflood the maximum PCTs increased by [ ]when Optimized ZIRLO™ data were used for all three properties (where the combined effect was greater than the sum of the individual effects). No examples were provided for the combined effects for CE plants.

3.2.5 Emissivity

Emissivity is important when high cladding temperatures are experienced in certain accident analyses such as LOCAs. W has measured emissivity for Zircaloy-4, standard ZIRLO™ and Optimized ZIRLO™ in a vacuum up to [ ] and found that the three are very similar, i.e., differences [ ]. However, when the Zircaloy-4 emissivity data measured in a vacuum in this submittal are compared to emissivity data obtained in a steam atmosphere there are considerable differences. It should be noted that the measurement of emissivity in a steam atmosphere are more prototypic of the application of this material property in accident analyses. This is not too surprising because there will be little or no Zr-oxide layer in a vacuum while a much larger oxide layer exists in a steam atmosphere. Therefore, the emissivity applicable to accident analyses is that for Zr-oxide and not for the bare metal as measured by W. However, the emissivity for the Zr-oxide on Optimized ZIRLO™ is expected to be similar to that for standard ZIRLO™ because the structure of the oxide is similar.

Therefore, PNNL concludes that the values proposed by W for emissivity are acceptable for licensing applications with Optimized ZIRLO™ cladding up to currently approved burnup levels.

3.2.6 Oxidation

The Optimized ZIRLO™ application that results in the most severe oxidation for both normal and accident operation is the fuel cladding. Cladding oxidation due to normal operation is discussed in Section 3.3.4 and those for LOCA in Section 3.5 and will not be discussed further in this section.

3.2.7 Ultimate Tensile Strength

As noted earlier, the microstructure of both Optimized ZIRLO™ and standard ZIRLO™ differs depending on the application. For example, for fuel cladding W uses a [ ] Optimized ZIRLO™ while for standard ZIRLO™ the microstructure is [ ]. For guide tubes the Optimized ZIRLO™ microstructure is [ ] similar to the microstructure of standard ZIRLO™ guide tubes. The strength of [ ] material is considerably lower than for [ ] or [ ] material such that different strength properties are used for fuel cladding versus guide tubes. In addition, W uses unirradiated strengths for CE fuel designs while it uses irradiated strengths for W fuel designs. It appears that W is not proposing to change this methodology but originally proposed the use of YS of standard ZIRLO™ ([ ] for guide tubes and [ ] for cladding) to determine stress intensity limits (see Section 3.2.8). However, it is not clear whether W uses the ultimate tensile strength (UTS) of irradiated standard ZIRLO™ as a stress limit in any of these loading analyses for W fuel designs, therefore, the following discussion is related to the possible use of UTS of irradiated standard

ZIRLO™ by W in their cladding and structural loading analyses for Optimized ZIRLO™ application to W fuel designs similar to that used for CE fuel designs (based on Reference 6 guidelines).

W has measured the UTS for both unirradiated standard ZIRLO™ **[ ]** *material and Optimized ZIRLO™* **[ ]** *material and found that the latter is* **[ ]** *within the temperature range of normal reactor operation. W has stated that there is no difference between the irradiated mechanical properties of Optimized ZIRLO™ and standard ZIRLO™. The W submittal claims that irradiation hardening will decrease any differences in mechanical properties such that there will not be a significant difference between these two materials once irradiation commences. However, PNNL noted that there will be a difference in irradiated strengths between Optimized ZIRLO™ and standard ZIRLO™. This difference in irradiated strengths is expected to remain similar to the difference in unirradiated strengths up to a given irradiation level and then begin to merge to similar values after a higher level of irradiation as discussed in Section 3.2.8 below.*

Westinghouse has agreed (Reference 4) to account for the relative differences in unirradiated strength (YS and UTS) between Optimized ZIRLO™ and standard ZIRLO™ in cladding and structural analyses until irradiated data for Optimized ZIRLO™ is provided.

The NRC staff has imposed a condition (Section 5.0, Condition 8) on the use of Optimized ZIRLO™ to resolve the NRC staff's concerns for this material property.

3.2.8 Yield Strength (0.2% Offset)

W originally proposed that the standard ZIRLO™ YS be used in W fuel designs to determine the stress limits for Optimized ZIRLO™ cladding and other structural materials. It is noted that W takes credit for the increase in irradiated strength of standard ZIRLO™ in their stress limits for W designed plants; however, for CE designed plants W does not take credit for the increase in strength due to irradiation.

W has measured the YS for both unirradiated standard ZIRLO™ in the **[ ]** *and Optimized ZIRLO™ in the* **[ ]** *and found that the latter was* **[ ]** *for standard ZIRLO™ within the temperature range of normal reactor operation. W has stated that there is no difference between the irradiated mechanical properties of Optimized ZIRLO™ and standard ZIRLO™. The W submittal claims that irradiation hardening will decrease any differences in mechanical properties between the unirradiated materials such that there will not be a significant difference between these two materials after irradiation begins. PNNL agrees that this may be true for standard ZIRLO™ and Optimized ZIRLO™ in the* **[ ]** *condition (similar strengths between both* **[ ]** *materials) as proposed for use as guide tubes but this may not be true for the differences in fuel cladding between standard ZIRLO™ in the* **[ ]** *and Optimized ZIRLO™ in the* **[ ]** *where there is a* **[ ]**.

*W was questioned on what was the basis for stating that irradiated mechanical properties would be nearly identical between Optimized ZIRLO™ (***[ ]***) and standard ZIRLO™ fuel cladding*

([ ]) even though they are different by [ ] in the unirradiated condition without having performed mechanical property tests on irradiated Optimized ZIRLO™. Westinghouse responded that the irradiation strengthening that occurs with the initial fuel operation negates the starting differences in the mechanical strength. The W response also offered Zircaloy-4 data from [ ] cladding and data from [ ] Zircaloy-4 thimble tubes irradiated to high fluences (high burnups) that showed only small differences in YS even though the unirradiated YS of these two Zr-4 types were significantly different due to their different heat treatments and microstructure.

PNNL responded that References 7 and 8 show that if there are differences in mechanical YS that these differences do not disappear by a fast fluence of 3.0 x 10^{21} n/cm^2 that is equivalent to approximately 15 to 17 GWd/MTU burnup. PNNL acknowledged that the cladding strengths between Optimized ZIRLO™ and standard ZIRLO™ may eventually become similar due to irradiation damage at high burnup but the differences do not disappear until later in a fuel rods lifetime in-reactor. It was also noted that many times limiting peak stress conditions are either beginning-of-life or early-in-life for any given fuel design such that differences in properties between these two materials need to be accounted for in these analyses.

W has offered data in Reference 4 that shows that YS differences between RXA, 20% coldworked and 40% coldworked Zr-2 had disappeared in the longitudinal direction by a fluence of 2.5 x 10^{21} n/cm^2. The differences in the transverse (hoop) direction were considerably reduced between the RXA and 20% coldworked Zr-2 by a fluence of 2.5 x 10^{21} n/cm^2 but there was still ~10% difference between RXA and 40% coldworked Zr-2 at this fluence. W also argued that the starting YS differences [ ] in their [ ] Optimized ZIRLO™ and standard ZIRLO™ was much smaller than the starting differences in [ ] and [ ] standard ZIRLO™ such that any differences at fluences of 3.0 x 10^{21} n/cm^2 would be small and within the scatter of the YS data.

Westinghouse has agreed (Reference 4) to account for the relative differences in unirradiated strength (YS and UTS) between Optimized ZIRLO™ and standard ZIRLO™ in cladding and structural analyses until irradiated data for Optimized ZIRLO™ is provided.

The NRC staff has imposed a condition (Section 5.0, Condition 8) on the use of Optimized ZIRLO™ to resolve the NRC staff's and contractor's concerns for this material property.

3.2.9 Ductility

Cladding ductility needs to be retained to avoid brittle failures. Generally, irradiation damage and hydride formation (due to corrosion) have been found to decrease the ductility of zirconium alloys (References 9, 10, and 11). The NRC does not have a specific minimum limit on cladding ductility; however, Section 4.2 of the SRP (Reference 5) suggests a limit for total (elastic + plastic) cladding uniform strain of 1% that should not be exceeded during normal operation and AOOs. Therefore, the SRP would suggest a minimum total strain capability of at least 1% in order to prevent cladding failure below the 1% strain limit.

W has measured the total elongation strain in the axial and circumferential direction of both unirradiated Optimized ZIRLO™ and standard ZIRLO™ that show Optimized ZIRLO™ has a *higher strain at failure. This is reasonable because the cladding strength is lower than standard ZIRLO™ such that lower strength in a material generally increases the ductility. However, W has not measured the strains at failure for Optimized ZIRLO™ after irradiation.*

The French organizations, IRSN and CEA, have measured the plastic uniform elongation of standard ZIRLO™ fuel cladding at burnups up to 75 GWd/MTU with oxidation thicknesses as high as 90 microns. These tests show plastic uniform strain between 0.4% to 0.6% that provides a total (elastic + plastic) uniform strain of 1.1% to 1.4% that is within the SRP guideline of 1% discussed above. The total uniform strain for Optimized ZIRLO™ at high burnups is most likely similar to that for standard ZIRLO™ or may provide even a slightly higher strain because of the lower YS and UTS of the former.

PNNL concludes that the 1% strain limit is acceptable for application to Optimized ZIRLO™ cladding in W and CE fuel designs up to currently approved burnup levels.

3.2.10 Creep

High temperature thermal creep and rupture important for accidents such as LOCA is discussed in Section 3.4.6 of this SE. This section will address cladding creep of Optimized ZIRLO™ during normal operation.

W has provided out-of-reactor thermal creep data for Optimized ZIRLO™ and standard ZIRLO™ to demonstrate that the creep behavior of these two materials is nearly identical. However, irradiation enhanced creep is the phenomenon of interest for in-reactor operation and thermal out-of-reactor creep is not important to in-reactor fuel rod performance. For example, thermal creep makes up less than 5% of the total creep in-reactor and irradiation induced creep makes up greater than 95%. Out-of-reactor thermal creep behavior of different materials many times gives a qualitative indication of the relative creep in-reactor behavior due to irradiation but seldom is a good indicator of the quantitative differences in creep between two materials. Therefore, the claim by W that there is no quantitative difference between Optimized ZIRLO™ and standard ZIRLO™ creep in-reactor without in-reactor creep data to support this conclusion is speculative at best. In addition, there is data from References 12, 13 and 14 that demonstrate decreasing the tin in zirconium alloys increases the creep rate. However, there is also creep data to suggest that **[**

] *seen in standard ZIRLO™. However, without irradiation creep data it is impossible to determine if the* **[**

] *as observed from the thermal creep data.*

W has noted in their responses to the RAIs (response to RAI # 3.b) that there is an irradiation growth and creep program in Vogtle Unit 2 to measure the growth and creep rate of both Optimized ZIRLO™ and standard ZIRLO™ tubes (without fuel). W has committed to share the results of this data with the NRC as it becomes available and to notify the NRC if it demonstrates that the Optimized ZIRLO™ has different creep behavior from standard ZIRLO™. The first set of Optimized ZIRLO™ creep data from this program will be obtained in late 2004 or early 2005 that is prior to Optimized ZIRLO™ cladding being used in reload fuel for any plants.

PNNL does note that no creep data is planned for LTAs with Optimized ZIRLO™ cladding. PNNL acknowledges that the controlled and well characterized in-reactor creep tests as those being performed in Vogtle will in most instances give more precise creep data than from LTAs, however, it would be prudent to obtain some creep data from LTAs to verify that the controlled creep tests and the creep from the more prototypical LTAs are consistent with each other.

PNNL concludes that W has addressed the creep characteristics of Optimized ZIRLO™ and conditional approval [conditions of the NRC staff's approval are listed in Section 5.0] is provided for W and CE fuel designs up to currently approved burnup levels based on W's commitment to collect irradiation creep data for Optimized ZIRLO™ that is applicable to W and CE fuel designs to confirm that this data is enveloped by the standard ZIRLO™ irradiation creep model. The definition of the Optimized ZIRLO™ data being enveloped by the standard ZIRLO™ irradiation creep model is that Optimized ZIRLO™ cladding has essentially the same irradiation creep as that for standard ZIRLO™.

3.2.11 Poisson's Ratio

W uses a constant value for Poisson's ratio with temperature for Optimized ZIRLO™ that is consistent with the value used for Zr-4. W has measured the Poisson's ratio for both unirradiated standard ZIRLO™ and Optimized ZIRLO™ and found that there is essentially no difference within the uncertainty of the data. In addition, PNNL has proprietary data for Poisson's ratio from other zirconium alloys that show this property does not change with minor changes in composition or even relatively significant changes in fabrication for Zr-4 cladding. Poisson's ratio does not change with irradiation for zirconium alloys. PNNL concludes that the W value of Poisson's ratio for Optimized ZIRLO™ is acceptable for licensing applications with Optimized ZIRLO™ cladding in W and CE fuel designs up to currently approved burnup levels.

3.2.12 Modulus of Elasticity (Young's Modulus)

Young's modulus is used to determine the elastic strain experienced by the cladding or assembly structural component and, therefore, also impacts the amount of plastic deformation experienced. W has measured the Young's modulus for both unirradiated standard ZIRLO™ and Optimized ZIRLO™ and found that there is essentially no difference within the uncertainty of the data. W uses the same correlation for Young's modulus for Zr-4, standard ZIRLO™ and Optimized ZIRLO™. PNNL concludes that the W correlation of Young's modulus for Optimized ZIRLO™ is acceptable for licensing applications with Optimized ZIRLO™ cladding in W and CE fuel designs up to currently approved burnup levels.

3.2.13 Hardness (Meyer)

*Meyer hardness is used in calculating the contact conductance between the fuel and cladding when the fuel-to-cladding gap is closed. It should be noted that a large change in Meyer hardness is required to make a significant effect on calculated fuel temperatures. W utilizes the same correlation for Meyer hardness for Zr-4, standard ZIRLO™ and Optimized ZIRLO™. W has measured the microhardness for both unirradiated standard ZIRLO™ and Optimized ZIRLO™ and found that there are small differences with between **[ ]** in Optimized ZIRLO™. This change in hardness is consistent with the lower YS and UTS of*

Optimized ZIRLO™. PNNL concludes that this difference will have a negligible impact on fuel temperature calculations and the W correlation for Meyer hardness of Optimized ZIRLO™ is acceptable for licensing applications with Optimized ZIRLO™ cladding in W and CE fuel designs up to currently approved burnup levels.

3.2.14 Growth

Both fuel rod and assembly (guide tube) growth are important in maintaining acceptable fuel rod and assembly configuration in-reactor that prevents fuel failures and allows for control rod insertions. Guide tube growth needs to be evaluated to prevent the assembly holddown springs from bottoming out that would result in assembly and fuel rod bowing and interfere with control rod insertion (see Section 3.3.7 of this SE). Fuel rod growth can result in an interference fit with the upper assembly structure because the fuel rod cladding grows faster than the assembly guide tubes in the axial direction. Also cladding irradiation axial growth needs to be considered in applicable fuel performance codes, e.g., PAD fuel performance code (Reference 15), for calculating rod pressures.

Irradiation growth of zirconium alloys is generally related to irradiation creep of the alloy such that when one increases the other increases with irradiation. W has measured both fuel rod and assembly irradiation growth of Optimized ZIRLO™ from two LTAs in Byron Unit1 after two cycles of irradiation and compared these measured values to those from standard ZIRLO™ rods and assemblies in the same reactor. The results from these two LTAs demonstrate that the assembly growth of Optimized ZIRLO™ and standard ZIRLO™ guide tubes is within [ ]. The Optimized ZIRLO™ and standard ZIRLO™ fuel rod cladding growths are also relatively close at [ ].

W has also noted in their responses to the RIAs (response to RAI # 3.b) that there is an irradiation growth and creep program in Vogtle Unit 2 to measure the growth and creep rate of both Optimized ZIRLO™ and standard ZIRLO™ tubes (without fuel). W has committed to share the results of this data with the NRC as it becomes available and to notify NRC if it demonstrates that the Optimized ZIRLO™ has different creep or growth behavior from standard ZIRLO™. The first set of Optimized ZIRLO™ growth data from this program will be obtained in late 2004 or early 2005 that is prior to Optimized ZIRLO™ cladding being used in reload fuel for plants.

PNNL concludes that W has adequate testing programs in place to verify that the irradiation growth for Optimized ZIRLO™ is similar to standard ZIRLO™ prior to full reloads of this material and this is acceptable for licensing applications with Optimized ZIRLO™ cladding in W and CE fuel designs up to currently approved burnup levels.

3.2.15 Hydrogen Pickup Fraction

Hydrogen and hydrides increase with increased corrosion and have been shown to have a degrading effect on cladding ductility (References 9, 10 and 11). As a result, Westinghouse has a limit on hydrogen pickup from waterside corrosion (see Section 3.4.1 below). W has not measured the hydrogen pickup fraction for Optimized ZIRLO™. However, the hydrogen pickup fraction of Optimized ZIRLO™ is not expected to be that different from standard ZIRLO™

because the pickup fraction for the latter is slightly lower than for Zr-4 (Reference 16). In addition, the corrosion is reduced for Optimized ZIRLO™ such that the overall hydrogen pickup and impact on cladding performance should be improved over that for standard ZIRLO™ and Zr-4.

PNNL concludes that the W application of hydrogen pickup fraction for standard ZIRLO™ for Optimized ZIRLO™ is acceptable for licensing applications with Optimized ZIRLO™ cladding in W and CE fuel designs up to currently approved burnup levels.

3.2.16 α ÷β Phase Transformation Temperatures

The α ÷ α + β and α + β ÷ β transformation temperatures are only important for those accidents where the cladding temperatures exceed these temperatures, i.e., get relatively hot. The phase transition temperatures determine the break points in many cladding properties such as specific heat, thermal conductivity, thermal expansion and rupture strain. W has measured the α ÷ α + β phase transition temperature for ZIRLO™ as a function of tin content that shows the phase transition temperature drops by ***[ ]****.*

PNNL concludes that W has adequately determined the impact of the phase transformation temperature on the performance of Optimized ZIRLO™ for licensing applications with Optimized ZIRLO™ cladding in W and CE fuel designs up to currently approved burnup levels.

3.3 Fuel System Damage Mechanisms

SRP 4.2.II.A.1 states, "To meet the requirements of GDC 10 as it relates to SAFDLs for normal operation, including AOOs, fuel system damage criteria should be given for all known damage mechanisms."

In support of the NRC staff's review, PNNL evaluated the fuel system damage mechanisms and the impact of Optimized ZIRLO™ on fuel reliability. The NRC staff has reviewed and concurs with PNNL's assessment, provided below. Reference and section numbers within the PNNL text have been changed in order to integrate it into this SE.

The design criteria presented in this section should not be exceeded during normal operation including AOOs. The evaluation portion of each damage mechanism evaluates the Optimized ZIRLO™ properties and analysis methods used for W and CE fuel designs to demonstrate that the specific design criteria are not exceeded during normal operation including AOOs for their fuel designs utilizing Optimized ZIRLO™. In most case the Bases/Criteria or evaluation methods have not changed with the exception of the changes in Optimized ZIRLO™ properties discussed above.

3.3.1 Stress

Bases/Criteria - In keeping with the GDC 10 SAFDLs, fuel damage criteria for cladding stress should ensure that fuel system dimensions remain within operational tolerances and that functional capabilities are not reduced below those assumed in the safety analysis.

The W design basis for fuel assembly, fuel rod, burnable poison rod, and upper end fitting spring stresses is that the fuel system will be functional and will not be damaged due to excessive stresses. The W design limit for fuel rod cladding stress under Condition I (normal operation) and Condition II (AOOs) of operation is that the volume averaged effective stress calculated with the Von Mises equation, considering interference due to uniform cylindrical pellet-to-cladding contact (caused by pellet thermal expansion and swelling, uniform cladding creep, and fuel rod/coolant system pressure differences), is less than the ZIRLO™ (Optimized or standard) 0.2 percent offset YS with consideration of temperature and irradiation effects as described in References 1 and 17.

For the CE design limit during Condition 1 and 2 events, with a primary tensile stress in the clad and the end cap welds, the tensile stress must not exceed 2/3 of the minimum unirradiated yield strength of the material at the applicable temperature. During Condition 3, the primary tensile stress limit is the yield strength and during Condition 4 seismic and LOCA (mechanical excitation only) conditions the stress limit is the lesser of 0.7 Su or 2.4 Sm (Su and Sm are stresses as defined by Reference 6). For Condition 1, 2 and 3 events, with a primary compressive stress in the clad and the end cap welds, the tensile stress must not exceed the minimum unirradiated yield strength of the material at the applicable temperature. During Condition 4 seismic and LOCA (mechanical excitation only) conditions, the stress limit is the lesser of 0.7 Su or 2.4 Sm as defined by Reference 6.

*Evaluation - W has not requested a change in the use of irradiated strengths for W fuel designs nor the use of unirradiated strengths for CE fuel designs. However, W has proposed to use the UTS or YS of standard ZIRLO™ (**[ ]**) to determine the stress intensity limits for the cladding and structural components of their W and CE fuel assembly designs with Optimized ZIRLO™ during seismic-LOCA and other assembly loading analyses.*

It should be noted that Section 3.2.8 above has found that Optimized ZIRLO™ has a lower YS than standard ZIRLO™ in the unirradiated condition and this difference in strength may be retained at low to moderate burnups even though the strength of both Optimized ZIRLO™ and standard ZIRLO™ are increasing with irradiation (fast fluence/burnup). Due to the lack of irradiated properties, Westinghouse has agreed (Reference 4) to account for the relative differences in unirradiated strength (YS and UTS) between Optimized ZIRLO™ and standard ZIRLO™ in cladding and structural analyses.

The NRC staff has imposed a condition (Section 5.0, Condition 8) on the use of Optimized ZIRLO™ to resolve NRC staff's concerns for this material property.

*The W and CE analysis methods have not been changed for Optimized ZIRLO™ and the use of this material has no impact on the analyses other than the differences in Optimized ZIRLO™ properties discussed in Section 3.2 and the changes noted above. The major impact is the lower YS and UTS of Optimized ZIRLO™(**[ ]**) will reduce the margins to the stress limits for this material compared to those for standard ZIRLO™ (**[ ]**).*

3.3.2 Strain

Bases/Criteria - The W design basis for fuel rod cladding strain is that the fuel system will not be damaged due to excessive cladding strain. In order to meet this design basis, the W design limit for cladding strain during steady-state operation is that the total plastic tensile creep and uniform cylindrical fuel pellet expansion due to fuel swelling and thermal expansion is less than 1% from the unirradiated condition. For AOO transients, the design limit for cladding strain is that the total tensile strain due to uniform cylindrical pellet thermal expansion during the transient is less than 1% of the pretransient value.

The CE cladding strain design limit for fuel or integral burnable absorbers is that the net unrecoverable circumferential tensile cladding strain shall not exceed 1% based on beginning-of-life (BOL) cladding dimensions. This criterion is applicable to normal operating conditions, and following a single Condition 2 or 3 event or a single AOO. For fuel or integral-burnable-absorber rods having axial average burnups greater than **[**

], or a single AOO, shall not exceed 1%.

Evaluation – These design strain bases and limits are intended to preclude excessive cladding deformation during normal operation and AOOs. Section 3.2.9 above has concluded that Optimized ZIRLO™ will most likely meet the W 1% cladding strain limit criterion. PNNL concludes that the W 1% strain limit is applicable to Optimized ZIRLO™ for application in W and CE fuel designs up to currently approved burnup levels.

The W and CE strain analysis methods have not been changed for Optimized ZIRLO™ and the use of this material has no impact on the analyses other than the differences in the Optimized ZIRLO™ properties discussed in Section 3.2 above.

3.3.3 Strain Fatigue

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

The CE design limit is more conservative such that the fatigue life usage factor is less than 0.8 rather than the 1.0 value used for W fuel designs.

Evaluation - W has performed fatigue tests on Optimized ZIRLO™ that show the fatigue is somewhat below the best-estimate Langer-O'Donnell curve. However, the Optimized ZIRLO™ fatigue results are still considerably below the lower bound fatigue curve imposed by the conservatism on the Langer-O'Donnell curve discussed above. PNNL concludes that the W *and CE design basis and limits for fatigue are applicable for Optimized ZIRLO™ for application in W and CE fuel designs to up to currently approved burnup levels.*

The W and CE fatigue analysis methods have not been changed for Optimized ZIRLO™ and the use of this material has no impact on the analyses other than the differences in Optimized ZIRLO™ properties discussed in Section 3.2 above.

3.3.4 Fretting Wear

Bases/Criteria - Fretting wear is a concern for fuel, burnable poison rods, and guide tubes. Fretting, or wear, may occur on the fuel and/or burnable rod cladding surfaces in contact with the spacer grids if there is a reduction in grid spacing loads in combination with small amplitude, flow induced, vibratory forces on the fuel rods. Guide tube wear may result when there is flow induced motion between the control rod ends and the inner wall of the guide tube.

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

The W design basis for fuel rod fretting wear is that fuel rods shall be designed not to fail due to fretting wear during normal operation and AOO events. In order to meet this basis, W uses a general guide for wall thickness reduction in W fuel designs which is a percent of the original wall thickness (the specific value is proprietary) for evaluating cladding imperfections, including wear marks. W indicates that the cladding stress and fatigue limits, discussed in Sections 3.3.1 and 3.3.3 above, apply to fretting wear. W has also indicated (Reference 18) in the past that fretting wear will not have a significant effect on cladding stresses and, thus, need not be considered in stress related analyses. As long as the fretting wear in W fuel designs is demonstrated to be below the W guideline for cladding imperfections as stated in Reference 18, fretting wear is considered to be acceptable. W has not performed fretting wear tests on Optimized ZIRLO™, but fretting wear is not expected to be that much different from standard ZIRLO™.

The CE design basis is that fuel rods will not fail due to fretting; however, no limit on fretting wear is established. It is acknowledged that the only realistic approach to verifying fretting wear for fuel designs is in actual fuel rod operation because current analysis methods do not offer accurate predictions of fretting wear prior to the event.

Evaluation - Past changes in spacer grid/spring designs and changes in plant design or coolant flow appear to have a greater impact on fretting wear rather than past changes in cladding material. PNNL concludes that the W design basis for fretting wear is applicable for Optimized ZIRLO™ for application to up to currently approved burnup levels.

Fretting wear appears to be a function of grid spring relaxation loads and flow vibration. Therefore, fretting is dependent on the spacer spring design and material, spacer grid flow characteristics, plant design and coolant flow rather than the cladding material.

W utilizes three methods of evaluation for fretting wear: 1) experimental data from in-reactor performance; 2) 500 hour out-of-reactor wear testing; and 3) the use of previously established and NRC reviewed and approved fretting wear models. Previously established fretting wear models will only be used if fuel design changes do not change hydraulic or grid support conditions from those employed on previous designs. If the design changes impact the hydraulic conditions or rod support conditions and are outside of current experience, then the remaining two fretting wear testing methods are employed by W.

The CE approach for evaluating fretting wear is in visual examination data from in-reactor operation. CE is encouraged to adopt the out-of-reactor wear testing employed for W designs when grids and spacer springs designs are changed.

It is noted that failures due to fretting wear are still observed in some plants at low failure rates but these are due to flow induced vibrations resulting from cross flows from the core baffles, mixed cores or changes in the reactor coolant system (RCS) pump flow characteristics and, therefore, are plant specific.

W has not observed any fretting wear on their LTAs with Optimized ZIRLO™ examined to date and the fretting wear performance of assemblies utilizing Optimized ZIRLO™ will continue to be monitored.

3.3.5 Oxidation and Crud Buildup

Bases/Criteria – Section 4.2 of the SRP identifies cladding oxidation and crud buildup as potential fuel system damage mechanisms. The SRP does not establish specific limits on cladding oxidation and crud but does specify that their effects be accounted for in the thermal and mechanical analyses performed for the fuel. Recent out-of-reactor measured elastic and plastic cladding strain values from high burnup cladding from two PWR (pressurized water reactor) fuel vendors (References 9, 10 and 11) have shown a significant decrease in Zr-4 cladding ductilities when oxide thicknesses and hydrogen levels begin to exceed 80 to 100 microns and 500 to 800 ppm, respectively. As a result the NRC staff has encouraged fuel vendors to establish a maximum oxide thickness limit of 100 microns.

Evaluation – The W design basis for cladding oxidation is that the fuel system will not be damaged due to excessive cladding oxidation. In order to preclude a condition of accelerated oxidation, W imposes specific temperature limits on the cladding. The temperature limits applied to cladding oxidation are that calculated cladding temperatures (at the oxide-to-metal interface) shall be less than a specific (proprietary) value during steady-state operation and AOO transients (a higher limit is applied for AOO transients). However, the W temperature limit does not limit cladding oxidation to within acceptable oxide thicknesses, e.g., the 100 microns limit used by industry. W does have a limit on hydrogen pickup from waterside corrosion of ***[ ]*** *(see Section 3.4.1 below). This hydrogen limit will restrict corrosion to at or below the 100 micron limit but hydrogen is not readily measured in poolside examinations performed on LTAs while oxide thickness is measured.*

The CE design basis for cladding oxidation is that waterside corrosion not result in thermal or mechanical conditions which compromise cladding integrity, therefore, no specific limits on *cladding oxidation or hydrogen levels are defined. As noted above it has been shown that corrosion and the resulting hydrogen from this corrosion can be detrimental to the ductility of the cladding particularly in accident situations.*

Section 4.2 of the SRP states that the effects of cladding crud and oxidation need to be addressed in safety and design analyses, such as in the thermal and mechanical analyses. The amount of cladding oxidation is dependent on fuel rod power, water chemistry control, and primary inlet coolant temperature, but the amount of oxidation and crud buildup increases with burnup and cannot be eliminated. Therefore, the extended burnup levels of today's fuel designs result in thicker oxide layers that provide an extra thermal barrier and clad thinning that can affect the mechanical analysis. The degree of this effect is dependent on cladding material, reactor coolant temperatures and the ability of the water chemistry program to control oxidation. For example, standard ZIRLO™ has been shown to have nearly 100 microns peak oxide thicknesses in high duty plants (Reference 19) while it is anticipated that Optimized ZIRLO™ will reduce oxide thickness at similar duty plants.

W has measured oxidation from LTAs with Optimized ZIRLO™ cladding irradiated in Byron Unit 1 after two cycles of irradiation and compared these measured values to those from standard ZIRLO™ rods and assemblies in the same reactor. The results from these two LTAs demonstrate that the oxidation of Optimized ZIRLO™ and the variation in oxidation between rods is significantly lower than for standard ZIRLO™. W has committed to monitor oxidation up to currently approved burnup levels in the four plants with LTAs utilizing Optimized ZIRLO™. PNNL concludes that W has adequately addressed oxidation [per Westinghouse commitment in Condition 6] of Optimized ZIRLO™ for W and CE fuel designs.

In addition, the NRC staff has imposed a condition (Section 5.0, Condition 3) that limits fuel rod waterside corrosion to resolve NRC staff concerns.

3.3.6 Rod Bowing

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

Evaluation - Rod bowing has been found to be dependent on rod axial growth, the distance between grid spacers, the rod moment of inertia, flux distribution and other assembly design specific characteristics. All of these parameters are design dependent and not material dependent with the exception of rod growth. Therefore, the implementation of Optimized ZIRLO may potentially impact rod bowing only if this material exhibited more axial growth (see Section 3.3.7 below). The NRC has approved (References 16 and 20) rod bowing models for W and CE fuel designs with standard ZIRLO™ cladding up to currently approved burnup levels.

W has measured both fuel rod irradiation growth of Optimized ZIRLO™ from two LTAs in Byron Unit 1 (W plant) after two cycles of irradiation and compared these measured values to those from standard ZIRLO™ rods and assemblies in the same reactor. The results from these two

LTAs demonstrate that the assembly growth of Optimized ZIRLO™ and standard ZIRLO™ guide tubes is within ***[ ]****. The Optimized ZIRLO™ and standard ZIRLO™ fuel rod cladding growths are also relatively close at* ***[ ]****.*

PNNL concludes that the use of the W and CE approved rod bow methodologies for Optimized ZIRLO™ cladding is acceptable for application to licensing analyses up to currently approved burnup levels based on W's commitment to collect Optimized ZIRLO™ growth data up to currently approved burnup levels from both W and CE fuel designs to confirm that this data is enveloped by the standard ZIRLO™ growth model.

3.3.7 Axial Growth

Bases/Criteria - Failure to adequately design for axial growth of the fuel rods can lead to fuel rod-to-nozzle gap closure and fuel rod bowing and possible failure. Failure to adequately design for assembly growth can lead to collapse of the assembly hold-down springs, guide tube bowing and control rod insertion problems. The W and CE design bases are similar in that the fuel rods will be designed with adequate clearance between the fuel rod ends and the top and bottom nozzles to accommodate the differences in the growth of the fuel rods and the growth of the fuel assembly.

Evaluation - The W and CE design limits for fuel rod growth are similar in that no interference between the fuel rods and the fuel assembly top and bottom nozzles is allowed taking into account adequate uncertainties in the predictions. These bases and design limits have been accepted by the NRC for current W and CE fuel designs utilizing standard ZIRLO™ (References 16 and 20). PNNL concludes that they are acceptable for W and CE fuel designs with Optimized ZIRLO™ up to currently approved burnup levels based on W's commitment to collect Optimized ZIRLO™ growth data up to currently approved burnup levels from both W and CE fuel designs to confirm that this data is enveloped by the standard ZIRLO™ growth model.

W currently uses the same axial rod growth model for Zr-4 and standard ZIRLO™ for application to Optimized ZIRLO™ clad rods in both W and CE fuel designs. In addition, W applies the same fuel assembly growth model for ***[ ]*** *and standard ZIRLO™ thimble tubes for application to* ***[ ]*** *Optimized ZIRLO™ guide tubes. As noted in Section 3.2.14 above, W has both an LTA program for Optimized ZIRLO™ in W and CE plants and a test assembly with several zirconium alloys including Optimized ZIRLO™ that has been designed to expressly measure irradiation creep and growth. PNNL concludes that the fuel rod and assembly growth models proposed are acceptable for application to W and CE fuel designs utilizing Optimized ZIRLO™ based on W's commitment to collect Optimized ZIRLO™ fuel rod and assembly growth data up to currently approved burnup levels to confirm that this data is enveloped by the standard ZIRLO™ growth model.*

3.3.8 Rod Internal Pressure

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

The W and CE design basis for fuel rod internal pressure is that the fuel system will not be damaged due to excessive fuel rod internal pressure. The W and CE design limits utilized to meet this design basis are that the internal pressure of the lead rod in the reactor will be limited to a value below which could result in 1) the diametral gap to increase due to outward cladding creep during steady-state operation, and 2) extensive departure from nucleate boiling (DNB) propagation to occur. This design basis and the associated limits have previously been found acceptable by the NRC for current fuel designs and current burnup levels with standard ZIRLO™ (References 16, 20 and 21). The cladding creep and fuel swelling models significantly impact the rod pressure limit determined from Item 1 above. The issue of cladding creep for Optimized ZIRLO™ is discussed in Section 3.2.10 above and in the evaluation below. PNNL concludes that the design limits are also applicable to W and CE fuel designs that utilize Optimized ZIRLO™ up to currently approved burnup levels.

Evaluation - The models and methods used by W to evaluate whether the W and CE fuel designs meet the above Bases/Criteria are examined in this section. The models used by W for determining the rod pressure limit discussed under Bases/Criteria are the fuel swelling and cladding creep model (discussed in Section 3.2.10 above). The models that are important in determining the rod internal pressures are the thermal and fission gas release models. These latter models and the fuel swelling model are not impacted by the introduction of Optimized ZIRLO™; however, cladding creep may be impacted as discussed in Section 3.2.10. W claims that there is no quantitative difference between Optimized ZIRLO™ and standard ZIRLO™ creep in-reactor, but W has no in-reactor creep data to support this conclusion. **[**

]. *It should be noted that if irradiation creep were higher in Optimized ZIRLO™ than for standard ZIRLO™ this would result in a lower limit on rod pressure for fuel with Optimized ZIRLO™ cladding than with standard ZIRLO™ cladding and vice versa.*

W has noted in their responses to the RAIs (response to RAI #3.b) that there is an irradiation growth and creep program in Vogtle Unit 2 to measure the growth and creep rate of both Optimized ZIRLO™ (both **[ ]** *and* **[ ]***) and standard ZIRLO™ tubes (without fuel) along with tubes of their newer advanced alloys. W has committed to share the results of this data with the NRC as it becomes available and to notify NRC if it demonstrates that the Optimized ZIRLO™ has different creep behavior from standard ZIRLO™. The first set of Optimized ZIRLO™ creep data from this program will be obtained in late 2004 or early 2005; that is prior to fuel with Optimized ZIRLO™ cladding being used as reload fuel for plants. While PNNL acknowledges that the controlled and well characterized in-reactor creep tests as those being performed in Vogtle will in most instances give more precise creep data than from LTAs,* *it is prudent to obtain some creep data from LTAs to verify that the controlled creep tests and the creep from more prototypical LTAs are consistent with each other.*

PNNL concludes that W has addressed rod internal pressures and conditional approval [conditions of the NRC staff's approval are listed in Section 5.0] is provided for Optimized ZIRLO™ using currently approved analysis models for standard ZIRLO™ based on W's commitment to collect Optimized ZIRLO™ irradiation creep data applicable to W and CE fuel designs to confirm that this data is enveloped by the standard ZIRLO™ irradiation creep model prior to using Optimized ZIRLO™ for fuel reloads (LTA operation is excluded). The definition of the Optimized ZIRLO™ data being enveloped by the standard ZIRLO™ irradiation creep model is that Optimized ZIRLO™ cladding has essentially the same irradiation creep as that for standard ZIRLO™. This conditional approval [conditions of the NRC staff's approval are listed in Section 5.0] is also based on the assumption that W will confirm (1) that there is no difference between compressive and tensile creep and (2) that the current creep models have sufficient conservative margin in the rod pressure analyses (level of conservatism to be provided to the NRC).

3.4 Fuel Rod Failure

SRP 4.2.II.A.2 states, "To meet the requirements of (a) GDC 10 as it relates to SAFDLs for normal operation, including AOOs, and (b) 10 CFR Part 100 as it relates to fission product releases for postulated accidents, fuel rod failure criteria should be given for all known fuel rod failure mechanisms."

In support of the NRC staff's review, PNNL evaluated the fuel rod failure mechanisms and the impact of Optimized ZIRLO™ on fuel failures. The NRC staff has reviewed and concurs with PNNL's assessment, provided below. Reference and section numbers within the PNNL text have been changed in order to integrate it into this SE.

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

3.4.1 Hydriding

Bases/Criteria – Internal hydriding as a cladding failure mechanism is precluded by controlling the level of hydrogen impurities in the fuel during fabrication; this is an early-in-life failure mechanism. The moisture level for the fuel in W fuel designs is limited to less than or equal to 20 ppm, and this specification is compatible with the American Society for Testing and Materials (ASTM) specification (Reference 22), which allows two micrograms of hydrogen per gram of *uranium (i.e., 2 ppm). The moisture level for the fuel in CE fuel designs is limited to a value less than 20 ppm.*

Evaluation – *Internal hydriding is not generally impacted by the introduction of a new cladding material unless its reaction with water or hydrogen is significantly different from previous Zircaloys. This is not the case for Optimized ZIRLO™ and standard ZIRLO™ cladding. PNNL concludes that the moisture limit on the fuel remains applicable for fuel rods clad with Optimized ZIRLO™ up to currently approved burnup levels.*

*W also has a limit of **[ ]** of hydrogen pickup due to waterside corrosion up to the current burnup limit for W fuel designs. Cladding hydrogen pickup limits are required to prevent excessive degradation of cladding mechanical properties due to hydrogen embrittlement by the formation of zirconium hydride platelets when hydrogen is released during the cladding oxidation process. It should be noted that there is in most cases a relationship between oxidation thickness and hydride levels. W has previously indicated (Reference 17) that their test results show that ZIRLO™ and Zircaloy-4 have essentially the same relationship of hydrogen pickup at an equivalent level of oxidation. W has also stated that process controls and texture acceptance tests assure that W cladding maintains the proper hydride orientation (References 3 and 17). These same process and texture controls apply to Optimized ZIRLO™. There is no hydrogen pickup limit due to waterside corrosion for [current] CE fuel designs.*

The NRC staff has imposed a condition (Section 5.0, Condition 3) that limits fuel rod waterside corrosion to resolve NRC staff and contractor concerns.

PNNL concludes that the W limit on cladding hydrogen pickup due to waterside corrosion is acceptable for Optimized ZIRLO™ applications in W and CE fuel designs up to the current burnup limits based on the above recommendations.

Internal hydriding is controlled by limiting the moisture content in the fuel. The W corrosion analysis methods and, therefore, hydrogen pickup due to corrosion for standard ZIRLO™ are applied to Optimized ZIRLO™. This appears to be conservative because Optimized ZIRLO™ corrosion and resulting hydrogen levels appear to be significantly lower than for standard ZIRLO™. In addition, W has committed to monitor oxidation up to currently approved burnup levels in the four plants (including one CE plant) with LTAs utilizing Optimized ZIRLO™. PNNL concludes that W has adequately addressed waterside oxidation and hydrogen levels for application of Optimized ZIRLO™ in W and CE fuel designs based on their commitment to measure waterside corrosion in their LTA program up to currently approved burnup levels.

3.4.2 Cladding Collapse

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

Evaluation – The cladding model that has a significant impact on the cladding collapse analysis is the irradiation creep model discussed in Section 3.2.10 above. W utilizes the irradiation creep model developed for standard ZIRLO™ cladding for application to irradiation creep of Optimized ZIRLO™ cladding for both W and CE fuel designs. W has claimed that there is no quantitative difference between Optimized ZIRLO™ and standard ZIRLO™ creep in-reactor based on out-of-reactor thermal creep data but W has no in-reactor irradiation creep data to support this conclusion. As noted in Section 3.2.10 above, thermal creep is not always directly proportional to in-reactor creep.

W has noted in their responses to the RAIs (response to RAI # 3.b) that there is an irradiation growth and creep program in Vogtle Unit 2 to measure the growth and creep rate of both Optimized ZIRLO™ and standard ZIRLO™ tubes (without fuel) along with tubes of their newer advanced alloys. W has committed to share the results of this data with the NRC as it becomes available and to notify the NRC if it demonstrates that the Optimized ZIRLO™ has different creep behavior from standard ZIRLO™. The first set of Optimized ZIRLO™ creep data from this program will be obtained in late 2004 or early 2005 that is prior to Optimized ZIRLO™ cladding being used in reload fuel. PNNL does notice that no creep data is planned for LTAs with Optimized ZIRLO™ cladding. While PNNL acknowledges that the controlled and well characterized in-reactor creep tests as those being performed in Vogtle will in most instances give more precise creep data than from LTAs, it is prudent to obtain some creep data from LTAs to verify that the controlled creep tests and the creep from more prototypical LTAs are consistent with each other.

PNNL concludes that W has addressed cladding creep collapse and conditional approval [conditions of the NRC staff's approval are listed in Section 5.0] is provided for Optimized ZIRLO™ for W and CE fuel designs based on W's commitment to collect irradiation creep data for Optimized ZIRLO™ that is applicable to W and CE fuel designs to confirm that this data is enveloped by the standard ZIRLO™ irradiation creep model. The definition of the Optimized ZIRLO™ data being enveloped by the standard ZIRLO™ irradiation creep model is that Optimized ZIRLO™ cladding has essentially the same irradiation creep as that for standard ZIRLO™.

3.4.3 Overheating of Cladding

Bases/Criteria - The W and CE fuel design basis for the prevention of fuel failures due to overheating is that there will be at least a 95% probability at a 95% confidence level that DNB will not occur on a fuel rod having the minimum DNB ratio during normal operation and AOOs. This design basis is consistent with the thermal margin criterion of Section 4.2 of the SRP. The use of Optimized ZIRLO™ in place of standard ZIRLO™ cladding does not impact the critical heat flux (CHF) correlations for these designs.

Evaluation - As stated in the SRP, Section 4.2, adequate cooling is assumed to exist when the thermal margin criterion to limit DNB or boiling transition in the core is satisfied. W thermal *hydraulic codes used to demonstrate that satisfactory thermal margin exists have not been changed for Optimized ZIRLO™ other than the Optimized ZIRLO™ thermal properties discussed in Section 3.2 above.*

3.4.4 Overheating of Fuel Pellets

Bases/Criteria – As a second method of avoiding cladding failure due to overheating, W precludes centerline pellet melting during normal operation and AOOs for W and CE fuel designs. This design limit is the same as given in the SRP. In order to ensure that this basis is met, W imposes a design limit on fuel temperatures for W and CE fuel designs such that there is a 95% probability that the peak linear heat generation rate rod will not exceed the fuel melting temperature. The melting temperature of unirradiated UO_2 *is assumed to be 5080EF and decreased by 58EF per 10,000 MWd/MTU. The melting temperature may be further reduced by the addition of burnable poisons. This design basis and limit are not impacted by use of Optimized ZIRLO™ in place of standard ZIRLO™ cladding.*

Evaluation – The W evaluation methods used to verify that the above fuel melting limit is met have not been changed for Optimized ZIRLO™ for W and CE fuel designs other than the changes to the Optimized ZIRLO™ thermal properties discussed in Section 3.2 above.

3.4.5 Pellet-Cladding Interaction (PCI)

Bases/Criteria - As indicated in Section 4.2 of the SRP, there are no generally applicable criteria for PCI failure. However, two acceptable criteria of limited application are presented in the SRP for PCI: 1) less than 1% transient-induced cladding strain, and 2) no centerline fuel melting. Both of these limits are used by W for W and CE fuel designs as discussed in Sections 3.3.2 and 3.4.4 of this SE and, therefore, have been addressed by W.

Evaluation - The W evaluation methods used to verify that the cladding strain and fuel melting limits are met have not been changed for Optimized ZIRLO™ for W and CE fuel designs other than the changes to the Optimized ZIRLO™ thermal properties discussed in Section 3.2 above.

3.4.6 Cladding Rupture

Bases/Criteria – There are no specific design limits associated with cladding rupture other than the 10 CFR 50, Appendix K requirement that the degree of swelling not be underestimated. The W and CE rupture models are an integral portion of the W and CE emergency core cooling system (ECCS) evaluation models for determining the peak cladding temperature (PCT) for the respective W and CE fuel designs. The W design basis also states that the degree of cladding swelling or ballooning not be underestimated. This design basis is not impacted by use of Optimized ZIRLO™ in place of standard ZIRLO™ cladding.

Evaluation - The high temperature creep and rupture models used by W in their LOCA-ECCS analysis are directly coupled to their models for cladding ballooning and flow blockage. A detailed discussion of the cladding ballooning and flow blockage models is provided in Section 3.5.3 below. W has proposed using the cladding rupture model for standard ZIRLO™ to be *applied to W and CE fuel designs using Optimized ZIRLO™ cladding. The following is a discussion of the W Optimized ZIRLO™ cladding rupture data used to support this W proposal.*

*W has performed single rod burst tests that measured burst pressure versus burst temperature at **[ ]** temperature ramp rates of **[ ]** for both Optimized ZIRLO™ and standard ZIRLO™ cladding for comparisons. The rods were pressurized at **[ ]** initial pressures of **[ ]** psig spanning the range of possible internal rod pressures from low to high burnup fuel. The existing ZIRLO™ model for burst temperature for a given burst pressure were also compared to both sets of data. Only **[ ]** data points were taken for standard ZIRLO™ cladding for reference for these tests but several other data points were available for standard ZIRLO™ from previous tests while **[ ]** data points were taken for Optimized ZIRLO™ cladding. The Optimized ZIRLO™ data appeared to compare quite well against the existing burst model used for standard ZIRLO™ and provided a better comparison than the **[ ]** data points from standard ZIRLO™ cladding, but when previously measure data from past burst tests were included there did not appear to be a significant difference between Optimized ZIRLO™ and standard ZIRLO™ cladding burst behavior. The previous burst tests on standard ZIRLO™ were performed in the early 1990s when this cladding material was submitted to the NRC for review.*

*W also provided data from high temperature creep tests of Optimized ZIRLO™ and standard ZIRLO™ cladding where the cladding temperature was held constant at hoop stresses between **[ ]** MPa and creep strain was measured versus time resulting in an estimated steady-state creep rate to be applied to LOCA and other accident analyses. This particular testing method is not very applicable to transients where the cladding temperature changes rapidly with time such as large break LOCA because holding the cladding at high constant temperatures for relatively long times subjects the cladding to more oxidation than if the cladding temperature is at high temperature for only several seconds. The high temperature W creep tests demonstrated that at temperatures above **[ ]** the creep results for standard ZIRLO™ differed from previous creep results under a vacuum (non-oxidizing environment) due to the oxidation and oxygen diffusion into the metal. The important observation from these tests is that they demonstrated that Optimized ZIRLO™ creep strains are similar to standard ZIRLO™ at high temperatures. This is also consistent with the results of the high temperature rupture/burst tests that show no difference between Optimized ZIRLO™ and standard ZIRLO™.*

PNNL concludes that cladding rupture of Optimized ZIRLO™ and standard ZIRLO™are similar and the use of the high temperature creep and rupture models for standard ZIRLO™ for application to W and CE fuel designs with Optimized ZIRLO™ cladding is acceptable.

3.4.7 Fuel Rod Mechanical Fracturing

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

<u>Evaluation</u> - The discussion of the SSE-LOCA loading analysis is given in Section 3.5.4 of this SE.

3.5 Fuel Coolability

SRP 4.2.II.A.3 states, "To meet the requirements of GDC 27 and 35 as they relate to control rod insertability and core coolability for postulated accidents, fuel coolability criteria should be given for all damage mechanisms."

In support of the NRC staff's review, PNNL evaluated core coolability and the impact of Optimized ZIRLO™ properties on transient fuel behavior. The NRC staff has reviewed and concurs with PNNL's assessment, provided below. Reference and section numbers within the PNNL text have been changed in order to integrate it into this SE.

In addition to the PNNL evaluation, the NRC staff has considered the applicability of 10 CFR 50.46 ECCS performance criteria and 10 CFR Part 50 Appendix K to Optimized ZIRLO™. In light of recent speculation within the international research community concerning the applicability of the 10 CFR 50.46 criteria to ZrNb alloys, the NRC staff felt that further review was warranted.

In Addendum 1, Westinghouse provided metal-water reaction and residual-ductility testing results. Section B.15 test results provide evidence that at **[ ]**, the metal-water reaction rates of Optimized ZIRLO™ are bounded by the conservative Appendix K Baker-Just correlation and fit the best-estimate Cathcart-Pawel correlation. Further, Section B.16 provides evidence via ring-compression tests that for the same temperature range residual ductility was maintained up to the 17 percent equivalent clad reacted (ECR) limit in 10 CFR 50.46. Addendum 1 concludes that retained ductility of Optimized ZIRLO™ is effectively the same as that of standard ZIRLO™.

The international research community has also raised concerns related to testing conditions, test apparatus, and figure-of-merit used to judge post-LOCA residual ductility. To address these concerns, the NRC staff has reviewed recent test results from the ongoing NRC Research High Burnup Program at Argonne National Laboratories (ANL). ANL's test results provide an independent assessment of the post-LOCA performance of unirradiated standard ZIRLO™ based upon different testing conditions and procedures. Specifically, ANL testing included 1000EC, 1100EC, and 1200EC double-sided steam oxidation and post-quench ring-compression tests at room temperature and at 135EC based upon offset strain (as opposed to total displacement). ANL's testing confirms the applicability of Baker-Just and Cathcart Pawel correlations and demonstrate sufficient residual ductility for unirradiated standard ZIRLO™ up to 17 percent ECR.

The ongoing ANL program is also investigating in-reactor irradiation and corrosion effects on post-LOCA residual ductility. Early tests have linked a reduction in ductility with in-service hydriding. While a conclusive correlation between in-service effects has not yet been established, it is reassuring that the waterside corrosion rate (and associated hydrogen pickup) for Optimized ZIRLO™ is lower than standard ZIRLO™. Hence, for a given burnup level and fuel duty, Optimized ZIRLO™ should be no more susceptible to in-service effects than standard ZIRLO™.

Based upon the test results documented in Addendum 1, PNNL's evaluation (provided below), and the independent test results from ANL, the NRC staff concludes that the 10 CFR 50.46 ECCS performance criteria, Appendix K Baker-Just correlation, and best-estimate Cathcart-Pawel correlation are applicable to Optimized ZIRLO™.

For postulated and design basis accidents such as LOCA in which severe fuel damage might occur, core coolability must be maintained as required by several GDCs (e.g., GDC 27 and 35). In the following paragraphs, limits and methods used to assure that coolability is maintained are discussed for the severe damage mechanisms listed in the SRP.

3.5.1 Fragmentation of Embrittled Cladding

Bases/Criteria – The LOCA is the design basis event resulting in the most severe occurrence of cladding oxidation and possible fragmentation during an accident as a result of a significant degree of cladding oxidation during a LOCA. In order to limit the effects of cladding oxidation for a LOCA, W uses an acceptance criteria of 2200EF (1204EC) on peak cladding temperature (PCT) and 17% on maximum cladding oxidation for W and CE fuel designs as prescribed by 10 CFR 50.46.

*For the locked rotor accident, W uses a PCT criterion of **[ ]** for W fuel designs because the temperature history for such an event is much shorter than that of a LOCA. The W **[ ]** PCT limit was selected taking into consideration the short time (a few seconds) that the fuel is calculated to be in DNB for a locked rotor type event and the fact that the PCT and total metal-water reaction at the fuel hot spot is not expected to impact fuel coolable geometry. The NRC has approved (Reference 23) the **[ ]** PCT limit for short-term under-cooling events such as locked rotor as an acceptable coolability limit for W fuel designs with Zr-4 up to current burnup levels; however, W has not provided high temperature oxidation data for Optimized ZIRLO™ at **[ ]**. ANL has speculated that the oxidation of standard ZIRLO™ and Zr-4 were similar up to 2732EF (1500EC); however, no oxidation data at this temperature was provided by ANL nor W to support this conclusion (Reference 24).*

*W has provided high temperature oxidation for both Optimized ZIRLO™ and standard ZIRLO™ up to **[ ]** that demonstrates that the corrosion of both of these two materials is similar to Zr-4. From this data PNNL can conclude that for a locked rotor accident that a **[ ]** PCT limit is acceptable. Should W wish to increase this temperature limit to **[ ]** for Optimized ZIRLO™ (similar to that for Zr-4) they will need to obtain oxidation data up to this temperature to demonstrate the rate of Optimized ZIRLO™ oxidation is similar to or less than for Zr-4.*

The NRC currently does not have a cladding temperature limit on the severe reactivity insertion accident (RIA), such as a control rod (RCCA [rod cluster control assembly]) ejection accident, however, new coolability limits are being considered for this event.

Evaluation - The Baker-Just equation for the Zircaloy-4 water reaction rate is used by W to determine the amount of cladding oxidation for Zircaloy-4, standard ZIRLO™ and Optimized ZIRLO™ for W and CE fuel designs during a LOCA. The Baker-Just equation is prescribed in 10 CFR Part 50, Appendix K.

*W has measured the high temperature oxidation rate of unirradiated standard ZIRLO™ and Optimized ZIRLO™ at temperatures of **[ ]**. These results show nearly identical corrosion rates at these temperatures but it should be noted that only **[ ]** measurements were performed with Optimized ZIRLO™ at each of these temperatures. A comparison of these oxidation results to the Baker-Just equation has shown that this data is conservatively bounded by the Baker-Just equation. Therefore, PNNL concludes that the use of the Baker-Just equation for Optimized ZIRLO™ oxidation during a LOCA for W and CE fuel designs is acceptable.*

As noted above in Sections 3.2.2, 3.2.3 and 3.2.4, that the Optimized ZIRLO™ properties of thermal expansion, thermal conductivity and specific heat are significantly different than those currently used for accident analyses. W was questioned on what effect these differences have on several accident analyses where heat transfer is important in determining the outcome of the accident. W responded with some examples of results from large break LOCAs with maximum PCTs occurring during early and late reflood with these three properties modified to closely match the Optimized ZIRLO™ data. They also provided an example analysis for small break LOCAs for both W and CE designed plants with the thermal expansion, thermal conductivity and specific heat all changed to closely match the Optimized ZIRLO™ data.

*These W results demonstrated that for those analyses when the Optimized ZIRLO™ data were used the greatest change in PCTs occurred when PCTs were maximum early in the accident such as in blowdown or early in reflood. The one example provided (a W plant) of the combined effects of specific heat, thermal conductivity and thermal expansion for a plant with maximum PCTs during early reflood demonstrated that the PCTs increased by **[ ]** where specific heat contributes **[ ]** of this increase. W claimed that this deviation in PCT is small. It should be noted that a **[ ]** increase in PCT is not small for those plants with PCTs close to the 2200EF limit. In addition, whether this is a bounding analysis for maximum PCTs during early reflood cannot be confirmed given that only one analysis is performed for one plant (no CE plants) with early reflood even if W believes this is one of their limiting plants. PNNL further noted that using material property correlations that are known to be significantly different from property data for a given material is not good practice for safety analyses because designs and operation change with time such that their impact on safety analyses may change with time.*

As a result, W has agreed to use an empirical fit to Optimized ZIRLO™ specific heat data for analyses of both W plants licensed with LOCBART and CE plants licensed with STRIKIN-II that have a limiting PCT that occurs in blowdown or early reflood when Optimized ZIRLO™ is introduced to these plants. W has also committed to including the empirical fit to Optimized ZIRLO™ specific heat data for all plants using Optimized ZIRLO™ if a LOCBART or STRIKIN-II calculation is being performed to support some other plant or fuel rod design changes irregardless of the PCT timing. PNNL concludes that this is acceptable for Optimized ZIRLO™.

An RAI requested W to also examine those accidents where the phase transition temperature is exceeded other than for LOCA analyses and to determine what the effect of the use of Optimized ZIRLO™ versus the using standard ZIRLO™ or Zr-4 models would be on PCT results for these transients. W responded that there were only two events that resulted in PCTs above the $\alpha \div \alpha + \beta$ transition temperature and these events were the locked rotor and RCCA Ejection (Hot Full Power and Hot Zero Power, respectively). W has performed analyses for these events that show the impact of the use of Optimized ZIRLO™ fuel cladding in place of standard ZIRLO™ was negligible. PNNL concludes that the use of Optimized ZIRLO™ has no significant impact on the locked rotor and RCCA ejection events.

3.5.2 Violent Expulsion of Fuel

Bases/Criteria - In a severe reactivity insertion accident (RIA), such as a control rod ejection accident, large and rapid deposition of energy in the fuel could result in melting, fragmentation, and dispersal of fuel. The mechanical action associated with fuel dispersal might be sufficient to destroy the fuel cladding and rod bundle geometry and provide significant pressure pulses in the primary system. To limit the effects of an RIA event, Regulatory Guide 1.77 (Reference 25) recommends that the radially-averaged energy deposition at the hottest axial location be restricted to less than 280 cal/g and the onset of DNB is assumed to be the failure limit. It is noted that the NRC staff are currently reviewing both the 280 cal/gm limit and the limit for fuel failure and they may be decreased to a lower limit at high burnup levels. Recent RIA testing has indicated that fuel expulsion and fuel failure may occur before the 280 cal/gm limit and the onset of DNB, respectively (References 26 and 27). The NRC currently has under review proposed new limits submitted by the Electric Power Research Institute (EPRI) such that the issue of RIA limits will be covered by the EPRI review and is not covered as part of this review.

The W design criterion for fuel expulsion for this event is lower than that specified in Regulatory Guide 1.77, such that the peak fuel enthalpy for the hottest axial fuel rod location shall not exceed 200 cal/gm. For CE fuel designs there are two additional criteria for an RIA event; 1) no fuel melting, and 2) that peak RCS pressures do not cause clad stresses to exceed the faulted condition stress limits. Therefore, PNNL concludes that W design limits for fuel dispersal are acceptable at this time for application to Optimized ZIRLO™.

Evaluation - The W analysis methods for RIA events are not impacted by the use of Optimized ZIRLO™ other than the changes to the Optimized ZIRLO™ thermal properties discussed in Section 3.2 above and, therefore, remain acceptable for application to W and CE fuel designs.

3.5.3 Cladding Ballooning and Flow Blockage

Bases/Criteria - Zircaloy cladding will balloon (swell) under certain combinations of temperature, heating rate, and stress during a LOCA. There are no specific design limits associated with cladding ballooning other than the 10 CFR Part 50, Appendix K requirement that the degree of swelling not be underestimated. The W design limit state that the models utilize applicable test data in such a way as to properly estimate the pre-rupture clad strain, the rupture (burst) strain at the location of clad rupture and not underestimate the assembly flow blockage. For CE fuel designs, the only requirement is to not underestimate assembly flow blockage. These design *limits are consistent with the Appendix K requirement of not underestimating assembly flow blockage.*

*Evaluation - The W cladding ballooning and flow blockage model is directly coupled to the cladding rupture temperature model for the LOCA-ECCS analysis. W has performed single rod burst tests to measure burst strain as a function of burst temperature for both Optimized ZIRLO™ and standard ZIRLO™ cladding for comparisons. These single rods tests were performed at **[ ]** initial pressures of **[ ]** psig to provide data in the α, α+β, and β regimes encountered for low and high burnup fuel and at heating rates of **[ ]**. The burst strain is a function of the burst temperature (phase transition temperature) and cladding oxidation. For example, the burst strains are high in the α phase and drops significantly when the α+β region starts and then increases again when β phase transformation is more than **[ ]** complete. The burst strains again drop at temperatures above 1750EF in the β phase due to oxidation causing cladding embrittlement. The burst strain and burst temperature data for Optimized ZIRLO™ are very similar to those for standard ZIRLO™.*

W has a burst strain versus burst temperature curve (ballooning model) for standard ZIRLO™ based on single rod burst data from standard ZIRLO™ cladding presented in their original submittal for standard ZIRLO™ in the early 1990s. This burst strain versus burst temperature curve and the data for standard ZIRLO™ were compared to the current Optimized ZIRLO™ data showing reasonably good agreement, but on average lower failure strains were observed in Optimized ZIRLO™. W proposes to continue to use the burst strain versus burst temperature and flow blockage curves for standard ZIRLO™ for application to Optimized ZIRLO™ cladding for both W and CE fuel designs. PNNL concludes that the use of standard ZIRLO™ burst strain versus burst temperature and flow blockage curves for application of Optimized ZIRLO™ in W and CE fuel designs is acceptable based on the data comparisons provided.

An explanation is provided in the following narrative of how the rupture model (burst temperature versus burst pressure) curve is used in conjunction with the W cladding ballooning model (burst strain versus burst temperature) to determine flow blockage. The rod initial internal pressure at the start of an accident is known based on input from the W steady-state code, PAD 4.0 from steady-state operation, this is used in the LOCA code for the hot assembly average rod to determine burst temperature from the rupture model. The burst temperature is then used to determine burst strain from the ballooning model. The burst strain is then used to determine flow blockage at the rupture location using the W flow blockage curves versus cladding strain. The W flow blockage curve for standard ZIRLO™ is derived from the standard ZIRLO™ ballooning model based on the approach of NUREG-0630 (Reference 28) for relating cladding strain to blockage using the geometry of the fuel rods and assembly.

PNNL concludes that the ballooning and flow blockage models for standard ZIRLO™ are applicable to Optimized ZIRLO™ and are consistent with those in NUREG-0630 (Reference 28) and, therefore, remain acceptable for Optimized ZIRLO™ applications in W and CE fuel designs.

3.5.4 Fuel Assembly Structural Damage From External Forces

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

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

Evaluation - W has proposed to use Optimized ZIRLO™ in their spacer grids of W and CE fuel designs. The spacer grids are one of the main structural components maintaining fuel geometry and control rod insertability due to loading from seismic-LOCA accidents, therefore, the structural strength of this component is important for these accidents. W has measured the dynamic crush strength and stiffness of Optimized ZIRLO™ grids at 600EF and compared them to the dynamic crush strength and stiffness of standard ZIRLO™ spacer grids at the same operating temperature. These tests show that the Optimized ZIRLO™ has a little higher crush strength, stiffness and seismic factors ([ ]) than the standard ZIRLO™ spacer grids, but the crush test limits have not been defined for each design application for Optimized ZIRLO™. Therefore, the use of Optimized ZIRLO™ in spacer grids to replace either standard ZIRLO™ or Zr-4 spacer grids is dependent on the design, i.e., a design specific issue, and needs further evaluation [see Section 3.7].

3.6 Fuel Surveillance

Westinghouse's position is that Optimized ZIRLO™ falls within the original definition of ZIRLO™ and that the slight change in material composition would not significantly impact material performance, other than the desired improvement in corrosion resistance. Based on this position, Addendum 1 provides only a minimum amount of irradiated data for Optimized ZIRLO™.

Due to changes in both material composition and final annealed microstructure, the NRC staff has concerns that the in-reactor performance of Optimized ZIRLO™ may differ from the established performance of standard ZIRLO™. Several RAIs were issued by the NRC staff to address the lack of an adequate irradiated database in Addendum 1. In response to these RAIs, Westinghouse has committed to provide the NRC staff with a summary of the irradiated test results from both their Vogtle Creep and Growth Program and from LTA Programs at Byron, Calvert Cliffs, Millstone, and Catawba. Along with the data transmittal, Westinghouse will validate the fuel performance models against this recent irradiated data. Section 5.0 of this SE lists the associated conditions on the approval of Optimized ZIRLO™. A tentative schedule for completion of these irradiation programs is included in response to RAI #3 and #11 (Reference 3).

The NRC staff's review of any new clad alloy relies heavily on demonstrated material properties and in-reactor performance data. The NRC staff has approved Optimized ZIRLO™ fuel cladding based upon (1) similarities with standard ZIRLO™, (2) demonstrated material performance in Addendum 1 and RAI responses, and (3) a commitment to provide irradiated data and validate fuel performance models ahead of burnups achieved in batch applications. The NRC staff's approval of Optimized ZIRLO™, with its lack of an adequate irradiated database, should in no way represent an acceptable licensing path for future alloys.

3.7 Fuel Assembly Components

Following discussions with the NRC, Westinghouse decided to remove material from Addendum 1 describing the application of Optimized ZIRLO™ as fuel assembly components. Therefore, the staff's evaluation focuses on the use of Optimized ZIRLO™ as fuel rod cladding, rather than on its use for assembly components. Section 3.7 of the "-P" version of Addendum 1 will be removed prior to issuing the final "-P-A" version.

4.0 CONCLUSION

The stated purpose of Addendum 1 is to obtain NRC staff approval of an extension to the regulatory definition of ZIRLO™ as approved in WCAP-12610-P-A and CENPD-404-P-A. This extension would expand the allowable material composition of ZIRLO™. However, due to the inclusion of ZIRLO™ in 10 CFR 50.46, any alteration to its regulatory definition will necessitate rulemaking and may not be accomplished with an addendum to the previously approved TRs. As such, the NRC staff does not approve the proposed extension to the regulatory definition of ZIRLO™. The NRC staff's review instead focused on the acceptability of Optimized ZIRLO™'s material properties and performance as well as Westinghouse's ability to accurately model its in-reactor behavior.

The NRC staff recognizes the material referred to in Addendum 1 as Optimized ZIRLO™ based upon the regulatory definition and performance in Section 3.1. The NRC staff's review and approval of Optimized ZIRLO™ is limited to applications as fuel rod cladding only.

The NRC staff reviewed the effects of Optimized ZIRLO™ using the appropriate fuel design requirements of SRP 4.2 and 10 CFR Part 50, Appendix A, General Design Criteria and found that the TR provided reasonable assurance that under both normal and accident conditions, Westinghouse and CE fuel assembly designs implementing Optimized ZIRLO™ fuel cladding would be able to safely operate and comply with NRC regulations.

The NRC staff's review of any new clad alloy relies heavily on demonstrated material properties and in-reactor performance data. The NRC staff has approved Optimized ZIRLO™ fuel cladding based upon (1) similarities with standard ZIRLO™, (2) demonstrated material performance in Addendum 1 and in response to RAIs, and (3) a commitment to provide irradiated data and validate fuel performance models ahead of burnups achieved in batch applications. The NRC staff's approval of Optimized ZIRLO™, with its lack of an adequate irradiated database, should in no way represent an acceptable licensing path for future alloys.

Based upon its review of this TR, the NRC staff finds Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A acceptable with the recognition that the NRC staff does not approve the proposed extension to the regulatory definition of ZIRLO™. Licensees referencing this TR will need to comply with the conditions and limitations listed below in Section 5.0 of this SE.

5.0 CONDITIONS AND LIMITATIONS

Licensees referencing Addendum 1 to implement Optimized ZIRLO™ must ensure compliance with the following conditions and limitations:

1. Until rulemaking to 10 CFR Part 50 addressing Optimized ZIRLO™ has been completed, implementation of Optimized ZIRLO™ fuel clad requires an exemption from 10 CFR 50.46 and 10 CFR Part 50 Appendix K.

2. The fuel rod burnup limit for this approval remains at currently established limits: 62 GWd/MTU for Westinghouse fuel designs and 60 GWd/MTU for CE fuel designs.

3. The maximum fuel rod waterside corrosion, as predicted by the best-estimate model, will **[** **]** of hydrides for all locations of the fuel rod.

4. All the conditions listed in previous NRC SE approvals for methodologies used for standard ZIRLO™ and Zircaloy-4 fuel analysis will continue to be met, except that the use of Optimized ZIRLO™ cladding in addition to standard ZIRLO™ and Zircaloy-4 cladding is now approved.

5. All methodologies will be used only within the range for which ZIRLO™ and Optimized ZIRLO™ data were acceptable and for which the verifications discussed in Addendum 1 and responses to RAIs were performed.

6. The licensee is required to ensure that Westinghouse has fulfilled the following commitment: Westinghouse shall provide the NRC staff with a letter(s) containing the following information (Based on the schedule described in response to RAI #3 [Reference 3]):

   a. Optimized ZIRLO™ LTA data from Byron, Calvert Cliffs, Catawba, and Millstone.

      i. Visual
      ii. Oxidation of fuel rods
      iii. Profilometry
      iv. Fuel rod length
      v. Fuel assembly length

   b. Using the standard and Optimized ZIRLO™ database including the most recent LTA data, confirm applicability with currently approved fuel performance models (e.g., measured vs. predicted).

Confirmation of the approved models' applicability up through the projected end of cycle burnup for the Optimized ZIRLO™ fuel rods must be completed prior to their initial batch loading and prior to the startup of subsequent cycles. For example, prior to the first batch application of Optimized ZIRLO™, sufficient LTA data may only be available to confirm the models' applicability up through 45 GWd/MTU. In this example, the licensee would need to confirm the models up through the end of the initial cycle. Subsequently, the licensee would need to confirm the models, based upon the latest LTA data, prior to re-inserting the Optimized ZIRLO™ fuel rods in future cycles. Based upon the LTA schedule, it is expected that this issue may only be applicable to the first few batch implementations since sufficient LTA data up through the burnup limit should be available within a few years.

7. The licensee is required to ensure that Westinghouse has fulfilled the following commitment: Westinghouse shall provide the NRC staff with a letter containing the following information (Based on the schedule described in response to RAI #11 [Reference 3]):

   a. Vogtle growth and creep data summary reports.

   b. Using the standard ZIRLO™ and Optimized ZIRLO™ database including the most recent Vogtle data, confirm applicability with currently approved fuel performance models (e.g., level of conservatism in W rod pressure analysis, measured vs. predicted, predicted minus measured vs. tensile and compressive stress).

   Confirmation of the approved models' applicability up through the projected end of cycle burnup for the Optimized ZIRLO™ fuel rods must be completed prior to their initial batch loading and prior to the startup of subsequent cycles. For example, prior to the first batch application of Optimized ZIRLO™, sufficient LTA data may only be available to confirm the models' applicability up through 45 GWd/MTU. In this example, the licensee would need to confirm the models up through the end of the initial cycle. Subsequently, the licensee would need to confirm the models, based upon the latest LTA data, prior to re-inserting the Optimized ZIRLO™ fuel rods in future cycles. Based upon the LTA schedule, it is expected that this issue may only be applicable to the first few batch implementations since sufficient LTA data up through the burnup limit should be available within a few years.

8. The licensee shall account for the relative differences in unirradiated strength (YS and UTS) between Optimized ZIRLO™ and standard ZIRLO™ in cladding and structural analyses until irradiated data for Optimized ZIRLO™ have been collected and provided to the NRC staff.

   a. For the Westinghouse fuel design analyses:

      i. The measured, unirradiated Optimized ZIRLO™ strengths shall be used for BOL analyses.

ii. Between BOL up to a radiation fluence of 3.0 x 10^{21} n/cm^2 (E>1MeV), pseudo-irradiated Optimized ZIRLO™ strength set equal to linear interpolation between the following two strength level points: At zero fluence, strength of Optimized ZIRLO™ equal to measured strength of Optimized ZIRLO™ and at a fluence of 3.0 x 10^{21} n/cm^2 (E>1MeV), irradiated strength of standard ZIRLO™ at the fluence of 3.0 x 10^{21} n/cm^2 (E>1MeV) minus 3 ksi.

iii. During subsequent irradiation from 3.0 x 10^{21} n/cm^2 up to 12 x 10^{21} n/cm^2, the differences in strength (the difference at a fluence of 3 x 10^{21} n/cm^2 due to tin content) shall be decreased linearly such that the pseudo-irradiated Optimized ZIRLO™ strengths will saturate at the same properties as standard ZIRLO™ at 12 x 10^{21} n/cm^2.

b. For the CE fuel design analyses, the measured, unirradiated Optimized ZIRLO™ strengths shall be used for all fluence levels (consistent with previously approved methods).

9. As discussed in response to RAI #21 (Reference 3), for plants introducing Optimized ZIRLO™ that are licensed with LOCBART or STRIKIN-II and have a limiting PCT that occurs during blowdown or early reflood, the limiting LOCBART or STRIKIN-II calculation will be rerun using the specified Optimized ZIRLO™ material properties. Although not a condition of approval, the NRC staff strongly recommends that, for future evaluations, Westinghouse update all computer models with Optimized ZIRLO™ specific material properties.

10. Due to the absence of high temperature oxidation data for Optimized ZIRLO™, the Westinghouse coolability limit on PCT during the locked rotor event shall be **[ ]**.

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