Westinghouse Non-Proprietary Class 3

WCAP-14342-A & CENPD-404-NP-A
Addendum 1-A

July 2006

Optimized ZIRLO™

Westinghouse

Westinghouse Non-Proprietary Class 3

WCAP-14342-A & CENPD-404-NP-A
Addendum 1-A

Optimized ZIRLO™

Original Version: February 2003

Prepared by: H. H. Shah

Approved Version: July 2006

Compiled by: P. Schueren*
Fuel Engineering Licensing

Approved: R. B. Sisk*, Manager
Fuel Engineering Licensing

*Electronically approved records are authenticated in the Electronic Document Management System.

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

Table of Contents

Section A

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

June 10, 2005

Mr. James A. Gresham, Manager
Regulatory Compliance and Plant Licensing
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

SUBJECT: FINAL SAFETY EVALUATION FOR ADDENDUM 1 TO TOPICAL REPORT WCAP-12610-P-A AND CENPD-404-P-A, "OPTIMIZED ZIRLO™" (TAC NO. MB8041)

Dear Mr. Gresham:

On February 14, 2003, as supplemented by letters dated February 3, August 4, and October 29, 2004, and April 19, 2005, Westinghouse Electric Company (Westinghouse) submitted Addendum 1 to Topical Report (TR) WCAP-12610-P-A and CENPD-404-P-A, "Optimized ZIRLO™," to the Nuclear Regulatory Commission (NRC) staff for review. Because of the extensive comments on the first draft safety evaluation (SE), a second draft version was issued. The staff's disposition of Westinghouse's comments on the first and second draft SEs are discussed in the attachment to the final SE enclosed with this letter.

The staff has found that Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, "Optimized ZIRLO™," is acceptable for referencing in licensing applications to the extent specified and under the limitations delineated in the TR and in the enclosed SE. The SE defines the basis for acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that Westinghouse publish accepted proprietary and non-proprietary versions of this TR within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed SE after the title page. They must be well indexed such that information is readily located. Also, they must contain historical review information, including NRC requests for additional information and your responses. The accepted versions shall include a "-A" (designating accepted) following the TR identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, Westinghouse and/or licensees referencing it will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,

Herbert N. Berkow, Director
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 700

Enclosures:
1. Non-Proprietary Safety Evaluation
2. Proprietary Safety Evaluation
3. Comments Table

cc w/encls:
Mr. Gordon Bischoff, Manager
Owners Group Program Management Office
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

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

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 <u>TECHNICAL EVALUATION</u>

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, $\alpha \rightarrow \beta$ 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 1100°F. 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 3.0×10^{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 2.5×10^{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 2.5×10^{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 3.0×10^{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 $\alpha \rightarrow \beta$ Phase Transformation Temperatures

The $\alpha \rightarrow \alpha + \beta$ and $\alpha + \beta \rightarrow \beta$ 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 $\alpha \rightarrow \alpha + \beta$ 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 5080°F and decreased by 58°F 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).

Evaluation - 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 1000°C, 1100°C, and 1200°C double-sided steam oxidation and post-quench ring-compression tests at room temperature and at 135°C 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 2200°F (1204°C) 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 2732°F (1500°C); 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 2200°F 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 $\alpha \rightarrow \alpha + \beta$ 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 1750°F 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 600°F 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 [
].

6.0 REFERENCES

1. Letter from H. A. Sepp (Westinghouse) to U.S. Nuclear Regulatory Commission, "Submittal of Addendum 1 to WCAP-12610-P-A/WCAP-14342-A and CENPD-404-P-A/CENPD-404-NP-A, 'Addendum 1 to WCAP-14342-P-A and CENPD-404-P-A Optimized ZIRLO™', for NRC Review and Approval," LTR-NRC-03-2, February 14, 2003 (ADAMS Accession No. ML030520455).

2. Letter from J. A. Gresham (Westinghouse) to U.S. Nuclear Regulatory Commission, "Westinghouse Responses to NRC Request for Additional Information (RAIs) on Optimized ZIRLO™ Topical - Addendum 1 to WCAP-12610-P-A," LTR-NRC-04-12, February 3, 2004 (ADAMS Accession No. ML040420660).

3. Letter from J. A. Gresham (Westinghouse) to U.S. Nuclear Regulatory Commission, "Westinghouse Responses to NRC Request for Additional Information (RAIs) on

Optimized ZIRLO™ Topical - Addendum 1 to WCAP-12610-P-A," LTR-NRC-04-44, August 4, 2004 (ADAMS Accession No. ML042240408).

4. Letter from J. A. Gresham (Westinghouse) to U.S. Nuclear Regulatory Commission, "Response to NRC Request for Additional Information #3 for Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™," LTR-NRC-04-63, October 29, 2004 (ADAMS Accession No. ML043080395).

5. NUREG-0800, Standard Review Plan, Section 4.2, "Fuel System Design," Draft Revision 3, April 1996.

6. American Society of Mechanical Engineers. 1983 Edition. "Section III, Nuclear Power Plant Components." ASME Code. American Society of Mechanical Engineers, New York.

7. R. S. Kemper and D. L. Zimmerman, "Neutron Irradiation Effects on the Tensile Properties of Zircaloy-2," HW-52323, General Electric Company (1957).

8. D .H. Hardy, "The Effect of Neutron Irradiation on the Mechanical Properties of Zirconium Alloy Fuel Cladding in Uniaxial and Biaxial Tests" *Irradiation Effects on Structural Alloys for Nuclear Reactor Applications, ASTM STP 484*, p. 215, American Society for Testing and Materials, Toronto, Canada (1970).

9. Garde, A. M. September 1986. Hot Cell Examination of Extended Burnup Fuel from Fort Calhoun. DOE/ET/34030-11, CEND-427, Combustion Engineering, Inc., Windsor, Connecticut.

10. Newman, L. W. et al. 1986. The Hot Cell Examination of Oconee Fuel Rods After Five Cycles of Irradiation. DOE/ET/34212-50 (BAW-1874), Babcock & Wilcox, Lynchburg, Virginia.

11. Garde, A. M. 1989. "Effects of Irradiation and Hydriding on the Mechanical Properties of Zircaloy-4 at High Fluence." In Zirconium in the Nuclear Industry: Eighth International Symposium, ASTM STP 1023, pp. 548-569, Eds. L.F.P. VanSwam and C. M. Eucken. American Society for Testing and Materials, Philadelphia, Pennsylvania.

12. F.Garzarolli, H. Stehle, E. Steinberg, "Behavior and Properties in Power Reactors: A Short Review of Pertinent Aspects in LWR Fuel," Zirconium in the Nuclear Industry: Eleventh International Symposium, ASTM STP 1295, 1996, pp.12-32.

13. E.R. Bradley, A.L. Nystrom, "Microstructure and Properties of Corrosion-Resistant Zirconium-Tin-Iron-Chromium-Nickle Alloys," Zirconium in the Nuclear Industry, Tenth international symposium, ASTM STP 1245, 1994, pp.483-498.

14. C. Nam, B.K. Choi, M.H. Lee, Y.H. Jeong, "Creep strength of Zircaloy-4 cladding depending on applied stress and annealing temperature," Journal of Nuclear Materials 305, 2002, pp. 70-76.

15. Letter, H. A. Sepp (Westinghouse) to U.S. Nuclear Regulatory Commission, "Westinghouse Improved Performance Analysis and Design Model (PAD4.0), WCAP-15063-P, Revision 1," NSBU-NRC-99-5956, dated November 18, 1999.

16. Tsukuda, Y., Y. Kosaka, T. Kido, S. Doi, T. Sendo, P. Gonzales, and J.M. Alonso (Japan-NUPEC,NDC, MHI, and KEPCO, and Spain-ENDESA and ENUSA), 2003. "Perfomance of Advanced Fuel Materials for High Burnup," in ENS TopFuel 2003 Meeting, March 16-19, 2003, Wurzburg, Germany.

17. Davidson, S. L., et al. April 1995. VANTAGE+ Fuel Assembly Reference Core Report. WCAP-12610-P-A (Proprietary), Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

18. Kersting, P. J. (Editor). July 1982. *Extended Burnup Evaluation of Westinghouse Fuel.* WCAP-10125-P-A (Proprietary), Westinghouse Electric Corporation.

19. Kaiser, R. S., W. J. Leech, and A. L. Casadei, "The Fuel Duty Index (FDI) – A New Measure of Fuel Rod Cladding Performance," *LWR Fuel Performance Meeting,* Vol. 2, p. 393, Park City, USA (2000).

20. Westinghouse Electric Company. November 2001. Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs, CENPD-404-P-A.

21. Risher, D.H. (Editor). 1977. Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis. WCAP-8963 (Proprietary) and WCAP-8964 (Non-Proprietary).

22. American Society for Testing and Materials. 1977. Standard Specifications for Sintered Uranium Dioxide Pellets. ASTM Standard C776-76, Part 45, American Society for Testing and Materials, Philadelphia, Pennsylvania.

23. Davidson, D.L., and J.A.Iorii. May1982. Reference Core Report 17x17 Optimized Fuel Assembly. WCAP-9500-A (Proprietary), Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

24. Letter, M. Billone (ANL) to H. Scott (NRC), "Subject Steam Oxidation Kinetics of Zircaloy," June 11, 2002.

25. U.S. Nuclear Regulatory Commission. 1974. Assumptions Used for Evaluating a Control Rod Ejection Accident for Pressurized Water Reactors. Regulatory Guide 1.77, U.S. Nuclear Regulatory Commission, Washington, D.C.

26. Schmitz, F., et. al., March 1996. "New Results from Pulse Test in the CABRI Reactor," Proceedings of the 23rd Water Reactor Safety Information Meeting October 23-25,1995.

27. Fuketa, T., et. al., March 1996. "New Results from the NSRR Experiments with High Burnup Fuel," Proceedings of the 23rd Water Reactor Safety Meeting, October 23-25, 1995.

28. Powers, D. A., and R. O. Meyer. April 1980. Cladding, Swelling, and Rupture Models for LOCA Analysis. NUREG-0630, U.S. Nuclear Regulatory Commission, Washington, D.C.

29. Letter from U.S. Nuclear Regulatory Commission to P. W. Richardson (W), "Safety Evaluation of Topical Report CENPD-404-P, Revision 0, 'Implementation of ZIRLO Material Cladding in CE Nuclear Power Fuel Assembly Designs'," September 12, 2001 (ADAMS Accession No. ML012670041).

Principal Contributors: Paul Clifford, NRR
Carl Beyer, Pacific Northwest National Laboratory

Date: June 10, 2005

Westinghouse Comments on Optimized ZIRLO™ SE

TABLE 1: LICENSING AND FUTURE COMPLIANCE ISSUES

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L1	1.0	The "conditional approval" remark has no regulatory significance.	In the Conclusion section, the staff states: "The 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." Similar to L6 and L11, the approval is conditional because of outstanding commitments.	Leave as is.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L2	3.1 3.2 3.2.7 3.2.8 3.2.10 3.2.14 3.3.1	SPECIFICATION OF MICROSTRUCTURE Final anneal condition does not define Optimized ZIRLO™ and should be deleted from the regulatory definition. We have provided data and have experience with various final anneals and reduction schemes. Westinghouse wants to add: "Westinghouse will meet regulatory requirements on microstructure by ensuring the final material properties are consistent with their licensed model assumptions". - W wants the staff to delete specific reference to the clad material microstructure.	In the future, a material specification based upon performance-based criteria will be developed. Today, the NRC staff has chosen to define the material based on chemistry and microstructure along with broad statements that the material performance presented in the topical must be maintained. Altering the microstructure has an impact on several material properties including strength and creep. It would be a substantial effort to quantify what is meant by "consistent" material properties since a change in either direction may be detrimental and have synergistic effects. All of the test specimens presented in Addendum 1 were of a single specific microstructure, which means our understanding of its performance is based on this specific microstructure.	Maintain regulatory definition of Optimized ZIRLO™ including specific microstructure.
L3	3.1	Change "Allowable Range" for Tin from 0.6-0.8 wt% to 0.6-0.79 wt%.	Acceptable.	Change.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L4	3.2.8 3.3.1 3.7 5.0	Remove any text identifying application of Optimized ZIRLO™ to cladding as opposed to assembly components. Delete text on the future application of ZIRLO™. "Westinghouse will use the appropriate mechanical properties consistent with the unirradiated thermo mechanical properties of the material consistent with the GDC for structures." In a comment under Section 3.5.4, Westinghouse states: "The topical does not request approval for any design-specific applications of Optimized ZIRLO™ components. Design-specific requirements will be addressed as appropriate for the specific application per requirements defined in NUREG 0800 (Section 4.2 of the SRP)."	Westinghouse has provided almost no data to support the application of Optimized ZIRLO™ to assembly components. Of concern are the following 3 SRP items: • Grid cage strength. • Guide tube growth. • Fretting wear due to spring relaxation. Each design is potentially impacted to a different extent by the application of a new material and must be evaluated. Following the initial release of SRXB's Safety Evaluation, Westinghouse decided to remove from Addendum 1 all reference to application of Optimized ZIRLO™ to assembly components other than fuel clad. As a result, the staff's review was solely on the use of Optimized ZIRLO™ as fuel clad material.	Change to clarify staff's position.
L5	3.2.10 3.2.14	When describing Vogtle creep program, remove indication to other "advanced alloys". Westinghouse states that "reference to programmatic aspects of a test not related to the subject topical should be deleted from this SER".	Agree.	Change.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L6	3.2.10 3.3.8	"Reference to the timing of data availability from the Vogtle test relative to reload fuel application should be removed unless this is an explicit condition the NRC staff is imposing prior to licensing of Optimized ZIRLO™".	The timing is important. We are accepting this alloy because there are ongoing LTA programs and the ongoing Vogtle creep program. The timing is important because the fuel models will be validated based on these ongoing programs prior to the batch fuel achieving the same burnups.	Leave as is. Added time line to Conditions #6 and #7.
L7	3.2.10	Remove text that PNNL believes it would be prudent to include first cycle profilometry on LTAs. Westinghouse states, "In response to RAI 3b, Westinghouse has stated that profilometry is planned to be performed after completion of the third irradiation cycle on one cycle rods at Byron. This profilometry while planned is not viewed as a condition for approval of Optimized ZIRLO™."	PNNL believes that profilometry after 1 cycle is important to capture true clad creep - prior to pellet clad interaction. PNNL's comment is good background material for future licensing actions. It is not a commitment and the SE clearly indicates that it is not a Condition.	Leave as is.
L8	3.3.5 3.4.1 5.0	Remove text related to hydrides and Conditional hydride limit. Westinghouse also would like a paragraph on corrosion deleted. Delete 3.4.1 Hydriding since "None of the above text has any bearing on acceptability of Optimized ZIRLO™..."	The reduction in ductility is directly related to hydride levels. Even though these level are not readily measured (as are oxide thickness pool-side), it is still important from a design that hydrides are considered. Its important when developing alloys that the hydrogen pickup fraction be measured and a correlation be developed to equate to oxide measurements.	Leave as is.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L9	3.3.8	Remove a conditional statement, "there is no difference between compressive and tensile irradiation creep of either of these materials". Westinghouse states: "ZIRLO™ use is not currently limited under the assumption that tensile and compressive creep are equal, rather that there is sufficient margin in the PAD code to account for differences if they exist".	During the approval of ZIRLO™, the staff questions tensile versus compressive creep rates. Westinghouse stated that a test program was underway which would quantify both creep rates. The staff accepted ZIRLO™ with this in mind (although not a condition). Once again, the NRC staff is relying upon the ongoing program to validate the creep models. The comment implies that W has different models for tensile and compressive creep. W does not have different models which were the main issue in the review of their creep model.	Change to clarify staff's position.
L10	3.5.1 5.0	Remove statement concerning lack of high temperature oxidation data. Remove Condition which limits high temperatures in the Locked Rotor event.	Westinghouse has a cladding temperature limit for the Locked Rotor event. High temperature oxidation tests for Optimized ZIRLO™ were limited. As such, there is no basis for stating that acceptable oxidation kinetics are maintained beyond test measurements.	Leave as is.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L11	3.6	Westinghouse wants to acknowledge that the LTA data is the property of Westinghouse and the Licensees. Further, Westinghouse wants a statement added that indicates that delay in the LTA measurements and validation of the models will "in no way invalidate this SER".	Similar to L6. Timing is important. The NRC staff is relying on the ongoing LTA programs which are 2 cycles ahead of any batch application to validate models prior to achieving burnups in batch. We do not want Westinghouse to cancel or delay measurements. A reasonable delay is acceptable, but without data we have no basis for models which are impacted by prolonged exposure.	Add a condition that LTA data and confirmation of models be done prior to batch burnups.
L12	3.6 4.0	Remove statement "The NRC staffs approval of Optimized ZIRLO™, with its lack of an adequate irradiated database, should in no way represent an acceptable licensing path for future alloys.	Staff SEs often include guidance for future reviews. Similar to warning in approval of ZIRLO™ which stated that future alloys would need to update models (not rely on Zr4 properties).	Leave as is.
L13	5.0	Westinghouse objects to the statement: "The licensee is required to ensure that Westinghouse has fulfilled the following commitment" [related to supplying the staff with irradiated properties].	These SE conditions are aimed at the licensees. When a licensee adopts Optimized ZIRLO™, a licensing amendment will be submitted which will include a response to each of these commitments. The NRC reviewer will ensure that each condition has been satisfied.	Leave as is.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L14	5.0	Westinghouse wants to remove the statement: "Furthermore, the NRC staff strongly recommends that for future evaluations, Westinghouse update all computer models with Optimized ZIRLO™ specific material properties." Westinghouse claims that this statement could be misinterpreted by licensees as a requirement for approval.	It is poor book-keeping to maintain Zr4, ZIRLO™, and OPTIN material properties when modeling Optimized ZIRLO™. In meetings, Westinghouse has stated that they expect to update models in the future, but has only committed to update the specific heat in the LOCA models. We do "recommend" that all models be updated.	Leave as is. Added words to indicate that its not a condition.
L15	5.0	Remove condition limiting fuel duty until data is available. "This requirement is already self-imposed based on our licensed corrosion models that limit the fuel duty possible for any plant implementing ZIRLO™ or Optimized ZIRLO™. Since the models make no distinction between ZIRLO™ and Optimized ZIRLO™, it is not possible for any plant to use Optimized ZIRLO™ at a higher duty than currently possible with ZIRLO™ without first licensing a new corrosion model. Therefore, this condition should be removed."	Agree.	Remove.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
L16	3.6 5.0	Change: "Westinghouse has committed to provide the NRC staff with irradiated data from...." To: "Westinghouse has committed to provide the NRC staff with a summary of the irradiated test results from..." Specify Vogtle data as "data summary reports or presentations".	The staff needs to see the irradiated data and confirmation of the models predictions. This is clearly stated in the Condition. Westinghouse has a point that we may not necessarily want to see large quantities of "raw data". However, its important that an adequate amount of information is presented to allow the staff to independently verify the models. Delete "or presentations" from proposed text.	Change.
L17	5.0	Westinghouse wants to replace "validate" with "confirm applicability with" currently approved models.	No objection.	Change.

TABLE 2: TECHNICAL ISSUES

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
T1	3.2.10	Reword text. Westinghouse believes that quantitative differences between out-of-reactor and in-reactor creep data to be accurate indicator. PNNL's text should be reworded to indicate this phenomena.	The Westinghouse comment states that there is a direct relationship between the two. If they mean a direct qualitative relationship this does not disagree with our second paragraph. If they mean a direct quantitative relationship, the staff disagrees. The staff's position is that there is no quantitative relationship between out-of-reactor and in-reactor creep.	Leave as is.
T2	3.3.8	Westinghouse wants text deleted which simply state that if irradiation creep were higher than a lower rod pressure limit would be required. Westinghouse states that Vogtle data is now available that indicates similar creep rates.	Statement is true and provides information on the impact "if" irradiation creep were higher. Its too late in the process to issue new RAIs requesting Vogtle creep data which just became available.	Leave as is.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
T3	3.5.1	Westinghouse believes that the discussion in the SE on LOCA incorrectly paraphrases an RAI response.	The technical explanation as to why specific heat and other clad properties were important during early reflood (when fuel stored energy is high) would also apply to the blowdown period. The limited scoping study did not investigate all possibilities. It is reasonable to infer that both blowdown and early reflood would be sensitive to these material properties.	Leave as is.
T4	5.0	Westinghouse indicates that Condition #8 was incorrectly derived from response to RAI #3 (Oct 29, 2004).	Agree.	Change.

TABLE 3: CLARIFICATION & IMPROVEMENT

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
C1	3.2.7	Delete discussion on tensile strength since it is "not relevant to the acceptability of Optimized ZIRLO™".	Text contains background and discussion on methods. Keep it.	Leave as is.
C2	3.2.7 3.2.8	Change "implies" to "claims"	Agree.	Change.
C3	3.2.7 3.2.8 5.0	Text is negatively worded. Change "Due to the lack of irradiated properties, ..." to "...until irradiated data for Optimized ZIRLO™ is provided."	Agree.	Change.
C4	3.2.7 3.3.1	Remove "and contractor's" from the statement discussing the staff's concerns.	Agree.	Change.
C5	3.3.2	Remove text on methods since no change is being sought.	Text provides background.	Leave as is.
C6	3.3.4	Remove discussion on fretting wear since it "has no bearing on acceptability of subject topical". Reword text on fretting "unless explicit requirements related to acceptability of Optimized ZIRLO™ as an approved cladding are contingent upon a defined outcome or expectation of the NRC staff with regard to fretting wear".	The current text simply states that Westinghouse has indicated no fretting wear on the LTAs to date and that these LTAs will be monitored in the future for signs of fretting wear. I agree that the cladding material has little to do with fretting. Instead it's the grid design and spring material. No Condition is specified in Section 5.0.	Leave as is. Text on fretting wear modified as agreed by the staff.

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
C7	3.3.8	Rewrite text on reporting requirements for future creep measurements.	The NRC staff wants Westinghouse to notify us if the creep data is "different" than ZIRLO™, not "outside the assumptions used for ZIRLO™". Any change in creep, in either direction, has an impact. The NRC staff wants Westinghouse to validate the creep models when more creep measurements become available - providing the staff with both the data and the validation.	Leave as is.
C8	3.5.2	Remove text which has no bearing on accepting Optimized ZIRLO™.	Background material describing what the reviewer was considering.	Leave as is.
C9	5.0	Add ZIRLO™ to Condition 5 since both ZIRLO™ and Optimized ZIRLO™ continue to apply the same methodologies for both material definitions.	No objection.	Change.
C10	3.3.5 3.4.6 3.5.1 3.5.2 3.5.3 3.6	Miscellaneous editorial comment. Westinghouse proposed change for clarity.	No objection.	Change.

TABLE 4: PROPRIETARY MATERIAL

Number	Sections	Westinghouse Comment	Staff's Response	Disposition
P1	ALL	Westinghouse has identified numerical values which quantify difference in material performance and test which characterize the final microstructure as proprietary.	Agree.	Change.
P2	Bracketed and Bolded	Westinghouse has identified manufacturing process descriptions which are proprietary.	Agree.	Withheld

Section B

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Direct tel: 412-374-5282
Direct fax: 412-374-4011
e-mail: sepp1ha@westinghouse.com

Our ref: LTR-NRC-03-2

Attention: J. S. Wermiel, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

February 14, 2003

Subject: Submittal of Addendum 1 to WCAP-12610-P-A/WCAP-14342-A and CENPD-404-P-A/CENPD-404-NP-A, "Addendum 1 to WCAP-14342-P-A and CENPD-404-P-A Optimized ZIRLO™", for NRC Review and Approval (Proprietary / Non-proprietary)

Dear Mr. Wermiel:

Enclosed are copies of the Proprietary and Non-Proprietary versions of the Westinghouse document "Addendum 1 to WCAP-14342-P-A and CENPD-404-P-A Optimized ZIRLO™", Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A (Proprietary) and Addendum 1 to WCAP-14342-A and CENPD-404-NP-A (Non-Proprietary). The purpose of this Addendum is to obtain Nuclear Regulatory Commission ("NRC") approval of an extension to the regulatory definition of ZIRLO™ as approved in WCAP-12610-P-A and CENPD-404-P-A. This extension of the regulatory definition of ZIRLO™ is designed to extend the "allowed material composition" to encompass the full range of ZIRLO™ as defined by Westinghouse Electric Company ("Westinghouse") and as described in this topical report. The proposed change allows for the optimization of ZIRLO™ for enhanced corrosion resistance.

Also enclosed are:

1. One (1) copy of the Application for Withholding, AW-03-1600 with Proprietary Information Notice and Copyright Notice.

2. One (1) copy of Affidavit, AW-03-1600.

This submittal contains Westinghouse proprietary information of trade secrets, commercial or financial information which we consider privileged or confidential pursuant to 10 CFR 9.17(a)(4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used solely for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the expressed prior written approval of Westinghouse.

Correspondence with respect to this Application for Withholding should reference AW-03-1600 and should be addressed to H. A. Sepp, Manager of Regulatory and Licensing Engineering, Westinghouse Electric Company, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Enclosure

Copy to:
R. Caruso, NRR
G. Shukla, NRR
U. Shoop, NRR
S. L. Wu, NRR

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Attention: J. S. Wermiel, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Direct tel: 412-374-5282
Direct fax: 412-374-4011
e-mail: sepp1ha@westinghouse.com

Our ref: AW-03-1600

February 14, 2003

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

Subject: Submittal of Addendum 1 to WCAP-12610-P-A/WCAP-14342-A and CENPD-404-P-A/CENPD-404-NP-A, "Addendum 1 to WCAP-14342-P-A and CENPD-404-P-A Optimized ZIRLO™", for NRC Review and Approval (Proprietary / Non-proprietary)

Reference: Letter from H. A. Sepp to J. S. Wermiel, LTR-NRC-03-2, dated February 14, 2003

Dear Mr. Wermiel:

The application for withholding is submitted by Westinghouse Electric Company LLC, a Delaware limited liability company ("Westinghouse"), pursuant to the provisions of paragraph (b)(1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-03-1600 accompanies this application for withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-03-1600 and should be addressed to the undersigned.

Very truly yours,

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Proprietary Information Notice

Transmitted herewith are proprietary and non-proprietary versions of documents furnished to the NRC. In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

Copyright Notice

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC, a Delaware limited liability company ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

KAY E. GONGAWARE COMMONWEALTH OF PENNSYLVANIA NOTARY PUBLIC

Henry A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 14th day
of February, 2003.

Notary Public

Notarial Seal
Kay E. Gongaware, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires Feb. 7, 2005
Member, Pennsylvania Association of Notaries

(1) I am Manager, Regulatory and Licensing Engineering, in the Nuclear Services, of the Westinghouse Electric Company LLC, a Delaware limited liability company ("Westinghouse") and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Electric Company.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Electric Company in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked , Addendum 1 to WCAP-12610-P-A/WCAP-14342-A and CENPD-404-P-A/CENPD-404-NP-A, "Addendum 1 to WCAP-14342-P-A and CENPD-404-P-A Optimized ZIRLO™", February 14, 2003, for submittal to the Commission, being transmitted by Westinghouse Electric Company (W) letter (LTR-NRC-03-2) and Application for Withholding Proprietary Information from Public Disclosure, Henry A. Sepp, Westinghouse, Manager Regulatory and Licensing Engineering to the attention of J. S. Wermiel, Chief, Reactor Systems Branch, Division of Systems Safety and Analysis. The proprietary information as submitted by Westinghouse Electric Company is that associated with Westinghouse's request for NRC ("NRC") approval of an extension to the regulatory definition of ZIRLO™ as approved in WCAP-12610-P-A and CENPD-404-P-A. The proposed change allows for the optimization of ZIRLO™ for enhanced corrosion resistance. The document is being submitted for NRC review and approval.

This information is part of that which will enable Westinghouse to:

(a) Obtain generic NRC licensed approval for the use of Optimized ZIRLO™.

(b) Promote internal integration within Westinghouse.

Further this information has substantial commercial value as follows:

(a) Enhanced fuel performance.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar technical evaluation justifications and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed improved core thermal performance methodology.

Further the deponent sayeth not.

Table of Contents

Table of Contents for Appendix A: Test Methods

Table of Contents for Appendix B: Test Results

List of Tables

List of Tables for Appendix B: Test Results

List of Figures

List of Figures for Appendix B: Test Results

List of Figures for Appendix B: Test Results

1.0 Introduction

1.1 Purpose

The purpose of this Addendum is to obtain Nuclear Regulatory Commission ("NRC") approval of an extension to the regulatory definition of ZIRLO™ as approved in WCAP-12610-P-A and CENPD-404-P-A. This extension of the regulatory definition of ZIRLO™ is designed to extend the "allowed material composition" to encompass the full range of ZIRLO™ as defined by Westinghouse Electric Company ("Westinghouse") and as described in this topical report. The proposed change allows for the optimization of ZIRLO™ for enhanced corrosion resistance.

The optimization of the material composition of the current licensed material ZIRLO™ to Optimized ZIRLO™ is similar to the approach used to extend the material composition of Zircaloy-4 to "Improved Zircaloy-4" (i.e., a slight reduction in tin content for improved in-reactor corrosion resistance). As in the case of Zircaloy-4 and as demonstrated by this report, a minor material composition change does not appreciably change the ZIRLO™ physical or mechanical properties or have any appreciable impact on analysis models and methods. This change is designed to enhance corrosion resistance of the ZIRLO™ material in more adverse in-reactor primary chemistry environments and at higher fuel duties with higher burnups.

This Addendum provides details and results of material testing of the Optimized ZIRLO™ (hereafter referred to as "Optimized ZIRLO™") compared to the current licensed ZIRLO™ (hereafter referred to as "Standard ZIRLO™") and demonstrates that the Standard ZIRLO™ material properties utilized in various models and methodologies can be applied to analyses of Optimized ZIRLO™.

1.2 ZIRLO™ Definition

ZIRLO™ material was first licensed by the NRC as part of the VANTAGE+ fuel product in WCAP-12610 (Reference 1). The topical report received NRC (Reference 2) approval in July 1991 and the approved version (Reference 3) was issued with all the associated NRC Safety Evaluations (SE) for the base document and the various appendices in April 1995. In August 1992, the NRC promulgated a regulatory change (Reference 4) to 10 CFR 50.44, 10 CFR 50.46, and 10 CFR Part 50 Appendix K to allow the use of ZIRLO™ without obtaining exemption approval. Between July 1991 and August 1992, Westinghouse had numerous meetings with the NRC, and in particular, the Office of the General Counsel (OGC), to describe ZIRLO™ and to obtain a change in the Code of Federal Regulations (CFRs). Based on information presented to the NRC during this period, the description of ZIRLO™ material in both the NRC SE and Appendix A of WCAP-12610, and also accounting for descriptions of ZIRLO™ in patent documents, the following definition is the basis for the ZIRLO™ material licensed by the NRC in both WCAP-12610 and in changing the Code of Federal Regulations.

> "ZIRLO™ alloy is Westinghouse's 1% niobium-tin-iron zirconium-based alloy having a microstructure comprising second phase precipitates (specifically, a body-centered cubic beta-niobium-zirconium phase and a hexagonal zirconium-niobium-iron inter-metallic phase) homogeneously distributed throughout the zirconium matrix. ZIRLO™ is a modification of Zircaloy-4 that includes a reduction in the tin, iron and chromium content, and addition of nominally one percent niobium."

Based on the above definition of ZIRLO™, the numerous meetings held between Westinghouse and the NRC; the technical justification of ZIRLO™ as documented in WCAP-12610 (Reference 3); and the technical review of ZIRLO™ as documented in Reference 2, the changes to 10 CFR 50.44, 10 CFR 50.46, and 10 CFR Part 50 Appendix K were made and noticed to the public in Reference 4. The proposed optimization of ZIRLO™ still meets the above definition of ZIRLO™. This Addendum provides the technical justification that the optimization of ZIRLO™ does not invalidate any of the bases for ZIRLO™ that the NRC previously reviewed and approved. Thus the optimization of the ZIRLO™ material will only result in a slight change in the material composition of ZIRLO™ and the material will still be ZIRLO™, similar to the optimization of Zircaloy-4.

1.3 Applicability (WCAP-12610-P-A & CENPD-404-P-A)

Both WCAP-12610-P-A (Reference 3) and CENPD-404-P-A (Reference 5) define the material properties for licensed ZIRLO™. This Addendum covers both topicals and demonstrates that Standard ZIRLO™ material properties currently utilized in various models and methodologies are applicable to analyses of Optimized ZIRLO™.

2.0 Material Specification

2.1 Original Licensing Basis

As noted in the previous section, the material composition of ZIRLO™ is specified in Appendix A of WCAP-12610-P-A. Specifically, the wording in Appendix A is as follows:

"ZIRLO™ represents a modification of Zircaloy-4 which has been achieved by reducing the tin and iron content, eliminating the chromium content, and adding one percent niobium. The following table compares the two alloys:

Element	ZIRLO™ Alloy	Zircaloy-4 Alloy
Sn, wt %	0.8 – 1.2	1.2 – 1.7
Fe, wt %	0.09 – 0.13	0.18 – 0.24
Cr, wt %	- -	0.07 – 0.13
Fe + Cr, wt %	- -	0.28 – 0.37
Nb, wt %	0.8 – 1.2	- -
Zr, wt %	Balance	Balance"

2.2 Revised Licensing Basis

As noted in Section 1.1, this Addendum defines the optimized material composition of ZIRLO™ (or "Optimized ZIRLO™") and demonstrates that the material is essentially the same as the currently licensed ZIRLO™. Optimized ZIRLO™ meets the definition of ZIRLO™ provided to the NRC during the period when the regulatory change was obtained to the Code of Federal Regulations. Therefore, the proposed change to the above wording is as follows:

"ZIRLO™ alloy is Westinghouse's 1% niobium-tin-iron zirconium-based alloy having a microstructure comprised of second phase precipitates (specifically, a body-centered cubic beta-niobium-zirconium phase and a hexagonal zirconium-niobium-iron inter-metallic phase) homogeneously distributed throughout the zirconium matrix. ZIRLO™ is a modification of Zircaloy-4 that includes a reduction in the tin, iron and chromium content, and addition of nominally one percent niobium. The following table compares the two alloys:

Element	ZIRLO™ Alloy	Zircaloy-4 Alloy
Sn, wt %	0.6 – 1.2	1.2 – 1.7
Fe, wt %	0.09 – 0.13	0.18 – 0.24
Cr, wt %	- -	0.07 – 0.13
Fe + Cr, wt %	- -	0.28 – 0.37
Nb, wt %	0.8 – 1.2	- -
Zr, wt %	Balance	Balance"

The remainder of this Addendum documents material properties for Standard ZIRLO™ material versus the Optimized ZIRLO™ material and shows the differences to be negligible and that any minor differences have no appreciable impact on any design or safety analysis area.

3.0 Material Properties and ZIRLO™ Testing

3.1 Tin Content - Lower Bound Limit

[ ] a, c of Optimized ZIRLO™ were sectioned from different and randomly selected tubes and sent to the Westinghouse Western Zirconium Plant for detailed chemical analyses using standard production equipment and procedures. Samples from each of the [ ] a,c. A summary of the tin content is shown in the table below.

Table 3.1-1
Nominal Measured Tin Content

[ ] a, b, c

Based on a statistical analysis, the tin content range is as follows:

[ ] a, b, c

Based on the above review, it can be seen that the test material used for the analysis has a tin content in the range of [ ] a, b, c, which supports a lower bound limit of 0.6%.

It should be noted that "[ ] a, c" tin content referred to in various tables and text throughout this document refers to a nominal tin content. Actual tin content of the lots used for testing is as stated above.

3.2 ZIRLO™ Test Program

A series of tests of key characteristics for both Standard ZIRLO™ material and the Optimized ZIRLO™ have been performed (refer to Table 3.3-1). The test data have been evaluated by various disciplines to determine the relative impact of the change to Optimized ZIRLO™ and to show that the Optimized ZIRLO™ is essentially the same as Standard ZIRLO™.

The currently licensed minimum tin content of ZIRLO™ is 0.8%. The proposed revision of minimum tin content is 0.6%. No other changes in ZIRLO™ composition are proposed. Therefore, there is only a minimal impact on the associated models and methods, which have been confirmed by the various tests and evaluations conducted and documented in this report.

3.3 Properties Tested

The physical, mechanical, microstructural and LOCA related testing of the Optimized ZIRLO™ material is delineated in the table below (Table 3.3-1). Test procedures and results are specified in Appendices A and B, respectively.

Table 3.3-1
Summary of Tests Conducted

a, c

3.4 Test Facilities

Thermophysical Properties Research Laboratory, Inc. (TPRL), 3080 Kent Avenue, West Lafayette, IN 47906. Contact: [ ]^{a,c}. Thermophysical properties were measured at TPRL under the observation of Westinghouse personnel according to TPRL procedures. NIST traceable calibration standards were used during the course of testing performed at TPRL. The results were formally reported to Westinghouse.

UJP-Praha (formerly SKODA-UJP), Nad Kaminkou 1345, 156 10 Praha 5 - Zbraslav, Czech Republic. Contact: [ ]^{a,c}. UJP-Praha is a ISO 9001 certified facility. Oxidation weight gain measurements were performed according to ASTM G2M-88 specifications and formally reported to Westinghouse.

Commissariat a l'Énergie Atomique – Centre De Saclay (CEA-Saclay), 91191 Gif Sur Yvette Cedex, France. Contact: [ ]^{a,c}. CEA-Saclay is a French national laboratory and ISO-9001 certified facility. The Department of Nuclear Materials performed high temperature creep tests using the EDGAR-2 facility and methodologies to evaluate the high temperature creep performance of ZIRLO™. The results were formally provided to Westinghouse.

Tests were also performed at various Westinghouse sites: Science and Technology Department, George Westinghouse Research & Technology Park, 1340 Beulah Road, Churchill, PA 15235; Western Zirconium Plant, Nuclear Fuel, 10,000 W. 900 S., Ogden, Utah 84404-9799; and the Columbia Site, Nuclear Fuel, 5801 Bluff Road, Columbia, SC 29250. All Westinghouse test facilities are governed by the Westinghouse Quality Management System (QMS). The Westinghouse QMS system is frequently reviewed by the NRC to ensure compliance with the Code of Federal Regulations. Revision 5 of the Westinghouse QMS received NRC approval in a letter from the NRC to Westinghouse, dated September 13, 2002. Westinghouse is also ASME and ISO-9001 certified.

3.5 Irradiation Experience

The Optimized ZIRLO™ material has been used in Lead Test Assemblies (LTAs) in several plants, domestically and internationally. A list of those plants where Optimized ZIRLO™ has been tested is summarized below:

[ ] a, c

The following three figures provide representative in-reactor performance results for the Optimized ZIRLO™.

Figure 3.5-1
Irradiation Experience – Rod Oxide

[ ] a, b , c

Figure 3.5-2
Irradiation Experience – Rod Growth

a, b, c

Figure 3.5-3
Irradiation Experience – Assembly Growth

a, b, c

4.0 Fuel Design and Accident Analysis Effects

4.1 Fuel Assembly Mechanical Design

The fuel assembly designs can be impacted by [ ]^{a,c} however the mechanical strength of the [ ]^{a,b,c} The minimum yield strength value for Optimized ZIRLO™ is [ ]^{a,c} Similar relationship exists for other material conditions. Thus, the Optimized ZIRLO™ will meet the existing fuel assembly material design criteria. The other area of fuel assembly design that is affected by the change from Standard ZIRLO™ to Optimized ZIRLO™ is the reduction in corrosion or oxidation and a corresponding reduction in hydrogen pickup. These later impacts are benefits with respect to the final assembly structural capability and with respect to fuel assembly growth considerations.

The other key area of the fuel assembly design that must be addressed, when considering the [ ]^{a,c}. The grid assembly must withstand the dynamic loads from Condition I and II events, including Operating Basis Earthquake (OBE). Grid deformation due to the most limiting dynamic loads resulting from Condition III and IV events, including Safe Shutdown Earthquake (SSE) and Loss-of-Coolant-Accident (LOCA), must not result in unacceptable guide thimble tube distortion, which could impede control rod insertion. The flow channel area reduction must not cause the peak cladding temperature to exceed 2200 °F during a LOCA event.

Therefore, grid impact testing was performed, at operating temperature (600 °F) in air, to determine the impact crush strength and stiffness of the Standard ZIRLO™ and Optimized ZIRLO™ for a representative Westinghouse mid-grid. The table below details the results and shows that the [ ]^{a,c}.

[ ]^{a,b,c}

Based on the [ ]a,c for the Optimized ZIRLO™, the satisfaction of the SSE/LOCA design criteria for the ZIRLO™ mid-grid design will not be affected by the use of Optimized ZIRLO™ for the grid assemblies.

4.2 Fuel Rod Design

Since Westinghouse has two fuel performance codes (PAD 4.0 and FATES3B) and two fuel rod design methodologies (Westinghouse fuel designs and CE fuel designs), the change to Optimized ZIRLO™ from Standard ZIRLO™, with respect to these codes and methods, will be addressed separately.

4.2.1 Westinghouse Fuel Design

The Westinghouse fuel designs are analyzed to the following design criteria[3]. Each criterion is specified along with the evaluation of the use of Optimized ZIRLO™ on the specific criterion.

- Rod Internal Pressure - Gap Reopening Limit/DNB Propagation

  Criterion: The internal pressure of the lead fuel rod in the reactor will be limited to a value below that which could cause the diametrical gap to increase due to outward cladding creep during steady state operation and the internal pressure of the lead fuel rod in the reactor will be limited to a value below that which could cause extensive DNB propagation to occur.

  Evaluation: There is no effect of Optimized ZIRLO™ on the [ ]* a, c thus, there will be no effect on evaluating the gap reopening limit criterion. Since there is no effect of Optimized ZIRLO™ on the rod internal pressure, there will be no effect on evaluating the DNB propagation.

- Clad Stress

  Criterion: The design limit for the fuel rod clad stress is that the volume average effective stress calculated with the von Mises equation considering interference due to uniform cylindrical pellet-cladding contact, caused by pellet thermal expansion, pellet swelling and uniform cladding creep, and pressure differences, is less than the ZIRLO™ 0.2% offset yield stress under Condition I and II modes of operation, with due consideration to temperature and irradiation effects. While the cladding has some capability for accommodating plastic strain, the yield stress has been established as the conservative design limit.

---

[*]a,c

Evaluation: There is no effect of Optimized ZIRLO™ on the [ ] * a, c Therefore, there will be no effect on evaluating the clad stress.

- Clad Strain - Steady State/Transient

Criterion: The design limit for the fuel rod clad strain is the total plastic tensile creep strain due to uniform cladding creep and uniform cylindrical fuel pellet expansion due to swelling and thermal expansion is less than 1% from the unirradiated condition, and that the total tensile strain due to uniform cylindrical pellet thermal expansion during a transient is less than 1% from the pre-transient value.

Evaluation: There is no effect of Optimized ZIRLO™ on the [ ] *a, c. Therefore, there will be no effect on evaluating the transient clad strain.

- Corrosion

Criterion: The corrosion-related licensing criteria for the fuel rod cladding are:

1. The ZIRLO™ cladding metal-oxide interface temperature shall not exceed the following limits:
   Steady-State Operation [ ] a, b, c
   Condition II Transients [ ] a, b, c
2. The best estimate hydrogen pickup in the ZIRLO™ cladding shall not exceed [ ] a, c at end of life.
3. The steady-state ZIRLO™ cladding oxidation must be considered in the calculation of the total local oxidation in the Loss of Coolant Accident (LOCA). The 10 CFR 50.46 acceptance criterion is that the maximum total localized oxidation shall not exceed 17% of the cladding thickness.

Evaluation: Optimized ZIRLO™ will be modeled with approved ZIRLO™ corrosion model. Therefore, there will be no impact on evaluating the clad corrosion criterion.

- Fuel Temperatures

Criterion: For Condition I and II events, the fuel system and protection system are designed to assure that a calculated centerline fuel temperature does not exceed the fuel melting temperature. The melting temperature of UO_2 is taken to be 5080 °F (unirradiated) and to decrease 58 °F per 10,000 MWD/MTU fuel burnup.

Evaluation: There is no change in the [ ] a, b, c. Therefore, there will be no effect of Optimized ZIRLO™ on the fuel temperature criterion evaluation.

---

[*] a, c
[*] a, c

- <u>Clad Free Standing</u>

Criterion: The cladding shall be short-term free standing at beginning of life, at power, and during hot hydrostatic testing.

Evaluation: The criterion is bounded by generic fuel assembly design analyses such as documented in References 3, 6 and 7. The assumptions made in the generic analyses are not affected by Optimized ZIRLO™.

- <u>Clad Fatigue</u>

Criterion: The fatigue life usage factor is limited to less than 1.0 to prevent reaching the material fatigue limit.

Evaluation: There is no change in the [ ]^{a,c}. Therefore, there will be no effect of Optimized ZIRLO™ on the clad fatigue evaluation.

- <u>Plenum Clad Support</u>

Criterion: The fuel rod in the unsupported plenum region will not collapse during normal operating conditions, nor distort so as to degrade fuel rod performance or preclude rod reconstitution during the assembly design lifetime.

Evaluation: There is no change to the [ ]^{a,c}. Therefore, there will be no effect of Optimized ZIRLO™ on the plenum clad support evaluation.

- <u>Clad Flattening</u>

Criterion: The fuel rod design shall preclude clad flattening during the projected exposure.

Evaluation: There is no change to the [ ]^{a,c}. Therefore, there will be no effect of Optimized ZIRLO™ on the clad flattening analysis.

- <u>Rod Growth</u>

Criterion: The fuel rods will be designed with adequate clearance between the fuel rod and the top and bottom nozzles to accommodate the differences in the growth of fuel rods and the growth of the fuel assembly.

Evaluation: There is no change to the [ ]^{a,c}. Therefore, there will be no effect of Optimized ZIRLO™ on the rod growth evaluation.

- Fuel Rod End-Plug Weld Integrity

Criterion: The fuel rod end plug shall maintain its integrity during Condition I and II events and shall not contribute to any additional fuel failures above those already considered for Condition III and IV events.

Evaluation: There is no change in the [ ]^{a,c}. Therefore, there will be no effect of Optimized ZIRLO™ on the fuel rod end plug weld integrity evaluation.

4.2.2 CE Fuel Design

The CE fuel designs are analyzed to the following design criteria (Reference 5). Each criterion is specified along with the results of an evaluation of the continued use of Standard ZIRLO™ properties and models for Optimized ZIRLO™ in the analyses performed with the Standard ZIRLO™ properties and models to satisfy each specific criterion

- Maximum Internal Gas Pressure

Criterion: The fuel rod internal hot gas pressure shall not exceed the critical maximum pressure determined to cause an outward clad creep rate that is in excess of the fuel radial growth rate anywhere locally along the entire active fuel length of the fuel rod.

Evaluation: Maximum internal gas pressure depends on [ ]^{a,c}. The critical pressure limit for NCLO (No Clad Lift-Off) depends on [ ]^{a,c} during normal operation. An evaluation demonstrated that the application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on maximum internal pressure and will have a conservative impact on the NCLO critical pressure limit. Thus, there will be no effect of Optimized ZIRLO™ on the maximum internal pressure criterion evaluation.

- Excessive Fuel Rod DNB Propagation

Criterion: The radiological dose consequences of DNB failures shall remain within the specified limits.

Evaluation: Calculation of DNB propagation depends on [ ]^{a,c}. An evaluation demonstrated that application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on [ ]^{a,c} and that the Standard ZIRLO™ [ ]^{a,c} can be applied to Optimized ZIRLO™. Thus, there will be no effect of Optimized ZIRLO™ on the fuel rod DNB propagation criterion evaluation and no change in contribution to dose.

- Fuel Rod Stress

Criterion: (1) During Conditions 1 and 2, the primary tensile stress in the clad and the end cap welds 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.

(2) During Conditions 1, 2 and 3, primary compressive stress in the clad and the end cap welds 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.

Evaluation: The above fuel rod stress criteria have been evaluated for the most recent 14x14 and 16x16 fuel designs containing Standard ZIRLO™ cladding and found to be satisfied. Those evaluations considered [ ] a, c. All of these parameters involve the material properties and capabilities of the cladding. An evaluation demonstrated that the application of Standard ZIRLO™ properties and models for all properties and models, except corrosion, to Optimized ZIRLO™, will have no impact on maximum stress. Application of Standard ZIRLO™ corrosion properties and models to Optimized ZIRLO™ is conservative in terms of calculated maximum stress. However, since the [ ] a, c for Optimized ZIRLO™, minor margin reductions are expected for fuel rods with Optimized ZIRLO™ cladding in the maximum stress criterion evaluation when the conservative treatment of corrosion is ignored.

- Fuel Rod Strain

Criterion: (1) At any time during the fuel or integral-burnable-absorber rod lifetime, 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 Anticipated Operational Occurrence (AOO).

(2) For fuel or integral-burnable-absorber rods having axial average burnups greater than 52 MWD/KGU, the total (elastic + plastic) circumferential cladding strain increment produced as a result of a single Condition 2 or 3 event, or a single AOO, shall not exceed 1%.

Evaluation: The above fuel rod strain criteria have been evaluated for the most recent 14x14 and 16x16 fuel designs containing Standard ZIRLO™ cladding and found to be satisfied. Those evaluations considered [ ] a, c. Further, an evaluation demonstrated that the application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on maximum cladding strain. Thus, there will be no effect of Optimized ZIRLO™ on the cladding strain criterion evaluation.

- Maximum Fuel Temperature

Criterion: The fuel rod centerline temperature shall not exceed the fuel melt temperature, accounting for degradation due to burnup and addition of burnable absorbers.

Evaluation: An evaluation demonstrated that the application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on maximum fuel temperature. Thus, there will be no effect of Optimized ZIRLO™ on the maximum fuel temperature criterion evaluation.

- Fuel Rod Fatigue Damage

Criterion: For the number and types of transients which occur during Condition 1 reactor operation, End-of-Life (EOL) cumulative fatigue damage in the clad and in the end cap welds must be less than 0.8.

Evaluation: The above fuel rod fatigue damage criterion has been evaluated for the most recent 14x14 and 16x16 fuel designs containing Standard ZIRLO™ cladding and found to be satisfied. The evaluations considered [ ] a, c. An evaluation demonstrated that the application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on maximum cladding fatigue damage. Thus, there will be no effect of Optimized ZIRLO™ on the cladding fatigue damage criterion evaluation.

- Cladding Creep Collapse

Criterion: The time required for the radial buckling of the clad in any fuel or integral-burnable-absorber rod must exceed the reactor operating time necessary for the appropriate batch to accumulate its design average discharge burnup. This criterion must be satisfied for continuous reactor operation at any reasonable power level and during any Condition 1, 2 or 3 situation. It will be considered satisfied if it can be demonstrated that axial gaps longer than 0.125 inch will not occur between fuel pellets and the plenum spring radial support capacity is sufficient to prevent clad collapse under all design conditions.

Evaluation: The above fuel rod clad collapse criterion has been evaluated for the most recent 14x14 and 16x16 fuel designs containing Standard ZIRLO™ cladding and found to be satisfied. Those evaluations considered [ ] a, c. An evaluation demonstrated that the application of Standard ZIRLO™ properties and models for all properties and models except corrosion to Optimized ZIRLO™ will have no impact on maximum stress. Application of Standard ZIRLO™ corrosion properties and models to Optimized ZIRLO™ is conservative in terms of calculated creep collapse. Thus, there will be no effect of Optimized ZIRLO™ on the cladding creep collapse criterion evaluation.

- Shoulder Gap

Criterion: The axial length between end fittings must be sufficient to accommodate differential thermal expansion and irradiation-induced differential growth between fuel rods and guide tubes such that it can be shown with 95% confidence that no interference exists.

Evaluation: The above design criterion is commonly referred to as shoulder gap and is evaluated using the [ ]^{a,c} of the fuel rod cladding. This criterion has been evaluated for the most recent 14x14 and 16x16 fuel designs containing Standard ZIRLO™ cladding and found to be satisfied. An evaluation demonstrated that the application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on predicted shoulder gap. Thus, there will be no effect of Optimized ZIRLO™ on the shoulder gap criterion evaluation.

- Seismic and LOCA Loads

Criterion: The fuel rod cladding shall be capable of withstanding the loads resulting from the mechanical excitations occurring during the seismic and/or LOCA without failure resulting from excessive primary stresses.

Evaluation: The analysis methodology is unaffected by the change to Optimized ZIRLO™. Minor changes to allowable stress margins may occur but there will be no impact since significant stress margins exist for cladding under the postulated loading conditions.

- Corrosion

Criterion: The predicted best-estimate ZIRLO™. cladding corrosion will remain below 100 microns for all locations on the fuel.

Evaluation: The Standard ZIRLO™ corrosion model will be used to model Optimized ZIRLO™. Thus, there will be no effect on the clad corrosion criterion evaluation.

4.3 Nuclear Design

As documented in References 3 and 5, the only effect of ZIRLO™ alloy on the nuclear design analytical models and methods is a slight enrichment penalty due to the presence of niobium. This enrichment penalty has a negligible effect on the nuclear analysis, even for full core ZIRLO™ analyses. Since the Optimized ZIRLO™ remains unchanged, with respect to the niobium content, there is no change in the nuclear analysis of a reload core. The ZIRLO™ composition is not explicitly modeled in nuclear design calculations.

4.4 Thermal and Hydraulic Design

As documented in previous topicals, the use of ZIRLO™ cladding or structural materials for the fuel assembly skeleton has no impact on the thermal-hydraulic analysis since the material properties are not modeled. The thermal-hydraulic analysis depends on the fuel assembly geometric conditions, the cladding surface finish and the heat transferred to the surface of the cladding. Since the [

]^{a,c} in the Optimized ZIRLO™ will have no effect on the thermal-hydraulic analysis.

4.5 Non-LOCA Accident Design

Section 5.1 of Reference 3 and Section 7.0 of Reference 5 describe the non-LOCA evaluations that were completed to support the introduction of ZIRLO™ cladding for Westinghouse and CE fuel designs, respectively. As discussed therein, the only difference of any consequence between Zircaloy-4 and ZIRLO™ was the change in specific heat, which was modeled in FACTRAN and STRIKIN-II and evaluated for the Locked Rotor/Sheared Shaft and Rod Ejection events. [

]^{a,c} These evaluations concluded that the change in specific heat had a negligible effect on results for the Locked Rotor/Sheared Shaft and Rod Ejection events.

As shown in Section B.2, the specific heats of Standard and Optimized ZIRLO™ are approximately equal within the accuracy of the data. Since the differences in specific heat between Zircaloy-4 and ZIRLO™ were previously determined to have either no effect or a negligible effect on non-LOCA transient results, the change from Standard to Optimized ZIRLO™ would also have either no effect or a negligible effect on non-LOCA transient results.

4.6 LOCA Design (Large Break and Small Break)

4.6.1 W ECCS Performance Evaluation Models

This section evaluates the Optimized ZIRLO™ cladding test results with respect to Large Break LOCA (Appendix K, Best Estimate, and SECY) and Small Break LOCA (Appendix K). Any differences between Standard and Optimized ZIRLO™ grids, thimble tubes, and instrument tubes are considered to have a negligible effect on Large and Small Break LOCA analysis results, so these components are not considered further here.

Specific Heat

Specific heat measurements for Standard and Optimized ZIRLO™ were taken at the Thermophysical Properties Research Laboratory. [

] a, c As discussed in Section B.2, the specific heats of Standard and Optimized ZIRLO™ are approximately equal within the accuracy of the data, with differences that are considered negligible for Large and Small Break LOCA.

Figure 4.6.1-1 compares the ZIRLO™ cladding specific heat models used in LOCBART and SBLOCTA ("Appendix K Model") and WCOBRA/TRAC ("Best Estimate Model") to the Standard and Optimized ZIRLO™ "Heating" data from Table B.2-1. (The "Cooling" data from Table B.2-1 are of minimal importance for licensing-basis LOCA transients, and are not considered further here.) Figure 4.6.1-1 indicates some disagreement between the models and the data that has been resolved as follows:

- For Appendix K Large Break LOCA, sensitivity calculations using the LOCBART code indicated that the differences between the model and data could lead to an increase in peak cladding temperature for some transients. To resolve these differences, the ZIRLO™ cladding specific heat model in LOCBART was modified to reflect the new Standard ZIRLO™ data. This change is being reported separately as an evaluation model change pursuant to 10 CFR 50.46, and any further differences in cladding specific heat between Standard and Optimized ZIRLO™ are considered negligible.

- For Appendix K Small Break LOCA, sensitivity calculations using the SBLOCTA code indicated that the differences between the model and data produce a negligible effect on results. However, for consistency with LOCBART, the ZIRLO™ cladding specific heat model in SBLOCTA was modified to reflect the new Standard ZIRLO™ data. This change is being reported separately as an evaluation model change pursuant to 10 CFR 50.46, and any further differences in cladding specific heat between Standard and Optimized ZIRLO™ are considered negligible.

- As shown in Figure 4.6.1-1, the model used in WCOBRA/TRAC for ZIRLO™ cladding specific heat shows better agreement with the data than the Appendix K model. (Note that the Best Estimate and SECY versions of WCOBRA/TRAC use the same model, and that HOTSPOT uses an approximation of the WCOBRA/TRAC model.) The main differences occur for temperatures between 1400 and 1600°F, which affect a relatively minor portion of a limiting large break LOCA transient and are considered negligible. This assessment is supported by sensitivity calculations using HOTSPOT, which showed that the differences between the ZIRLO™ model and the Optimized ZIRLO™ data produced a minimal effect on results. As a result, the ZIRLO™ cladding specific heat models in Best Estimate and SECY Large Break LOCA can reasonably be applied to Optimized ZIRLO™, and need not be modified to reflect the new Standard ZIRLO™ data.

Figure 4.6.1-1
Comparison of Specific Heat Data

a, b, c

[ ]

Thermal Conductivity

Thermal diffusivity measurements for Standard and Optimized ZIRLO™ were taken at the Thermophysical Properties Research Laboratory. [

]^{a,b,c} As discussed in Section B.3, the thermal conductivities of Standard and Optimized ZIRLO™ are approximately equal within the accuracy of the data, with differences that are considered negligible for Large and Small Break LOCA.

Figure 4.6.1-2 compares the ZIRLO™ cladding thermal conductivity models used in LOCBART and SBLOCTA ("Appendix K Model") and WCOBRA/TRAC ("Best Estimate Model") to the Standard and Optimized ZIRLO™ data from Table B.3-1. For Appendix K Large Break LOCA, sensitivity calculations using the LOCBART code indicated that the differences between the ZIRLO™ model and the Optimized ZIRLO™ data produce a negligible effect on results. This is consistent with the expected result, since radial temperature gradients in the cladding are of minimal importance for typical licensing-basis Large and Small Break LOCA transients. As a result, the ZIRLO™ cladding thermal conductivity model used in LOCBART can reasonably be applied to Optimized ZIRLO™, and need not be modified to reflect the new Standard ZIRLO™ data. These conclusions are also considered to apply to Best Estimate and SECY Large Break LOCA and Appendix K Small Break LOCA, which would be similarly insensitive to reasonable variations in the cladding thermal conductivity.

Figure 4.6.1-2
Comparison of Thermal Conductivity Data

a, b, c

Emissivity

Measurements of the hemispherical total emissivity for Standard and Optimized ZIRLO™ were taken at the Thermophysical Properties Research Laboratory. [

.] a, c As shown in Section B.4, the emissivities of Standard and Optimized ZIRLO™ are approximately equal within the accuracy of the data, with differences that are considered negligible for Large and Small Break LOCA.

[

] a, b, c

Burst Temperature, Burst Strain, and Assembly Blockage

Measurements of the burst temperature and circumferential burst strain for Standard and Optimized ZIRLO™ cladding were taken at the Columbia Burst Test Facility. [

] a, c As discussed in Section B.13, the burst temperature and circumferential burst strain were found to be in reasonable agreement with the prior ZIRLO™ test data from Reference 3.

Review of the pertinent code documentation indicates that the burst and blockage models vary somewhat from code to code, particularly in Best Estimate Large Break LOCA where the stochastic treatment of burst phenomena in HOTSPOT is fundamentally different than the deterministic approach used in other evaluation models. Since the new test data are effectively indistinguishable from the data upon which all of the current ZIRLO™ models are ultimately based, it is concluded that the current ZIRLO™ models for burst temperature and circumferential burst strain (and assembly blockage, which is based on a geometric conversion of the burst strain) can reasonably be applied to Optimized ZIRLO™, and need not be modified to reflect the new Standard ZIRLO™ data.

High-Temperature Creep

High-temperature creep measurements for Standard and Optimized ZIRLO™ were taken by the Commissariat a l'Energie Atomique in the EDGAR-2 facility. [

] a, c The results are provided in Tables B.14-1 and B.14-2, and compared in Figure B.14-1 to the current ZIRLO™ model from Appendix C of Reference 3.

[

]$^{a, b, c}$

High-Temperature Oxidation

High-temperature oxidation measurements for Standard and Optimized ZIRLO™ were taken by UJP Praha. [

] $^{a, b, c}$ As shown in Figure B.15-1, the parabolic rate constants for the Baker-Just equation bound the Standard and Optimized ZIRLO™ data, confirming that the model required by 10 CFR 50 Appendix K remains conservative. Also, the ZIRLO™ best estimate parabolic rate constants from Equation 3 of Appendix E to Reference 3 bound the Standard and Optimized ZIRLO™ data at all three temperatures, indicating that the Best Estimate model is conservative relative to the new data. Based on these results, it is concluded that the current models for high-temperature oxidation can be applied to Optimized ZIRLO™ for Appendix K Large and Small Break LOCA and Best Estimate Large Break LOCA, and need not be modified to reflect the new Standard ZIRLO™ data. This conclusion is also considered to apply to SECY Large Break LOCA which, per Reference 9, uses the Baker-Just correlation for "Appendix K" calculations, and a ZIRLO™-specific model for "Superbounded" calculations.

Other LOCA Models

Appendix B provides test results for density, thermal expansion, Young's Modulus, and Poisson's Ratio which are also used in the Westinghouse LOCA codes. These properties were measured over limited temperature ranges, which is considered to be adequate given their minimal importance in typical licensing-basis Large and Small Break LOCA transients. Given this, and since the data indicate very little sensitivity to variations in tin content, the current Zircaloy-4/ZIRLO™ models for these parameters can reasonably be applied to Optimized ZIRLO™, and need not be modified to reflect the new Standard ZIRLO™ data.

4.6.2 CE ECCS Performance Evaluation Models

This section describes the implementation of Optimized ZIRLO™ in the Westinghouse Emergency Core Cooling System (ECCS) performance evaluation models for Combustion Engineering (CE) designed PWRs (herein referred to as the CE evaluation models).

Optimized ZIRLO™ is implemented in the following versions of the CE Large Break Loss-of-Coolant Accident (LBLOCA) and Small Break Loss-of-Coolant Accident (SBLOCA) evaluation models:

- Large Break LOCA: 1999 EM (Reference 10)
- Small Break LOCA: S2M (Reference 11)

These are the same versions of the CE evaluation models that have been NRC-accepted for analysis of Standard ZIRLO™ (Reference 5). Both the 1999 EM and the S2M are Appendix K evaluation models. The CE post-LOCA long term cooling evaluation model (Reference 12) does not use any cladding material property models. Consequently, it is not impacted by the implementation of Optimized ZIRLO™ and, therefore, is not addressed herein.

The LBLOCA and SBLOCA evaluation models contain models for the thirteen cladding properties listed in Table 4.6.2-1. Section 6.3 of Reference 5 describes the cladding models for Standard ZIRLO™ that are used in the CE evaluation models for LBLOCA and SBLOCA for each of the thirteen properties. Note that in many cases, as described in Section 6.3 of Reference 5, the models are the same as those that are used for Zircaloy-4 cladding.

Table 4.6.2-1
Cladding Properties Modeled in the CE Evaluation Models

Specific Heat	Thermal Expansion	Rupture Temperature
Density	Modulus of Elasticity	Rupture Strain
Thermal Conductivity	Poisson's Ratio	Assembly Blockage
Thermal Emissivity	Hardness	Pre-Rupture Plastic Strain
		Metal-Water Reaction Rate

The following sections address the impact of implementing Optimized ZIRLO™ on the thirteen cladding properties used in the LBLOCA and SBLOCA evaluation models. The Optimized ZIRLO™ and Standard ZIRLO™ test data, which are documented in Appendix B, are compared to the models for

Standard ZIRLO™ cladding that are used for each property in the CE evaluation models. Differences between the data and the models are noted and evaluated.

Specific Heat

The test data for the specific heat of Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.2 of Appendix B. Data were generated for both heatup and cooldown transients [ ] a, b, c Section B.2 concludes that the specific heats of Optimized ZIRLO™ and Standard ZIRLO™ are equal within the accuracy of the data.

As described in Section 6.3.1 of Reference 5, the CE evaluation models represent the specific heat of Standard ZIRLO™ with a table of values as a function of temperature. Linear interpolation is used to calculate the specific heat for a given temperature. The table of values is documented in Table 6.3.1-2 of Reference 5. The same model is used for both cladding heatup and cooldown.

The Optimized ZIRLO™ and Standard ZIRLO™ data for heatup and cooldown are compared to the ZIRLO™ model in Figures 4.6.2-1 and 4.6.2-2, respectively. As observed in Figure 4.6.2-1, the heatup data and the model are in reasonable agreement in the alpha phase (less than approximately 1400°F) and the beta phase (greater than approximately 1700°F). In the phase transition temperature range where the heat of transformation is included in the specific heat, the data show [

] a, b, c. The data and the model agree reasonably well in terms of the peak specific heat in the phase transition temperature range and the subsequent decrease as the values approach the specific heat of the beta phase.

As observed in Figure 4.6.2-2, the cooldown data exhibit [ ] a, c relative to the model for Standard ZIRLO™. [

] a, b, c

Since a LOCA is primarily a heatup transient, the heatup data is the more important data set. As noted above, the Optimized ZIRLO™ data and the model for Standard ZIRLO™ are in good agreement over most of the temperature range. The exception is the low end of the alpha-to-beta phase transition temperature range, from approximately 1400°F to 1600°F. The difference between the data and the model between 1400°F to 1600°F will impact the cladding heatup rate when the cladding temperature passes through that temperature range. However, the difference will not have a significant impact on the peak cladding temperature for LBLOCA and SBLOCA for the following reasons.

Figure 6.5.1.3-1 of Reference 5 shows a typical cladding temperature transient for the hot spot of the hot rod during a LBLOCA. The cladding heats up through the 1400°F-1600°F temperature range in approximately five seconds during blowdown and again in approximately fifteen seconds in early reflood. The peak cladding temperature occurs at approximately 250 seconds during late reflood. Since the model shows a greater specific heat than the data in the subject temperature range, the model will calculate a slower heatup rate during the two time periods that the temperature is in the subject temperature range. However, the cladding passes through the subject temperature range very quickly and the peak cladding temperature occurs significantly later in the transient when the cladding temperature is primarily controlled by the cladding-to-coolant heat transfer. As a result, if the experimentally determined values for specific heat were to be used in the evaluation model, the resultant increase in cladding temperature that would occur while the cladding is heating up through the subject temperature range would be small in magnitude and would decrease during the remainder of the reflood period. The result would be an insignificant change to the peak cladding temperature that is achieved in late reflood.

For reasons similar to those described above for the heatup data, the differences between the cooldown data and the model will also have an insignificant impact on peak cladding temperature. As shown in Figure 6.5.1.3-1 of Reference 5, prior to the peak cladding temperature, a period of cooldown only occurs for a brief period during blowdown.

The differences in specific heat will not have a significant impact on either the maximum or the core-wide cladding oxidation since the differences occur over a temperature range for which the rate of oxidation is low. Furthermore, as described above, there is only a small impact on cladding temperature within the temperature range.

Figure 6.5.2.3-1 of Reference 5 compares the hot spot cladding temperature transient for Standard ZIRLO™ and Zircaloy-4 cladding for a typical SBLOCA transient. In the case that is depicted, the location of the hot spot is not the elevation of cladding rupture. Since the cladding models that are different between Standard ZIRLO™ and Zircaloy-4 in the SBLOCA evaluation model are the models for specific heat, rupture temperature and rupture strain, the only meaningful difference between the two cases at the elevation depicted in Figure 6.5.2.3-1 is the difference in specific heat. The Standard

ZIRLO™ and Zircaloy-4 specific heat models are compared in Figure 6.3.1-1 of Reference 5. The difference between the two models is greater than the difference between the Optimized ZIRLO™ data and the Standard ZIRLO™ specific heat model (Figure 4.6.2-1). The difference in the peak cladding temperatures for the Standard ZIRLO™ and Zircaloy-4 cases depicted in Figure 6.5.2.3-1 of Reference 5 is 4°F. Because the difference between the specific heats of the Optimized ZIRLO™ data and the Standard ZIRLO™ model is smaller than the difference between the Standard ZIRLO™ and Zircaloy-4 specific heat models, the impact on peak cladding temperature of implementing an Optimized ZIRLO™ specific heat model rather than using the current Standard ZIRLO™ specific heat model in a SBLOCA analysis would be comparable to the difference shown in Figure 6.5.2.3-1 of Reference 5, i.e., approximately 4°F.

In summary, for the reasons described above, it is concluded that the model for the specific heat of Standard ZIRLO™ that is used in the CE evaluation models is acceptable for application to Optimized ZIRLO™ cladding.

Density

The test data for the density of Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.1 of Appendix B. The data were obtained at room temperature. Section B.1 concludes that the data suggest a minor decrease in density with lower tin content.

As described in Section 6.3.2 of Reference 5, the CE evaluation models use a constant value of 409 lbm/ft^3 (6.552 gm/cm^3) for the density of Standard ZIRLO™. The same value is used for Zircaloy-4 cladding.

The experimentally determined values for Optimized ZIRLO™ and Standard ZIRLO™, which are listed in Table B.1-1 of Appendix B, are less than [ ]^{a,b,c} different from the value used in the CE evaluation models for Standard ZIRLO™. Section 6.3.2 of Reference 5 documents that a 2% difference in cladding density is insignificant in the CE evaluation models. On that basis, it is concluded that the value for the density of Standard ZIRLO™ that is used in the CE evaluation models is applicable to Optimized ZIRLO™ cladding.

Thermal Conductivity

The test data for the thermal conductivity of Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.3 of Appendix B. [ ]^{a,c} Section B.3 concludes that the thermal conductivities of Optimized ZIRLO™ and Standard ZIRLO™ are indistinguishable within the accuracy of the data.

As described in Section 6.3.3 of Reference 5, the CE evaluation models use a [ ]^{a,c} function of temperature for the thermal conductivity of Standard ZIRLO™. (The CEFLASH-4AS computer code uses a somewhat different [ ]^{a,c} than the other evaluation model computer codes.) The models are the same as those used for Zircaloy-4 cladding.

The test data for Optimized ZIRLO™ and Standard ZIRLO™ are compared to the models used in the CE evaluation models in Figure 4.6.2-3. The data for Optimized ZIRLO™ compare very well with the models [

]^{a,b,c}

This difference between the Optimized ZIRLO™ data and the model is comparable to the difference that is described in Section 6.3.3 of Reference 5 and is subsequently justified in the response to the Request for Additional Information (RAI) Question 10a in Reference 5. The justification is based on the fact that the thermal resistance of the cladding does not limit the fuel-to-coolant heat transfer during a LOCA. Consequently, differences in the cladding thermal conductivity of the subject magnitude do not significantly impact the cladding temperature transient. Therefore, based on the comparison and evaluation provided above, it is concluded that the models for the thermal conductivity of Standard ZIRLO™ that are used in the CE evaluation models are acceptable for application to Optimized ZIRLO™ cladding.

Thermal Emissivity

The test data for the thermal emissivity of oxidized zirconium alloys (Optimized ZIRLO™, Standard ZIRLO™, and Zircaloy-4) are documented in Section B.4 of Appendix B. Data were obtained [

] [a, b, c] Section B.4 concludes that the emissivity of Optimized ZIRLO™, Standard ZIRLO™, and Zircaloy-4 are indistinguishable within the accuracy of the data.

As described in Section 6.3.4 of Reference 5, the model for the thermal emissivity of Standard ZIRLO™ used in the CE evaluation models is a second order polynomial function of temperature. It is the same model that is used for Zircaloy-4 cladding.

The test data for Optimized ZIRLO™, Standard ZIRLO™, and Zircaloy-4 are presented in Figure B.4-1 of Appendix B. The test data for the three zirconium alloys indicate [

] [a, b, c]

As described in the discussion of emissivity in Section 4.6.1, emissivity is generally [

] [a, b, c] This value is comparable to the CE model for emissivity at high temperatures where rod-to-rod radiation becomes an important heat transfer mechanism.

As shown in Figure B.4-1, the test data show that the emissivity of Optimized ZIRLO™, Standard ZIRLO™, and Zircaloy-4 are reasonably similar when measured on a consistent basis, in this case, in a vacuum. Thus, the data do not give any reason to suggest that the emissivities of the three alloys would be dissimilar in the high temperature steam environment of a LOCA.

Base on the above, it is concluded that the model for the thermal emissivity of Standard ZIRLO™ that is used in the CE evaluation models is acceptable for application to Optimized ZIRLO™ cladding.

Thermal Expansion

The test data for the thermal expansion of Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.5 of Appendix B. [

] [a, b, c] The data were used to define mean coefficients of thermal expansion for

[ ] a, b, c The diametral coefficients range from [ ] a, b, c Section B.5 concludes that the diametral thermal expansion of ZIRLO™ alloys is independent of tin content, with more than 90% confidence.

The CE evaluation models use diametral thermal expansion. The same model is used for both Standard ZIRLO™ and Zircaloy-4 cladding. The model is described in Section 6.3.5 of Reference 5. A least square linear fit to the heatup portion of the model [ ] a, b, c gives a slope (i.e., coefficient of thermal expansion) of [ ] a, b, c

Section 6.3.5 of Reference 5 describes a sensitivity study that demonstrated the insensitivity of peak cladding temperature to differences in thermal expansion at high temperature (>1500°F). The study calculated an insignificant change in peak cladding temperature [ ] a, b, c for the change in thermal expansion that was investigated.

A similar sensitivity study was performed for Optimized ZIRLO™ to demonstrate that the peak cladding temperature is insensitive to differences in thermal expansion over the complete range of temperatures encountered during a LOCA. The study consisted of two cases. The first used the CE model for thermal expansion. The second used a single value of [ ] a, b, c for the coefficient of thermal expansion. This value, which is greater than the largest Optimized ZIRLO™ value, was used for both heating and cooling and for all temperatures. The result was the same as the previous study; i.e., the peak cladding temperature changed by [ ] a, b, c

Based on the results of the sensitivity study, it is concluded that the model for the thermal expansion of Standard ZIRLO™ that is used in the CE evaluation models is acceptable for application to Optimized ZIRLO™ cladding.

Modulus of Elasticity

The test data for the modulus of elasticity of Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.7 of Appendix B. Data were obtained [

] a, b, c Section B.7 concludes that the modulus of elasticities of Optimized ZIRLO™ and Standard ZIRLO™ are indistinguishable.

The CE evaluation models use a model for modulus of elasticity in the circumferential direction. The model, which is used for both Standard ZIRLO™ and Zircaloy-4, is described in Section 6.3.6 of Reference 5. The model consists of [ ] [a, b, c] The model and the data for Optimized ZIRLO™ and Standard ZIRLO™ are in reasonable agreement over the temperature range covered by the data.

In providing the basis for the applicability of the Zircaloy-4 model for modulus of elasticity to Standard ZIRLO™ in the absence of any test data for Standard ZIRLO™, Section 6.3.6 of Reference 5 describes how variations in the modulus of elasticity between Standard ZIRLO™ and Zircaloy-4 will not have a significant impact on the cladding dimensions and, consequently, on the gap conductance, gap pressure, and cladding temperature. Based on those arguments and on the reasonable agreement between the test data and the model shown at low temperature, it is concluded that the model for the modulus of elasticity of Standard ZIRLO™ that is used in the CE evaluation models is acceptable for application to Optimized ZIRLO™ cladding.

Poisson's Ratio

The test data for Poisson's ratio for Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.7 of Appendix B. Data were obtained [ ] [a, b, c] Section B.7 concludes that the Poisson's ratios for Optimized ZIRLO™ and Standard ZIRLO™ are indistinguishable.

As described in Section 6.3.7 of Reference 5, the model for Poisson's ratio used in the CE evaluation models consists of a linear equation [ ] [a, b, c] The same model is used for both Standard ZIRLO™ and Zircaloy-4 cladding.

For the same reasons used for modulus of elasticity, Section 6.3.7 of Reference 5 reasoned that any differences in Poisson's ratio between Standard ZIRLO™ and Zircaloy-4 will have an insignificant impact on gap conductance and gap pressure and, hence, on the cladding temperature. Therefore, in the absence of any data, it was concluded that the model is acceptable for application to Standard ZIRLO™ cladding. Given the relative insensitivity of cladding temperature to variations in Poisson's ratio established in Reference 5, the same conclusion is reached for Optimized ZIRLO™ cladding. That is, the model for Poisson's ratio that is used in the CE evaluation models for Standard ZIRLO™ is acceptable for application to Optimized ZIRLO™ cladding.

Hardness

The test data for the microhardness of Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.8 of Appendix B. The data were obtained [

] a, c Section B.8 concludes that the difference in hardness between Optimized ZIRLO™ and Standard ZIRLO™ is minor.

The model for hardness that is used for Standard ZIRLO™ cladding in the CE evaluation models is described in Section 6.3.8 of Reference 5. It is the same model that is used for Zircaloy-4 cladding. The model consists of [

] a, b, c

The mean values listed in Table B.8-1 for the hardness of Optimized ZIRLO™ and Standard ZIRLO™ at room temperature differ from the value of [ ] a, b, c given by the CE evaluation model by [
.] a, b, c

In the CE evaluation models, cladding hardness is used in the calculation of the gap conductance when the fuel and cladding are in contact. Given the limited conditions under which the fuel and cladding are in contact during a LOCA, Section 6.3.8 of Reference 5 reasoned that any difference in hardness between Zircaloy-4 and Standard ZIRLO™ would have an insignificant impact on the gap conductance and, hence, on cladding temperature. Consequently, in the absence of hardness test data, it was concluded that the Zircaloy-4 cladding hardness model was suitable for application to Standard ZIRLO™ cladding. The room temperature data for Standard ZIRLO™ and Optimized ZIRLO™ support the continued applicability of that conclusion. Therefore, it is concluded that the model for the hardness of Standard ZIRLO™ that is used in the CE evaluation models is acceptable for application to Optimized ZIRLO™ cladding.

Rupture Temperature

The test data for the rupture temperature of Optimized ZIRLO™ cladding are documented in Section B.13 of Appendix B. Data were [

] [a, b, c] Section B.13 concludes that the data for Optimized ZIRLO™ are indistinguishable from the original data for Standard ZIRLO™.

As described in Section 6.3.9 of Reference 5, the model for the rupture temperature of Standard ZIRLO™ cladding that is used in the CE evaluation models is a table of rupture temperature versus engineering hoop stress.

Figure B.13-2 compares the test data to the model. The agreement between the data and the model is similar to the agreement between the original Standard ZIRLO™ test data that was used to develop the model and the model (Figure D-1 of Reference 1).

Based on the agreement between the Optimized ZIRLO™ test data and the Standard ZIRLO™ model, it is concluded that the model for the rupture temperature of Standard ZIRLO™ cladding that is used in the CE evaluation models is applicable to Optimized ZIRLO™ cladding.

Rupture Strain

The test data for the circumferential rupture strain of Optimized ZIRLO™ cladding are documented in Section B.13 of Appendix B. Data were obtained [

] [a, b, c] Section B.13 concludes that the data for Optimized ZIRLO™ are indistinguishable from the original data for Standard ZIRLO™.

As described in Section 6.3.10 of Reference 5, the model for the circumferential rupture strain of Standard ZIRLO™ cladding that is used in the CE evaluation models is a table of circumferential rupture strain versus rupture temperature.

Figure B.13-1 compares the test data to the model. The agreement between the data and the model is similar to the agreement between the original Standard ZIRLO™ test data that was used to develop the model and the model (Figure D-6 of Reference 1).

Based on the agreement between the Optimized ZIRLO™ test data and the Standard ZIRLO™ model, it is concluded that the model for the circumferential rupture strain of Standard ZIRLO™ cladding that is used in the CE evaluation models is applicable to Optimized ZIRLO™ cladding.

Assembly Blockage

As described in Section 6.3.11 of Reference 5, the assembly blockage model for Standard ZIRLO™ cladding that is used in the CE evaluation models was developed from the rupture strain model using the geometric conversion methodology from NUREG-0630 (Reference 13). Since it was concluded above that the Standard ZIRLO™ rupture strain model is applicable to Optimized ZIRLO™ cladding, it follows that the Standard ZIRLO™ assembly blockage model is also applicable to Optimized ZIRLO™ cladding.

The Standard ZIRLO™ assembly blockage model, which consists of a table of assembly blockage as a function of rupture temperature, is documented in Table 6.3.11-1 of Reference 5.

Pre-Rupture Plastic Strain

The CE LBLOCA evaluation model uses a pre-rupture plastic strain (i.e., high temperature creep) model that calculates plastic strain as a function of cladding temperature, cladding rupture temperature, and cladding rupture strain. The model was prescribed by the NRC during the initial review of the CE LBLOCA evaluation model and, hence is referred to as the "NRC model". It is used in STRIKIN-II to determine the inside diameter of the cladding that is used in the calculation of the fuel-to-cladding gap conductance and in the calculation of the fuel rod internal pressure. The model is also used in the CEFLASH-4A dynamic fuel rod internal pressure model. Because the results of SBLOCA analyses are less sensitive to the fuel-to-cladding gap conductance, the CE SBLOCA evaluation model does not use a plastic strain model.

As described in Section 6.3.12 of Reference 5, the NRC model is applied to Standard ZIRLO™ cladding with no changes to the model itself. When the model is applied to Standard ZIRLO™ cladding, the Standard ZIRLO™ models for rupture temperature and rupture strain are used to determine the cladding rupture temperature and rupture strain in the above equation.

The results of the Optimized ZIRLO™ high temperature creep tests are presented in Section B.14 of Appendix B and are further discussed in Section 4.6.1. Section 4.6.1 concludes that the Optimized ZIRLO™ and Standard ZIRLO™ data are [

]^{a,b,c} Similarly, it is judged that the pre-rupture plastic strain model that is used in the CE LBLOCA evaluation model for Standard ZIRLO™ (i.e., the NRC model) is acceptable for application to Optimized ZIRLO™ cladding.

Metal-Water Reaction Rate

The test data for the high temperature metal-water reaction rate for Optimized ZIRLO™ and Standard ZIRLO™ are documented in Section B.15 of Appendix B. [

]$^{a, b, c}$

Parabolic reaction rates were calculated [ ]$^{a, c}$ for each material lot. Section B.15 concludes that all the test data fall well below the Baker-Just metal-water reaction rate model.

The CE evaluation models use the Baker-Just metal-water reaction rate model for Standard ZIRLO™ cladding. Applicability of the Baker-Just model to Standard ZIRLO™ cladding is described in Section 6.3.13 of Reference 5.

Figure B.15-1 compares the parabolic reaction rate constants calculated from the test data to the Baker-Just model. The comparison shows that the Baker-Just model predicts higher reaction rate constants than those calculated for Optimized ZIRLO™. Based on this comparison, it is concluded that the Baker-Just model is conservatively applicable to Optimized ZIRLO™ cladding.

Summary

The previous sections compare and evaluate the Optimized ZIRLO™ test data relative to the corresponding cladding models for Standard ZIRLO™ that are used in the CE evaluation models. The evaluations conclude that the models used for Standard ZIRLO™ are acceptable for application to Optimized ZIRLO™ cladding in ECCS performance analyses using the CE evaluation models.

Figure 4.6.2-1
Specific Heat (Heatup) Comparison of Test Data and CE Evaluation Model

[ ]a, b, c

Figure 4.6.2-2
Specific Heat (Cooldown) Comparison of Test Data and CE Evaluation Model

a, b, c

Figure 4.6.2-3
Thermal Conductivity Comparison of test Data and CE Evaluation Model

a, b, c

4.6.3 Applicability of 10 CFR 50.46 to Optimized ZIRLO™

Ring compression tests were performed on Optimized ZIRLO™ and Standard ZIRLO™ to assess the retained ductility of the cladding following oxidation in high temperature steam at conditions up to and beyond the maximum cladding oxidation and peak cladding temperature requirements specified in 10 CFR50.46. The results show that the retained ductility of Optimized ZIRLO™ is equivalent to that of Standard ZIRLO™. Therefore, the 10 CFR 50.46 requirements applicable to Standard ZIRLO™ are also applicable to Optimized ZIRLO™. Details of the testing methods and results are provided in the Appendices A and B.

4.7 Radiological

As documented in the original submittal to the NRC[3], the introduction of ZIRLO™ cladding did not have any appreciable effect on source terms and radiological dose analyses. The principal radiological effect that was discussed, was related to the increased burnup of the fuel from 60 GWD/MTU to 75 GWD/MTU. Even though Reference 3 was only licensed by the NRC to 60 GWD/MTU, the evaluations/analyses performed in support of that submittal would still be considered bounding for the application of Optimized ZIRLO™, which is requested to be licensed by the NRC to 62 GWD/MTU.

The original source terms and radiological analyses assumed Zircaloy-4 as a cladding material. Reference 3 introduced ZIRLO™ cladding and this addendum discusses the Optimized ZIRLO™ product. In reviewing the constituent makeup of ZIRLO™ or Optimized ZIRLO™, the addition of a nominal amount of niobium has a negligible effect on source terms or dose analyses. The reduction in tin content, in the Optimized ZIRLO™, will have no impact on source terms or dose analyses.

5.0 Conclusions

Extensive characterization tests performed on Standard and Optimized ZIRLO™ verify that the minor material composition change does not appreciably change the ZIRLO™ physical, mechanical, microstructural or LOCA properties. Therefore, the minor composition change also does not have any impact on analysis models and methods. Standard ZIRLO™ material properties currently utilized in various models and methodologies will be applied to analyses of Optimized ZIRLO™.

6.0 References

1. Letter from W. J. Johnson (Westinghouse) to V. H. Wilson (NRC), "WCAP-12610, VANTAGE + Fuel Assembly Reference Core Report (Proprietary)," NS-NRC-90-3519, June 13, 1990.

2. Letter from A. C. Thadani (NRC) to S. R. Tritch (Westinghouse), "Acceptance for Referencing of Topical Report WCAP-12610 'VANTAGE + Fuel Assembly Reference Core Report'," TAC. NO. 77258, July 1, 1991.

3. Davidson, S. L. (Ed.), et al., "VANTAGE + Fuel Assembly Reference Core Report," WCAP-12610-P-A, April 1995.

4. "Use of Fuel with Zirconium-Based (Other than Zircaloy) Cladding (10 CFR 50.44, 50.46, and Appendix K to Part 50)," Federal Register, Vol. 57, No. 169, Rules and Regulations, pg. 39353 and 39355, August 31, 1992.

5. "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," CENPD-404-P-A, Revision 0, November 2001.

6. Davidson, S. L. (Ed.), et al., "Reference Core Report 17x17 Optimized Fuel Assembly," WCAP-9500-A, May 1982.

7. Davidson, S. L. and Kramer, W. R., "Reference Core Report VANTAGE 5 Fuel Assembly," WCAP-10444-P-A, September 1985.

8. "SCDAP/RELAP5/MOD 3.3 Code Manual: MATPRO - A Library of Materials Properties for Light-Water-Reactor Accident Analysis," NUREG/CR-6150, Volume 4, Revision 2, INEL-96/0422, January 2001.

9. Spaargaren, J. S., "10 CFR 50.46 Evaluation Model Report: WCOBRA/TRAC Two-Loop Upper Plenum Injection Model Updates to Support ZIRLO™ Cladding Option," WCAP-13677-P-A, February 1994.

10. "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," CENPD-132, Addendum 4-P-A, March 2001.

11. "Calculative Methods for the ABB CE Small Break LOCA Evaluation Model," CENPD-137, Addendum 2-P-A, April 1998.

12. "Post-LOCA Long Term Cooling Evaluation Model," CENPD-254-P-A, June 1980.

13. NUREG-0630, "Cladding Swelling and Rupture Models for LOCA Analysis," April 1980.

APPENDIX A
TEST METHODS

Physical Properties

A.1 Density:

Procedure/Technique: The immersion density method was used to experimentally determine the densities of the two tin levels of the Optimized ZIRLO™. The density of each specimen was calculated using the following equation,

$$\rho = (W_{air} * \rho_{solution})/(W_{air} - W_{solution})$$

where:

ρ = Density of the specimen
$\rho_{solution}$ = Density of the solution
W_{air} = Weight of the specimen in air
$W_{solution}$ = Weight of the specimen in the solution

A.2 Specific Heat:

Procedure/Technique: Measurements were made using the methods of ASTM E1269-01, Differential Scanning Calorimetry. The sample is heated electrically at a set rate, measured by thermocouple, and the heat input required to achieve the desired rate is recorded.

A.3 Thermal Conductivity:

Procedure/Technique: In order to determine thermal conductivity, thermal diffusivity was measured by the methods of ASTM E1461 in which one side of a disk-shaped sample is heated with a laser pulse of known energy and the temperature on the back side of the sample is measured with an infrared sensor. The sample is preheated to the desired base temperature in a furnace. The temperature rise on the front face is [ ]$^{a, b, c}$ on the back face. The thermal diffusivity is calculated from the temperature-time profile on the back of the specimen, and converted to thermal conductivity according to the equation,

$$\lambda = \kappa \rho c_p$$

where

λ = thermal conductivity
κ = thermal diffusivity
ρ = density; and
c_p = specific heat, with heats of transformation subtracted out.

A.4 Emissivity:

Procedure/Technique: Hemispherical total emissivity was measured by passing a current through a tubular sample in vacuum ($p < 1$ mPa) to heat it, measuring the temperature with an embedded thermocouple, surrounding it with a chilled, blackened bell jar, and calculating the heat input necessary to maintain the temperature. This is consistent with the ASTM method (C835-00), except that a tubular specimen was used instead of a strip. It is judged that the difference in shape had minimal effect on the results, whereas it allowed the tests to be performed on standard material. The temperature range accessible was limited by the tendency of the ends of the samples to reach a higher temperature than the center, so that chemical interactions between the specimen and the holders occurred when the test region was at relatively low temperatures.

A.5 Thermal Expansion (Dilatometry):

Procedure/Technique: The dilatometer measures the dimensional change of the specimen as a function of temperature. Axial test specimens were nominally 2 inches long (51 mm). For diametral measurements, half inch long samples were placed adjacent to each other to obtain a nominal gauge length of 47.5 mm. For some of the diametral measurements, the stability of the stack was increased by placing an Inconel rod though holes drilled in the tube sections.

The specimens were heated at a rate of 3 °C/minute and the length change was monitored by a digital transducer at the end of a push rod in contact with the specimen. Data were collected at 30-second intervals or about every 1.5 °C. The resolution of the digital transducer was 0.001 mm (1 µm). The specimen was heated in a closed system that was evacuated and backfilled with argon. A small flow of argon was maintained during the measurement to minimize oxidation of the sample. [

]$^{a, b, c}$

The system was calibrated by running a sapphire reference sample from Anter Corporation. The calibration run was conducted using the same parameters that were used during measurement of the test specimens (i.e., heating and cooling rates of 3 °C/minute). Deviation between the measured expansion and book value for the sapphire expansion was attributed to the system expansion. This deviation was then used to correct the measured expansion of the Zr alloy samples for system expansion.

$$(\Delta L/L)_{corrected} = (\Delta L/L)_{measured} + Deviation$$

A.6 Phase Transition Temperature:

Procedure/Technique: This analysis used data from deviations from smooth curves in the dilatometry (described above) and in the specific heat measurements (also described above) to determine the phase transition temperatures.

A.7 Mechanical Tests:

Procedure/Technique: Mechanical tests were performed on [ ]$^{a, b, c}$ lots of ZIRLO™ cladding with nominal tin content ranging from [ ]$^{a, b, c}$ w/o. Test temperatures were [ ]$^{a, b, c}$ Measured properties include elastic modulus, Poisson's ratio (temperature ≤ 200 °C), 0.2% offset yield stress, ultimate stress and total elongation.

Testing was performed on a 50,000-pound Instron (Model 1127) tensile machine. An extensometer was attached to the 2-inch gauge section of the tubes to monitor sample elongation. Load versus elongation was recorded on two x-y chart recorders. One chart recorder measured the yield portion of the tensile curve and was used for determining the elastic modulus and 0.2% offset yield. The second chart recorder measured the full load versus elongation curve and provided the ultimate load and total elongation.

Poisson's ratio was measured for the low temperature tests (RT and 200 °C). A stain gauge (Micro-Measurements WK-03-125CA-350) was attached to the specimen to measure diametral strain while the extensometer measured axial displacement over the 2-inch gauge length. Poisson's ratio was determined from the slope of the diametral strain versus axial displacement curve.

Strain rate was controlled by the crosshead speed of the tensile machine. For selected samples, axial displacement over the 2-inch gauge was recorded as a function of time with the slope of the curve being proportional to strain rate. These curves were used to determine strain rates through the 0.2% offset yield and through uniform elongation to determine appropriate crosshead speeds to meet the test requirement of < 0.2%/minute through 1% strain and < 2%/minute for strains greater than 1%.

The hoop tests were based on two articles published in The Journal of Testing and Evaluation which describe a split-D type procedure. Testing was performed on a 50,000-pound servohydraulic testing machine. Specialized tooling and extensometer were developed in-house. Load, time, and displacement were recorded digitally with the testing system controller.

A.8 Microhardness Test:

Procedure/Technique: A Vickers microhardness test (ASTM E384-99e1) was performed by pressing an indenter of standardized shape into the specimen with a known force, and measuring the size of the indentation. Because it measures a very small region of the sample, it is useful in determining the uniformity of mechanical properties through the thickness of a tube wall or strip. The data reported here were measured on either surfaces parallel to the long axis of the tube ("longitudinal") or perpendicular to the long axis ("transverse").

A.9 Creep:

Procedure/Technique: The thermal creep test was performed at 725 °F, at an effective stress of 15.6 ksi, for a total of 40 days. The test was conducted in accordance with Westinghouse internal procedures.

A.10 Fatigue:

Procedure/Technique: The test was performed using push and pull loading conditions in the tube axial direction and conducted in accordance with Westinghouse internal procedures. [

]a, b, c

A.11 Texture:

Procedure/Technique: Direct x-ray pole measurements were made at mid-wall, inner and outer diameter locations. The measurements were made in accordance with Westinghouse internal procedures.

A.12 Corrosion:

Procedure/Technique: The alloys were corrosion tested in 680 °F water and 800 °F steam environments. The water test was conducted in accordance with the ASTM G2 while the 800 °F steam tests were performed in accordance with Westinghouse internal procedures.

A.13 Single Rod Burst Test:

Procedure/Technique: Westinghouse performed high temperature burst tests on ZIRLO™ cladding samples in the late 1980s. Upon completion of the tests and over time, the original test equipment has been dismantled and scrapped. To perform the high temperature burst tests on the current materials, a new test facility was designed and built. The new burst test facility and procedures were designed to minimize any differences from the prior ZIRLO™ test program. Axial and azimuthal temperature measurements taken as part of the facility qualification indicated that the new facility would be capable of closely replicating the prior burst test results. This was confirmed by performing burst tests with control samples of standard ZIRLO™ tubing.

Each single rod burst test was conducted using [

]a, b, c The burst temperature for each sample was recorded, and the circumference at the rupture location was measured for use in calculating the circumferential burst strain.

A.14 High Temperature Creep Test:

Procedure/Technique: The French Commissariat a l'Energie Atomique (CEA) in Saclay, France using the EDGAR-2 facility performed the creep tests. Individual samples of cladding were inductively heated to the test temperatures in steam and pressurized with argon. The system pressure was controlled such that a constant hoop stress state was maintained within the cladding. The change in diameter of the cladding was monitored by a laser measurement device and periodic readings were recorded as a function of time.

Plots of the diametral strain as a function of time were analyzed. The slope of a line originating at zero strain, drawn tangent to strain versus time curve produces a creep rate for each hoop stress and temperature combination at 1183 °K or lower. For Tests at 1273 °K the secondary phase of creep was measured. The creep rates as a function of hoop stress are reported in Appendix B of this report. The solid lines represent the results obtained for Standard ZIRLO™ as part of the initial ZIRLO™ licensing effort (as reported in Appendix C of Reference 3).

A.15 Metal Water Reaction Test:

Procedure/Technique: [ ]a, b, c lots of Optimized ZIRLO™ samples were tested, along with one lot of Standard ZIRLO™ for control and comparison purposes. 1.5-inch long samples of cladding were prepared from each material lot. The sample dimensions were measured and the pre-oxidized masses were noted. [ ]a, b, c The oxidized mass of each sample, exposure temperature, and the exposure time were recorded for each sample.

A parabolic reaction rate for each temperature was then calculated using a series of plots and linear fits. The measured mass gains for each temperature were squared and then plotted as a function of time. This results in a linear relationship between mass gained from oxidation as a function of time. A linear regression analysis on this data provides a slope value that corresponds to a parabolic reaction rate. This reaction rate defines the relationship between exposure time and oxide formation. This analysis was repeated for each material at each of the [ ]a, b, c oxidizing temperatures.

A.16 Ring Compression Test:

Procedure/Technique: A collection of oxidized Standard ZIRLO™ and Optimized ZIRLO™ samples that were prepared as part of the metal-water reaction analysis were submitted for ring compression testing. Ring samples were taken from oxidation specimens with targeted ECR values of [ ]a, b, c

The tests were performed at 275 °F. The load and deflection data were then analyzed to determine the retained ductility of the cladding.

APPENDIX B

TEST RESULTS

Physical Properties

B.1 Density:

Results: The densities of each alloy were calculated based on weight measurements of each sample in air and immersed in water using the formula described in Appendix A. The results are tabulated in the table below. The result suggests a minor decrease in density with lower tin content. The new measured densities are slightly higher compared to the value, [ ][a, b, c] reported previously. This small difference may be due to differences in equipment sensitivity and experimental procedure.

Table B.1-1
Density of Standard and Optimized ZIRLO™

a, b, c

Table B.1-2 (cont.)
Detailed Sampling of Standard and Optimized ZIRLO™ for Density

a, b, c

[ ]

B.2 Specific Heat:

Results: [

]a, b, c

Within the accuracy of this data, the specific heats of Standard ZIRLO™ and Optimized ZIRLO™ are equal.

[

]a, b, c

Figure B.2-1
Specific Heat of Standard and Optimized ZIRLO™ on Heating

[ ]a, b, c

Figure B.2-2
Specific Heat of Standard and Optimized ZIRLO™ on Cooling

[ ]a, b, c

Table B.2-1
Specific Heat of Standard and Optimized ZIRLO™ on Heating and Cooling

a, b, c

Table B.2-1 (cont.)
Specific Heat of Standard and Optimized ZIRLO™ on Heating and Cooling

a, b, c

Table B.2-1 (cont.)
Specific Heat of Standard and Optimized ZIRLO™ on Heating and Cooling

a, b, c

Table B.2-1 (cont.)
Specific Heat of Standard and Optimized ZIRLO™ on Heating and Cooling

a, b, c

[ ]

Table B.2-1 (cont.)
Specific Heat of Standard and Optimized ZIRLO™ on Heating and Cooling

a, b, c

[ ]

B.3 Thermal Conductivity:

Results: Thermal diffusivity is shown in Figure B.3-1 and thermal conductivity in Figure B.3-2. Within the accuracy of this data, thermal transport properties (diffusivity and conductivity) of Standard ZIRLO™ and Optimized ZIRLO™ are indistinguishable, as would be expected.

Figure B.3-1
Thermal Diffusivity of Standard and Optimized ZIRLO™

a, b, c

[ ]

Figure B.3-2
Thermal Conductivity of Standard and Optimized ZIRLO™

a, b, c

[ ]

Table B.3-1
Thermal Diffusivity and Conductivity of Standard and Optimized ZIRLO™

a, b, c

[ ]

B.4 Emissivity:

Results: The measurements are shown in Figure B.4-1. Within the accuracy of this data, the emissivity of Standard ZIRLO™, Optimized ZIRLO™, and Zircaloy-4 are indistinguishable. Emissivity measurement uncertainty is estimated as ± 2%.

Figure B.4-1
Thermal Emissivity of Oxidized Zirconium Alloys

a, b, c

[ ]

Table B.4-1
Thermal Emissivity of Oxidized Zirconium Alloys

a, b, c

[ ]

B.5 Thermal Expansion (Dilatometry):

Results: The axial thermal expansion of ZIRLO™ from room temperature to 500 °C is independent of tin content for the materials tested, with more than 99% confidence.

The diametral thermal expansion of ZIRLO™ from room temperature to 500 °C is independent of tin content for the materials tested, with more than 90% confidence.

a, b, c

[ ]

Figure B.5-1
Axial Thermal Expansion Curve

a, b, c

[ ]

Table B.5-1
Axial Thermal Expansion Data

a, b, c

[ ]

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

[ ]a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

[ ]a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

**Table B.5-1 (cont.)
Axial Thermal Expansion Data**

a, b, c

[ ]

Table B.5-1 *(cont.)*
Axial Thermal Expansion Data

a, b, c

Table B.5-1 (cont.)
Axial Thermal Expansion Data

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

a, b, c

Figure B.5-2
Typical Diametral Thermal Expansion Curve

[ ]

Table B.5-2

Diametral Thermal Expansion Data

a, b, c

[ ]

a, b, c

[ ]

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

[ ]a, b, c

**Table B.5-2 (cont.)
Diametral Thermal Expansion Data**

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

**Table B.5-2 (cont.)
Diametral Thermal Expansion Data**

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

**Table B.5-2 (cont.)
Diametral Thermal Expansion Data**

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

[ ]a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

[ ]a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

[ ]a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

Table B.5-2 (cont.)
Diametral Thermal Expansion Data

a, b, c

B.6 Phase Transition Temperature:

Results: Phase transition temperatures are determined from a break in the curve of some property which is known to show a discontinuous change across phase transitions. For the present work, [

.][a, b, c]

[ ] a, b, c

Figure B.6-1
α↔ α + β Phase Transition as a Function of Tin Content in ZIRLO™

a, b, c

[ ]

Table B.6-1
$\alpha \leftrightarrow \alpha + \beta$ Phase Transition as a Function of Tin Content in ZIRLO™

a, b, c

[ ]

B.7 Mechanical Test:

a, b, c

Results: [ ]

In measures of ductility (total elongation in the longitudinal direction, failure strain circumferentially), Optimized and Standard ZIRLO™ are indistinguishable at temperatures above room temperature.

In elastic properties (longitudinal and circumferential Young's modulus and circumferential/longitudinal Poisson's ratio), Optimized and Standard ZIRLO™ are indistinguishable.

Figure B.7-1
Longitudinal Yield Stress of ZIRLO™ with Three Tin Levels

a, b, c

[ ]

Figure B.7-2
Longitudinal Ultimate Tensile Stress of ZIRLO™ with Three Tin Levels

a, b, c

[ ]

a, b, c

Figure B.7-3
Longitudinal Total Elongation of ZIRLO™ with Three Tin Levels

[ ]

Figure B.7-4

Longitudinal Young's Modulus of ZIRLO™ with Three Tin Levels

a, b, c

[ ]

Figure B.7-5
Poisson's Ratio, Hoop/Longitudinal, of ZIRLO™ with Three Tin Levels

a, b, c

[ ]

Figure B.7-6
Circumferential Yield Stress

a, b, c

Figure B.7-7
Circumferential Failure Stress

a, b, c

Figure B.7-8
Circumferential Failure Strain

a, b, c

Figure B.7-9
Circumferential Young's Modulus

a, b, c

Table B.7-1
Tensile Data

a, b, c

Table B.7-1 (cont.)
Tensile Data

[ ]a, b, c

B.8 Microhardness Test:

Results: The results are plotted in Figures B.8-1 and B.8-2. The difference between the Optimized ZIRLO™ and the Standard ZIRLO™ is minor.

[ ]a, b, c

[ ]a, b, c

Figure B.8-1
Longitudinal Microhardness

a, b, c

Figure B.8-2
Transverse Microhardness

a, b, c

Table B.8-1
Microhardness Data

a, b, c

[ ]

B.9 Creep:

Results: [

]a, b, c

Figure B.9-1
Optimized ZIRLO™ and Standard ZIRLO™ Thermal Creep Data

a, b, c

[ ]

B.10 Fatigue:

Results: The fatigue test results and the Westinghouse fatigue design limit are plotted in Figure B.10-1.

Figure B.10-1
Optimized ZIRLO™ Fatigue Test

[ ] a, b, c

B.11 Texture:

Results: [ ] a, c

Table B.11-1
Optimized and Standard ZIRLO™ Texture Values

[ ] a, b, c

a, b, c

a, b, c

[ ] a, b, c

[ ] a, c

B.12 Corrosion:

Results: [ ] a, b, c

Figure B.12-1
800 °F Corrosion Test

a, b, c

[ ]

Table B.12-1
800 °F Steam Corrosion Test Results

a, b, c

[ ]

Figure B.12-2
680 °F Corrosion Test

[ ] a, b, c

Table B.12-2

[ ] a. b. c

B.13 Single Rod Burst Tests

Results: [

] a, b, c

[

] [a, b, c]. As shown in Figure B.13-1, the new data for Standard and Optimized ZIRLO™ are indistinguishable from the prior ZIRLO™ data.

[

] [a, b, c]

a, b, c

Figure B.13-1

Figure B.13-2

a, b, c

Table B.13-1
Standard ZIRLO™ Burst Test Control Data for Comparison to Optimized ZIRLO™

a, b, c

Table B.13-2
Optimized ZIRLO™ Burst Test Data

a, b, c

B.14 High Temperature Creep Test:

Results: [

]a, b, c

As shown in Figure B.14-1, the Standard and Optimized ZIRLO™ creep rates are in reasonable agreement with the current ZIRLO™ model for temperatures between [

]a, b, c

Figure B.14-1
Creep Rates for Standard and Optimized ZIRLO™

a,b, c

Table B.14-1
Creep Rates for Optimized ZIRLO™

a, b,c

[ ]

Table B.14-2
Creep Rates for Standard ZIRLO™

a, b c

[ ]

B.15 Metal Water Reaction Test:

Results: [

] a, b, c All of the test data fall well below the Baker-Just model. This satisfies the 10 CFR 50 Appendix K requirement that Baker-Just be used to conservatively predict the oxidation behavior of the cladding under LOCA conditions. [

] a, b, c

The calculated reaction rates are provided in Table B.15-1.

Table B.15-1
Reaction Rates for Standard and Optimized ZIRLO™

[ ] a, b c

Figure B.15-1
Reaction Rates for Standard and Optimized ZIRLO™

a, b, c

B.16 Ring Compression Test:

Results: The results for the 275°F ring compression tests for two lots of the Optimized ZIRLO™ and for one lot of Standard ZIRLO™, which was the reference case, are shown graphically in Figure B.16-1. [

] a, b, c

[

] a, b, c This data is presented for information only. [
] a, b, c

Based on these tests, all of the 275°F ring compression tests satisfy the 10% relative displacement criterion at ECR values above 17%, satisfying the minimum ductility requirement. The majority of the Standard ZIRLO™ and the Optimized ZIRLO™ data points fall within the population of ZIRLO™ data collected previously and presented to the NRC staff. To summarize, the following conclusions may be drawn from these observations:

- The Optimized ZIRLO™ satisfies the minimum ductility requirement for material oxidized to 17% ECR,
- The retained ductility of the Optimized ZIRLO™ is effectively the same as that of Standard ZIRLO™, [
-

] a, b, c

Figure B.16-1
Relative Displacement versus Equivalent Clad Reacted (ECR) at 275°F

a, b, c

Table B.16-1
Ring Compression Test Results

a, b, c

Table B.16-2
Ring Compression Test Results for Samples Oxidized at 1300°C

a, b, c

[ ]

Section C

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Direct tel: (412) 374-4643
Direct fax: (412) 374-4011
e-mail: greshaja@westinghouse.com

Our ref: LTR-NRC-04-12

February 3, 2004

Enclosed is:

1. One (1) copy of "Westinghouse Responses to NRC Request for Additional Information (RAIs) on Optimized ZIRLO Topical – Addendum 1 to WCAP-12610-P-A" (Proprietary)

Also enclosed is:

1. One (1) copy of the Application for Withholding, AW-04-1792 (Nonproprietary) with Proprietary Information Notice.
2. One (1) copy of Affidavit (Nonproprietary).

This information is being submitted by Westinghouse Electric Company LLC to respond to RAIs on Optimized ZIRLO™ topical – Addendum 1 to WCAP-12610-P-A.

This submittal contains proprietary information of Westinghouse Electric Company LLC. In conformance with the requirements of 10 CFR Section 2.790, as amended, of the Commission's regulations, we are enclosing with this submittal an Application for Withholding from Public Disclosure and an affidavit. The affidavit sets forth the basis on which the information identified as proprietary may be withheld from public disclosure by the Commission.

Correspondence with respect to the affidavit or Application for Withholding should reference AW-04-1792 and should be addressed to J. A. Gresham, Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

J. A. Gresham, Manager
Regulatory Compliance and Plant Licensing

Enclosures

cc: D. Holland
B. Benney
E. Peyton

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Direct tel: (412) 374-4643
Direct fax: (412) 374-4011
e-mail: greshaja@westinghouse.com

Our ref: AW-04-1792

February 3, 2004

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

Subject: Westinghouse Responses to NRC Request for Additional Information (RAIs) on Optimized ZIRLO Topical Addendum 1 to WCAP-12610-P-A (Proprietary)

Reference: Letter from J. A. Gresham to Document Control Desk, LTR-NRC-04-12, dated Feb. 3, 2004

The Application for Withholding is submitted by Westinghouse Electric Company LLC (Westinghouse), pursuant to the provisions of Paragraph (b) (1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.790, Affidavit AW-04-1792 accompanies this Application for Withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this Application for Withholding or the accompanying affidavit should reference AW-04-1792 and should be addressed to J. A. Gresham, Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

J. A. Gresham, Manager
Regulatory Compliance and Plant Licensing

Enclosures

cc: D. Holland
B. Benney
E. Peyton

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared J. A. Gresham, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC (Westinghouse), and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

J. A. Gresham, Manager
Regulatory Compliance and Plant Licensing

Sworn to and subscribed
before me this 3rd day
of February, 2004

Sharon L. Fiori
Notary Public

Notarial Seal
Sharon L. Fiori, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires January 29, 2007
Member, Pennsylvania Association Of Notaries

(1) I am Manager, Regulatory Compliance and Plant Licensing, in Nuclear Services, Westinghouse Electric Company LLC (Westinghouse), and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rule making proceedings, and am authorized to apply for its withholding on behalf of Westinghouse.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse "Application for Withholding" accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by Westinghouse in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of

Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information that is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in "Westinghouse Responses to NRC Request for Additional Information (RAIs) on Optimized ZIRLO Topical – Addendum 1 to WCAP-12610-P-A," (Proprietary), dated January 24, 2004, for response to RAIs, being transmitted by Westinghouse letter (LTR-NRC-04-12) and Application for Withholding Proprietary Information from Public Disclosure, to the Document Control Desk. The proprietary information as submitted for use by Westinghouse is expected to be applicable in other licensee submittals in response to certain NRC Request for Additional Information on Westinghouse Request for Approval of PARAGON.

This information is part of that which will enable Westinghouse to:

(a) Obtain NRC approval of WCAP-16078-P, "Westinghouse BWR ECCS Evaluation Model: Supplement 3 to Code Description, Qualification and Application to SVEA-96 Optima2 Fuel".

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of this information to its customers for purposes of developing nuclear design input data into the Westinghouse nuclear design code system or as a stand-alone code or improving design.

(b) The information requested to be withheld reveals the distinguishing aspects of a methodology which was developed by Westinghouse.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar evaluations and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended.

Further the deponent sayeth not.

PROPRIETARY INFORMATION NOTICE

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

COPYRIGHT NOTICE

Westinghouse Responses to NRC Request for Additional Information (RAIs) On Optimized ZIRLO™ Topical – Addendum 1 to WCAP12610-P-A and CENPD404-P-A.

1. Section 1.2 provides a definition of ZIRLO™ material based upon descriptions presented in both the "NRC SE and Appendix A of WCAP-12610, and also accounting for descriptions of ZIRLO™ in patent documents". The table below lists the alloy content of ZIRLO™ found in these sources.

   <u>**Response 1:**</u>
   ZIRLO™ is a trademark commercially used by Westinghouse in connection with zirconium based alloys containing about 1% niobium (together with smaller amounts of iron and tin and other elements) and having a particular microstructure. The Abstract of US Patent No. 4,649,023 discusses zirconium alloys containing 0.5 to 2.0 percent niobium and "up to 1.5 percent tin". ***Westinghouse has the following patents relating to specific compositions*** **and/or processing: 4,649,023; 5,112,573; 5,125,985, 5,266,131 and 5,230,758. There is not a direct correspondence between the licensed alloy range and the alloy range of a specific patent. The patents are used for commercial protection and are not used to define a basis for a license composition.**

   a. Explain the differences in alloying content and why Optimized ZIRLO™ is within the definition of ZIRLO™ material.

   <u>**Response 1a:**</u>
   The difference in alloy content between the current ZIRLO™ and Optimized ZIRLO™ is the tin level. All other alloying additions remain within the current licensed ranges. ZIRLO™ is an alloy containing 98 % zirconium with added elements of niobium, tin, and iron. An important characteristic of ZIRLO™ is the type of precipitates that are formed in the alloy. Since the precipitates consist of niobium and iron with zirconium and not with tin, the small changes in tin content do not affect the precipitate structure.

   b. Explain why do the nickel and chromium alloying content remain in the patented description of ZIRLO™?

   <u>**Response 1b:**</u>
   The patents do not provide a definition of ZIRLO™. As stated above, patents provide commercial protection for a broader alloy range than the licensed version of ZIRLO™.

c. Will the ZIRLO™ patent be revised to reflect the Addendum 1 alloy content?

<u>Response 1c:</u>
There is no need to revise the above mentioned patents. They will not be revised.

d. A definition of ZIRLO™ is presented in quotation marks in Section 1.2. What is the source of this quote?

<u>Response 1d:</u>
The description quoted was developed by Westinghouse to provide a clear statement of the unique characteristics that define ZIRLO™ and is consistent with WCAP 12610. Optimized ZIRLO™ will continue to be within the definition of ZIRLO™.

2. The material properties of a metal alloy are strongly dependent on its microstructure, which is influenced by both alloy content and material processing.

<u>Response 2:</u>
The microstructure does have a strong effect on the material properties of all zirconium based alloys. The effect is most prominent in the un-irradiated condition. For the high temperature transient conditions the microstructure is changed with the effect that there is no significant residual impact of mildly different starting microstructures on the transient properties. With irradiation the majority of material differences due to processing are also eliminated. An example of this is the mechanical strength of fully recrystallize-annealed tubes which have similar irradiated strength to stress relief annealed tubes

a. Describe, in detail, each step of the current material processing employed to dictate the microstructure of ZIRLO™ (e.g. annealing temperature, beta quench, cold work, age hardening, etc.).

<u>Response 2a:</u>
ZIRLO™ is processed similar to Zircaloy 4 . The process includes:

1. **Ingot melting**
2. **Ingot forging**
3. **Beta quenching of the billet**
4. **Tube shell extrusion**
5. **Tube reductions by pilgering**
6. **Anneals between pilgering**
7. **Final tube annealing and surface conditioning**

ZIRLO™ differs from Zircaloy –4 primarily in the use of a lower annealing temperature to preclude the formation of beta zirconium. This lower

temperature requirement is a result of the lower phase transition temperature characteristic of niobium-containing alloys. Like Zircaloy 4 , the specific processing steps for ZIRLO™ are controlled but not licensed. The main control is on resultant material characteristics, which continue to be defined by the design models.

b. How will the current process described above be altered for Optimized ZIRLO™?

Response 2b:
The same basic processing steps are used in the production of all ZIRLO™.

c. Describe the Quality Control procedures on the control of microstructure (e.g. alloy content, size, and distribution of second phase particles, grain size, etc.).

Response 2c:
The precipitate microstructure is controlled primarily by the relative levels of niobium and iron and to a lesser degree by the processing parameters. The alloy content is controlled by specification and chemistry sampling. A series of qualifications are used to evaluate the product properties such as microstructure and second phase particle characteristics resulting from the prescribed processing. The established process parameters are monitored by Quality Control, in addition to the standard property testing of the final product required by the specifications.

d. Quantify the allowed manufacturing tolerances on alloy content and the control of microstructure?

Response 2d:
The alloy content tolerances are controlled by the applicable material specifications. The current Optimized ZIRLO™ specification has the following alloy chemistry ranges:

Niobium	**0.8 to 1.2 %**
Tin	**0.6 to 1.2 %**
Iron	**0.09 to 0.13%**

The precipitate microstructure is controlled by the qualified processing parameters. To preclude the presence of beta zirconium in the final product the anneal temperatures after extrusion are maintained at about [ ]^a, b, c^. The anneal times and temperatures are controlled to insure adequate formation and aging of the precipitate microstructure. For ZIRLO™, unlike Zircaloy-4, the precipitate microstructure is maintained relatively small. For optimum properties in Zircaloy-4 the precipitates are aged through high temperature anneals to produce large particle sizes for

PWR application. The lower processing temperatures used for ZIRLO™ ensure precipitation of the desired particles.

3. Irradiation experience with Optimized ZIRLO™ is discussed in Section 3.5.
   a. In light of the limited database presented, justify the material properties up to 62,000 MWD/MTU.

<u>Response 3a:</u>
The characterization testing reported in the addendum demonstrates that standard ZIRLO™ material properties currently used in various models and methodologies are applicable to analyses of Optimized ZIRLO™. The primary effects of a reduced tin level in ZIRLO™ are a minor reduction in the unirradiated mechanical strength and improvement in the corrosion resistance. The higher burn-up levels are associated with higher fluence levels. Since the precipitate structure remains the same for current and Optimized ZIRLO™, the past performance of ZIRLO™ precipitate structure at high burn-ups also envelopes the Optimized ZIRLO™ condition.

The irradiation strengthening that occurs with the initial fuel operation negates the starting differences in mechanical strength between Optimized and standard ZIRLO™. Optimized ZIRLO™ mechanical performance will thus be the same as the current ZIRLO™ performance within a few months. This effect has been reported in the literature. An example is found in ASTM STP 681 in an article by K. Pettersson on the effects of irradiation on the mechanical strength of Zircaloy tubes. Figure 2 from the Pettersson STP paper shows that irradiation strengthening occurs very early in the initial operating cycle (after about 2 x10^{21} n/cm^2). Information from hot cell testing of irradiated thimble tubes and cladding confirms the effects of irradiation strengthening negate minor differences in the starting un-irradiated mechanical strength. Due to processing differences the standard ZIRLO™ thimble tubes have a lower unirradiated strength [ ]$^{a, b, c}$ compared to unirradiated fuel cladding. Upon irradiation the mechanical strengths of both the thimble tube and the cladding are increased to similar levels. The difference in unirradiated mechanical strengths between Standard ZIRLO™ and Optimized ZIRLO™ is much less than the [ ]$^{a, c}$ difference between cladding and thimbles.

The difference in corrosion resistance is not removed with irradiation and is a positive result. The corrosion resistance comes primarily from both the precipitate microstructure and the tin levels. As indicated in earlier responses the precipitate structure is not changed with Optimized ZIRLO™, and the tin level reduction results in a lower corrosion rate. This has been confirmed during the second cycle of operation in Byron. The oxide thickness on the Optimized ZIRLO™ cladding continues to show significant improvement over standard ZIRLO™ cladding. Oxide reductions exceeding [ ][a, b, c] have been measured for Optimized ZIRLO™ compared to standard ZIRLO™ after 52 GWD/MTU.

b. Exemptions for LTAs containing Low-Tin ZIRLO™ have been issued for several plants. When will data be available for clad material approaching 0.60 w/o tin and 62,000 MWD/MTU?

Response 3b:
As indicated in Response 3a, we have data on Optimized ZIRLO™ [ ][a, c] now available up to burn-up level of 52,000 MWD/MTU from Byron. Data on fuel to burn-up level of >62000 MWD/MTU should be available in Spring 2005.

Additional data with similar burnup from another plant [ ][a, c] will be available later this year and data on fuel to burn-up level of >62000 MWD/MTU should be available in Spring 2005

In addition, several additional LTA programs with Optimized ZIRLO™ (Tin near [ ][a, c] are on-going or planned.

Plant B – Irradiation started in Fall 02, >62000 MWD/MTU burn-up by 2007
Plant C – Irradiation starting Fall 03, >62000 MWD/MTU burn-up by 2008
Plant D – Irradiation starting Fall 03, >62000 MWD/MTU burn-up by 2008

4. Byron LTAs include Optimized ZIRLO™ thimble tubes. Section 4.4 states, "the use of ZIRLO™ cladding or structural materials for the fuel assembly skeleton...". Is Westinghouse currently using or plan to use either ZIRLO™ or Optimized ZIRLO™ in fuel assembly components other than fuel clad?

Response 4:
Westinghouse is currently using ZIRLO™ in fuel assembly components (thimble tubes and grids). Similarly, Optimized ZIRLO™ has been in use in the Fuel Assembly thimbles and grids in the certain plants currently hosting

Optimized ZIRLO™ LTAs. Westinghouse plans to use Optimized ZIRLO™ in fuel assembly components (thimble tubes and grids) upon WCAP approval.

5. With regard to the continued use of Zircaloy-4 properties in the ZIRLO™ models, the SER for CENPD-404-P-A states, "the staff notes that this practice should not be used in the future, and future applications will be expected to fully measure and develop the material properties of proposed new cladding alloys". This Topical Report supports continued use of Zircaloy-4 properties for Optimized ZIRLO™. Please provide the technical bases and relevant data to support your position.

Response 5:

The implementation of standard ZIRLO™ in Combustion Engineering (CE) designed PWRs (CENPD-404-P-A) involved the application of some Zircaloy-4 correlations to standard ZIRLO™ properties because it was demonstrated that the differences were insignificant. However, the Nuclear Regulatory Commission's Safety Evaluation Report (NRC SER) for CENPD-404-P-A noted that this practice should not be used in the future and future applications would be "...expected to fully measure and develop the material properties of proposed new cladding alloys." In this instance, it is important to recognize three Westinghouse considerations in the development of Optimized ZIRLO™ properties.

1. **The first consideration is that Optimized ZIRLO™ is not a new alloy, rather it meets the established definition of ZIRLO™, albeit with a tighter specification on tin content. Consequently, Westinghouse did not consider the SER requirement in this situation to be applicable.**

2. **The second consideration is to note that although the sources of the ZIRLO™ property correlations were identified in CENPD-404-P-A (i.e., as ZIRLO™ or Zircaloy-4), the property was found to be essentially the same for both materials, and the proposed property correlation is a satisfactory correlation for both ZIRLO™ and Zircaloy-4.**

3. **Finally, and most importantly, even though Optimized ZIRLO™ is only a variation of ZIRLO™, Westinghouse developed and performed an extensive and complete test program (described in Appendix A of WCAP-12610-P-A and CENPD-404-P-A Addendum 1) to evaluate the required Optimized ZIRLO™ and standard ZIRLO™ thermal and mechanical properties and compared those properties to approved properties of ZIRLO™ (described in Appendix B of WCAP-12610-P-A and CENPD-404-P-A Addendum 1). It was concluded that the existing property correlations, whether originally from ZIRLO™ or from**

Zircaloy-4, are, in fact, no less applicable as Optimized ZIRLO™ property correlations. Thus, Westinghouse believes it has conformed to the referenced SER requirement that the properties should be fully measured. Westinghouse concluded, therefore, that the correlations for standard ZIRLO™ in CENPD-404-P-A are also Optimized ZIRLO™ property correlations.

6. WCAP-12610-P-A Section 2.5.5 addresses fuel clad wear. Why is this design criterion not included for Optimized ZIRLO? Will the models maintain the 10% design wall thickness reduction?

Response 6:
The Fuel Rod Clad Fretting was addressed in our internal Design Review Process. The Criterion, Basis, and Verification for the Fuel Rod Clad Fretting is as follows:

Criterion: Grid assembly springs shall be designed to limit fuel rod clad fretting to less than [ ]$^{a, c}$ of the clad wall thickness at the end of fuel assembly life, considering all pertinent factors such as spring relaxation due to irradiation, clad creep-down, grid growth, etc. (There is no change in this criterion).

Basis: Experience has shown that by meeting these spring requirements, excessive fretting of the fuel rod clad is prevented.

Verification: Based on VIPER test results, the fuel rods of ZIRLO™ material have demonstrated fretting wear resistance that is equal to or better than the fuel rods with Zircaloy-4 material. VIPER tests conducted on Optimized ZIRLO™ also met the fretting wear resistance criteria. As the reactor starts operation, an oxide film forms on both the spring and rod surfaces. It is these surfaces that are subject to any potential fuel clad wearing. Both surfaces are zirconium oxide and there are no expected differences in the Optimized ZIRLO™ oxide characteristics. Hence the wear rate for the Optimized ZIRLO™ fuel rods is expected to be comparable to the ZIRLO™ material. Therefore, the design criterion is satisfied.

7. The evaluation of DNB propagation in Section 4.2.1 concludes that since there is no effect on rod internal pressure, there will be no effect on DNB propagation.

a. The extent of DNB propagation would also depend on material properties (e.g., creep) and this needs to be addressed.

b. The criteria states that the internal pressure of the lead fuel rod in the reactor will be limited to a value below that which could cause extensive DNB propagation to occur. How is extensive DNB propagation quantified under normal and transient conditions? Are the potential clad failures associated with DNB propagation accounted for in the dose calculations?

Response 7a:

CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure", provides a more comprehensive discussion of DNB propagation than is offered in either WCAP-12610-P-A and CENPD-404-P-A, Addendum 1 or CENPD-404-P-A. Westinghouse agrees that the extent of DNB propagation depends on rod internal pressure and other material properties such as creep. It also depends on operating conditions such as linear heat rate and temperature of the cladding which, in turn, depends on the duration of the time in DNB, coolant temperature and pressure conditions, waterside corrosion and cladding loss, and the amount of rod-to-rod gap closure during a DNB transient. The evaluation in WCAP-12610-A and CENPD-404-P-A Addendum 1, Section 4.2.1, includes these dependencies as well as the potential distribution of fuel rods in DNB and above the reactor system coolant pressure. Since there is no effect of Optimized ZIRLO™ on normal plant operation, no effect on the individual DNB transient behavior relative to standard ZIRLO™, and no difference from ZIRLO™ material properties, there will be no effect on the distribution of fuel rod internal pressures relative to the distribution of fuel rods experiencing DNB during a DNB transient. As a result, there is no effect on the extent of DNB propagation. The only effect would be from reduced waterside corrosion and, therefore, reduced clad thinning and reduced creep, which would have a beneficial effect. This beneficial effect is ignored. Since this is not credited in the analyses, the result is no effect on DNB or DNB propagation.

Response 7b:

A specific limit on the fraction of rods allowed to experience DNB due to propagation is based on requiring that the total number of rods in DNB , including DNB propagation effects are within the limits for rod failure by DNB assumed in the offsite dose limit calculations. DNB propagation analyses are performed for each Condition III/IV DNB event identified. Typically, these events include: Single Rod Withdrawal at Power, Ejected Rod, and Locked Rotor. The actual number of rods allowed in DNB for each analysis is confirmed in the evaluation. Therefore, the clad failures associated with DNB propagation are bounded by the dose calculations.

8. WCAP-12610-P-A Section 2.5.3 lists a temperature limit for Condition I which differs from the corresponding value in Addendum 1. Is this a planned change to the criteria or a typo?

Response 8:

Yes, this is a typographical error; WCAP-12610-P-A Section 2.5.3 lists the correct temperature limit of 780 °F for Condition I. A correction will be made to the approved report WCAP-12610-P-A and CENPD-404-P-A Addendum 1.

9. Section 4.2.2 makes a statement concerning the "...continued use of Standard ZIRLO™ properties and models for Optimized ZIRLO™...". Identify when properties and models are based upon which clad material (e.g., Standard ZIRLO™, Optimized ZIRLO™, Zircaloy-4).

Response 9:

The Optimized ZIRLO™ measured properties and, therefore, model correlations, have been demonstrated to be equivalent to standard ZIRLO™ in Appendix B of WCAP-12610-P-A and CENPD-404-P-A Addendum 1. The implementation of standard ZIRLO™ in CE designed PWRs (see CENPD-404-P-A) involved the application of some Zircaloy-4 correlations to standard ZIRLO™ properties because it was demonstrated to be appropriate. This approach was accepted by the NRC as part of the review and approval of CENPD-404-P-A, as documented in the SER. The identification of when the source of property and model correlations were ZIRLO™ or Zircaloy-4 (OPTIN™) is summarized in CENPD-404-P-A Appendix A, Tables 7 through 25.

As stated in Response 5, however, it is concluded that the existing property correlations, whether originally from ZIRLO™ or from Zircaloy-4, are, in fact, directly applicable for use as Optimized ZIRLO™ properties.

10. Section 4.2.2 states that the calculation of DNB propagation depends on internal rod pressure, high temperature creep, and high temperature burst stress. Do DNB propagation calculations predict clad burst under non-LOCA transient conditions? If so, provide information on how the potential impacts of this failure mechanism have been addressed within the respective events dose calculation.

Response 10:

Under certain non-LOCA transient conditions, DNB propagation calculations may predict cladding burst. If clad burst is predicted, the fuel rod internal

pressure is relieved and no further cladding strain occurs. The dose contribution from the burst fuel rod is automatically accounted for in the dose calculation because it was already in DNB and, consequently, conservatively assumed to fail regardless of whether or not burst was actually predicted.

11. With regard to potential differences between tensile and compressive creep rates and the "relatively small creep database for ZIRLO™", the SER for CENPD-404-P-A states, "WEC committed to acquire more in-reactor creep data under both tensile and compressive stress conditions for ZIRLO™ material". The SER concludes, "On the basis of the approved creep model and the commitment to acquire additional data, the staff considers that the creep model for the NCLO criterion is acceptable for FATES3B".

    a. What is the current status of the "detailed irradiation program for ZIRLO™"?

    Response 11a:
    A detailed irradiation growth and creep program initiated irradiation in Vogtle unit 2 cycle 10 in November 2002. The first test assembly is scheduled to be discharged at the end of cycle 10 in May 2004.

    b. Addendum 1 states, "An evaluation demonstrated that the application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on maximum internal pressure and will have a conservative impact on the NCLO critical pressure limit". Did this evaluation consider in-reactor creep data from the above commitment?

    Response 11b:
    The in-reactor creep data from the above commitment is not yet available and thus was not used in the evaluation. The evaluation was based on the same out-reactor thermal creep behavior of Optimized ZIRLO™ and Standard ZIRLO™

12. Section 4.5 of Addendum 1 documents the potential affect of changes in specific heat on Non-LOCA transients.

    a. For all licensees, were all events which experience DNB or elevated clad temperatures evaluated for the further decrease in phase transition temperature (relative to both Zircaloy-4 and Standard ZIRLO™)?

    b. Provide a list of the events considered and the calculated peak clad temperature for each event.

c. Was FACTRAN and/or STRIKIN-II used to calculate peak clad temperature for Locked Rotor/Sheared Shaft as well as any other event which experienced DNB or elevated clad temperatures?

Westinghouse Plants

<u>Response:</u>

The Peak Cladding Temperatures (PCT) calculated in a number of FSAR analyses for 2, 3, and 4-loop plants were reviewed as part of the Standard ZIRLO™ licensing effort. It was found that the cladding temperature remains below the phase transition temperature (~1400°F) for the following events:

- **RCCA Withdrawal from Subcritical**
- **RCCA Withdrawal at Power**
- **Dropped RCCA/RCCA Bank Event**
- **Boron Dilution (all modes)**
- **Startup of an Inactive Reactor Coolant Loop**
- **Loss of Electrical Load and Turbine Trip**
- **Loss of Normal Feedwater and Station Blackout**
- **Excessive Heat Removal Due to Feedwater Malfunction**
- **Excessive Load Increase**
- **Accidental Depressurization of the Reactor Coolant System**
- **Steamline Break (core response and mass & energy release, at all power levels)**
- **Complete Loss of Flow**
- **Partial Loss of Flow**
- **Main Feedline Rupture**

The only events that result in PCTs higher than the phase transition temperature are Locked Rotor and RCCA Ejection (Hot Full Power and Hot Zero Power cases).

For these events, sensitivity studies using the FACTRAN code were completed to quantify the effect of the change in specific heat between Standard ZIRLO™ and Zircaloy-4. The sensitivity studies showed that the difference in specific heat between Zircaloy-4 and Standard ZIRLO™ has very little effect (~2°F in PCT) on the results. These results were judged to be applicable to Optimized ZIRLO™ since the specific heats of Standard and Optimized ZIRLO™ are the same within the accuracy of the data.

The PCTs calculated in the Locked Rotor and Rod Ejection analyses considered in the sensitivity studies are shown in Table 1 below.

Table 1: Locked Rotor and Rod Ejection PCT Results	
Event	PCT at Hot Spot, °F
Locked Rotor, Zircaloy-4	1973
Locked Rotor, ZIRLO™	1975
HZP Rod Ejection, Zircaloy-4	2685
HZP Rod Ejection, ZIRLO™	2682
HFP Rod Ejection, Zircaloy-4	2327
HFP Rod Ejection, ZIRLO™	2326

CE Plants

Response 12a:
CENPD-404-P-A, Rev 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs", November 2001, concluded that, with respect to cladding materials, only specific heat was of importance to one computer code used for non-LOCA analysis. Other computer codes are not sensitive to clad material properties, or the models used are adequate for modeling ZIRLO™. This was true for thermal conductivity where it was shown that Zircaloy-4 and ZIRLO™ have the same thermal conductivity equations. The one computer code that was impacted was the STRIKIN-II code used to perform CEA Ejection analysis. As discussed in CENPD-404-P-A, CEA Ejection is impacted because it is the only event that has the potential for exceeding the ZIRLO™ lower alpha-beta phase change temperature. Up to the phase change temperature, ZIRLO™ and Zircaloy-4 have virtually identical specific heat curves. After passing through the phase change temperature, the specific heats change and this could impact STRIKIN-II predicted total hot spot deposited energy (the acceptance criteria for CEA Ejection). For this reason STRIKIN-II and CEA Ejection were investigated. Analysis was performed for CENPD-404-P-A to quantify the impact on CEA Ejection results using ZIRLO™ specific heat inputs to STRIKIN-II. This was done for both CE 14x14 and 16x16 fuel designs. The conclusion presented in CENPD-404-P-A is that the impact is negligible

For the Optimized ZIRLO™ report, an evaluation was performed to determine the impact of the slightly lower phase change temperature of Optimized ZIRLO™. The evaluation (which relied on STRIKIN-II results using Zircaloy-4 and ZIRLO™ properties) found that the Optimized ZIRLO™ and ZIRLO™ specific heat are very similar up to the alpha-beta phase change temperature of Optimized ZIRLO™ (approximately 1250 °F vs 1380 °F for ZIRLO™). Additionally, the data indicates that Optimized ZIRLO™ and Zircaloy-4 are much more nearly equal than are Zircaloy-4 and ZIRLO™ during the phase change. Consequently, it was concluded that the impact of Optimized ZIRLO™ relative to ZIRLO™ was again negligible.

Response 12b:

CENPD-404-P-A, Table 7.3-1 provides a list of events considered. Since the Optimized ZIRLO™ properties are the same as ZIRLO™, the peak clad temperatures will be the same as CENPD-404-P-A, Section 7.3.

Response 12c:

FACTRAN and STRIKIN-II are used to calculate peak clad temperature for DNB events. FACTRAN is used by Westinghouse on Westinghouse designed PWRs and STRIKIN-II is used by Westinghouse on CE designed PWRs.

13. ZIRLO™ alloy is described as having a "...microstructure comprising second phase precipitates (specifically, a body-centered cubic beta-niobium-zirconium phase and a hexagonal zirconium-niobium-iron inter-metallic phase) homogeneously distributed throughout the zirconium matrix.".

a. Describe how the reduction in tin will influence the shape, size, distribution, and weight fraction of the second phase precipitates (beta-ZrNb and hcp-ZrNbFe).

Response 13a:
The two precipitate phases do not contain tin and thus their shape, size, distribution and weight fractions are not affected by the reduction in tin.

b. Describe how planned changes to the material processing will influence the shape, size, distribution, and weight fraction of the second phase precipitates (beta-Zr-Nb and hcp-Zr-Nb-Fe).

Response 13b:
The second phase or precipitate characteristics are a function primarily of the relative levels of niobium and iron in the alloy. The impacts of the process are focused on the reaching a near equilibrium condition in the precipitate microstructure. The Optimized ZIRLO™ processing follows the past ZIRLO™ processing and minor change in past ZIRLO™ annealing temperatures will not impact shape, distribution, size and weight fraction of the precipitates in Optimized ZIRLO™ compared to past ZIRLO™ production.

14. Sections 2.2 and 3.1 - It appears the mean tin content for Optimized ZIRLO™ will be around [ ]^{a,c}? Is this interpretation correct? To what tolerance limit will the [ ]^{a,c} value be applied in the fabrication of Optimized ZIRLO™?

Response 14:
The target tin content in Optimized ZIRLO™ will be [ ]a, c with lower limit of 0.6% and [ ]a, c. The test lot was fabricated with a target tin content of 0.6% to respond to NRC's concern to make certain that the characterization data bounds the desired [ ]a, c tin lower limit for Optimized ZIRLO™

15. Please provide the fabrication differences between the standard ZIRLO™, standard Zr-4, low tin Zr-4, and Optimized ZIRLO™ for cladding and guide tubes. This includes the intermediate cold-work and annealing steps but of particular interest is the final cold-work, annealing temperatures and times. If the annealing times have changed between the materials please provide the average grain size for the Standard and Optimized ZIRLO™ and any texture differences. Also what are the fabrication specifications for the Standard and Optimized ZIRLO™.

~~Response:~~
The basic fabrication difference in the production cycle for these materials is at the alloy additions for the ingot melting. At this stage all of the materials have different mixes of elements added to the electrode. Otherwise, a concise response to the question regarding fabrication process specific differences cannot be provided since the processing has many inherent variables. As an example for standard Zircaloy-4 numerous process modifications have occurred over time and there have been multiple production vendors of the Zircaloy-4 tubing that has been used in the past. Each of the vendors has had a mildly different process. Likewise for ZIRLO™; there have been multiple vendors that have produced ZIRLO tubing and strip. The initial ZIRLO ingot was made by a Wah Chang process. Subsequent ingots have been made by Western Zirconium. At the Westinghouse Specialty Metals Plant the ZIRLO processing has gone through multiple optimizations and the current process modification is referred to as the sixth route. Sandvik Special Metals has also produced ZIRLO tubing using their specific process.

Regarding the sub question about the final anneals; low tin Zircaloy-4 tubing has been produced with final anneals that have resulted in a stress relief anneal while other low tin Zircaloy-4 tubing has been produced with a partial recrystallization anneal and yet others have been produced (primarily for guide tubes) in the full recrystallize annealed condition. The annealing time and temperatures are varied to achieve the desired final product characteristics. Similar variations in the final anneal conditions exist for ZIRLO™ and optimized ZIRLO™.

Regarding the grain size question, since the final product used for ZIRLO™/Optimized ZIRLO™ cladding has a significant degree of cold worked

microstructure; the grain size can not be determined using standard procedures and thus, does not provide an accurate means of comparison. The grain on fully recrystallized material used for guide tubes is equivalent for ZIRLO and Optimized ZIRLO™ and is about ASTM [ ]a, c. Likewise the grain size in ZIRLO and Optimized ZIRLO™ strip is equivalent and about ASTM [ ]a, c.

Regarding the texture in the tubing; CSR is a measure of the tubing texture and the same CSR limits apply in the current tubing specifications and are equivalent for ZIRLO™ and Optimized ZIRLO™.

More important than the specific process variables is the final product being within the required alloy property ranges that are reflected in the models and design codes. These properties are monitored and controlled by the process qualifications, the design drawings and the product specifications along with other characterization tests. Westinghouse does not have a process specification for fuel cladding. The cladding specification identifies most of the key material characteristic ranges and the production facilities develop process plans that define version of the process that will be used to fabricate the cladding to meet the specification.

16. Section 4.6 (Page 20) - It is stated both the ZIRLO™ specific heat model used in WCOBRA/TRAC and the specific heat approximation used in HOTSPOT compared to the differences in the new specific heat data have a negligible affect on large break LOCA analyses even though there is a [ ]a,c difference between the models and the data within a [ ]a,c range. Please discuss further how the sensitivity analysis was performed and the results of the analysis that compare the ZIRLO™ model to the Optimized ZIRLO™ data. Also, explain the differences between the specific heat model in WCOBRA/TRAC and the approximation used in HOTSPOT. (Page 28) An argument is made for the CE evaluation model such that the [ ]a,c higher specific heat for the model compared to the Optimized ZIRLO™ data within the [ ]a,c range will not have a significant impact on peak cladding temperature for LBLOCA but no sensitivity analysis is provided to substantiate this claim. Please provide a sensitivity analysis that demonstrates that the over prediction of specific heat has no or an insignificant effect on LBLOCA results.

Westinghouse Response 16:

The model used in WCOBRA/TRAC for ZIRLO™ cladding specific heat is given in Table 10-18 of Reference 16-1, and is approximated as follows in HOTSPOT:

[ ]a, b, c

Linear extrapolation of the first two points is used below 300 K, and linear interpolation of the neighboring points is used for intermediate values. As shown in Figure 16-1, there are only minor differences between the two models, indicating that the simplified model used in HOTSPOT is adequate for the intended purpose.

Figure 16-1

[ ]a, b, c

For the HOTSPOT sensitivity calculation described in Section 4.6.1 of the Topical Report, the ZIRLO™ specific heat model was replaced with a table of 25 points representing the Optimized ZIRLO™ data. These points span the range of the "heating" data from Table B.2-1 of the Topical Report [ ]a,c with temperature values chosen to provide a close approximation of the data. Linear extrapolation was used for temperatures outside the data range, and linear interpolation was used for intermediate temperatures. As shown in Figure 16-2, the main differences between the Standard ZIRLO™

model and the 25-point representation of the Optimized ZIRLO™ data occur for temperatures between [ ]^{a,c}

Figure 16-2

a, b, c

The transient selected for the HOTSPOT sensitivity calculation has a peak cladding temperature (PCT) near the 10 CFR 50.46 limit of 2200°F that occurs early in the reflood phase of the transient. Relative to the Standard ZIRLO™ case, the Optimized ZIRLO™ case showed a 2.7°F increase in average PCT (from 2191.0°F to 2193.7°F) and a 1.7°F decrease in standard deviation (from 54.1°F to 52.4°F) that are considered to be negligible. This is consistent with the expected result, since the differences in specific heat are relatively minor over most of the temperature range of interest for large break LOCA, and since limiting licensing transients spend little time in the temperature range where the most significant differences are observed.

References

16-1. WCAP-12945-P-A Volume I (Revision 2) and Volumes II-V (Revision 1), "Westinghouse Code Qualification for Best Estimate Loss of Coolant Accident Analysis", March 1998.

<u>CE Response 16:</u>
A sensitivity analysis was performed to substantiate the argument provided on page 28 that the over prediction of specific heat between [ ]^{a,c} does not have a significant impact on peak cladding temperature (PCT) for

LBLOCA. The sensitivity study was performed using the 1999 EM (Reference 16-2) version of the STRIKIN-II hot rod heat-up code applied to a typical CE designed PWR. The study consisted of two cases. Case 1 represented the Optimized ZIRLO™ "heating" data for specific heat. Case 2 represented the ZIRLO™ model for specific heat, which over predicts the specific heat data between [ ][a,c]. The following table summarizes important results from the study relative to the argument provided on page 28.

a, c

Case 2, which represents the overprediction of the specific heat data between [ ][a,c] by the ZIRLO™ specific heat model, resulted in a decrease in PCT of 0.5°F. There was less than a one second difference in the time of PCT between the two cases and the PCT occurred at the same elevation (i.e., immediately above the elevation of cladding rupture) for both cases. As is typical of the 1999 EM version of the Westinghouse evaluation model for CE designed PWRs, the PCTs for both cases were calculated to occur during late reflood. The difference in maximum cladding temperature during blowdown was calculated to be 15°F, with the case representing the Optimized ZIRLO™ data (i.e., Case 1) having the higher temperature.

These results substantiate the argument on page 28 and demonstrate that the overprediction of the specific heat data between [1400°F and 1600°F][a,c] by the ZIRLO™ specific heat model has an insignificant effect on the LBLOCA PCT. In particular, the sensitivity analysis showed that, when the specific heat data is represented, there is an increase in cladding temperature during blowdown when the cladding temperature is passing through the subject temperature range. However, as shown by the sensitivity analysis, the increase is small (15°F for the maximum blowdown cladding temperature) and it subsequently decreases during the reflood period (to a difference of less than 1°F in PCT).

References

16-2 CENPD-132, Supplement 4-P-A, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," March 2001.

17. Section 4.6 (Page 24) - The measurements of high temperature creep rate plotted in Figure B.14.1 are implied to be determined from the secondary or steady-state creep rate. However, page A-6 in Appendix A explanation of how the creep rates were determined at and below 1183 °K for this figure appear to suggest that the creep rates are based on primary creep, i.e., tangential slope of strain versus time plot starting at zero strain. Please provide an example of how the strain rates were determined from an actual strain versus time plot for temperatures equal to and below 1183 °K and those at 1273 °K.

<u>Response 17:</u>

For the high-temperature creep tests, the strain rates were determined using a linear least-squares fit of data from the strain versus time record. At 1183 K and below, the samples exhibited secondary (linear) creep almost immediately. For these tests, the creep rate was determined from the slope of a line tangent to the initial portion of the strain versus time record. At 1273 K, three distinct phases of creep behavior are discernible: the initial high rate primary creep region, followed by a low rate steady-state region and the subsequent rapid expansion typical of tertiary creep. For these tests, the creep rate was determined from the slope of a line through the steady-state portion of the strain versus time record. Figures 17.1, 17.2, and 17.3 provide examples for Optimized ZIRLO™ at 1093 K, 1183 K, and 1273 K, respectively.

a, b, c

a, b, c

[ ]

18. Appendix B -- The tin concentrations of the Optimized ZIRLO™ data were not always provided in Appendix B. What were the tin concentrations of the Optimized ZIRLO™ properties data provided in Appendix B for emissivity, thermal expansion, high and low temperature thermal creep, fatigue, single rod burst, high temperature oxidation, and ring compression tests.

<u>**Response 18:**</u>
Refer to Response 14. As reported in section 3.1, nominal Tin content in Optimized ZIRLO™ lots used for testing was [ ]^{a,c}. However, the actual tin content of two different lots used had 95% confidence upper and lower limit of [ ]^{a,c} respectively. Both the lots were for tested for emissivity, diametral thermal expansion, low and high temperature thermal creep, fatigue, high temperature oxidation and ring compression tests. For single rod burst tests, lot Q40-1113 was used. For axial thermal expansion, lot Q40-1114 was used.

19. Appendix B.14 - The high temperature creep data demonstrate that the current high temperature creep model overpredicts cladding strain [ ]^{a,c} in a steam atmosphere. What are the consequences if cladding strains are overpredicted in the large and small break analysis? Is this

always conservative or are there instances where this could result in non-conservative results?

Response 19:

It cannot be stated that over-predicting the cladding strain prior to burst is always conservative for large and small break LOCA analyses. But the degree of over-prediction observed at [ ]a, b, c is not indicative of the expected effect on large and small break LOCA analysis results, and it was decided to conduct some additional tests under conditions more typical of a licensing-basis LOCA transient. [

]a, b, c

Predictions of the tests were obtained using a computer program adapted from the LOCBART swelling and rupture models for ZIRLO™ cladding. These models calculate the change in clad diameter vs. time due to thermal expansion, mechanical strain, and high-temperature creep, and can be readily compared against the test results which include transient measurements of the clad outside diameter. [

]a, c

[

] a, c

a, b, c

Figure 19-1

20. Section 4.6 - The non-linear increase in ZIRLO™ thermal conductivity observed [

]a,c Please explain. What were the heating rates of the laser diffusivity measurements?

<u>Response 20:</u>

The thermal conductivity does have a non-linear change near the temperature of 900 C [ ]a, b, c. To better understand the temperatures related to the change a plot was made of the incremental slope of the lines between the data points of the thermal conductivity data in Table B.3-1 of Appendix B to WCAP-12610-P-A. The following figure 20.1 shows the results of that calculation that focuses on the temperatures at which the thermal conductivity rate is changing. The chart indicates that the thermal conductivity rate with temperature starts to change at about [ ]a, b, c. This temperature range is similar to the start of the alpha to alpha + beta temperature range reported in section B.6 and observed in the specific heat measurements in section B.2.

Figure 20.1

[ ] a, b, c

The method used for the thermal conductivity/diffusivity measurements follows ASTM E1461 and involves relatively fast incremental heating rates. The sample is preheated to the test temperature and then pulsed with a laser of known energy. The temperature rise on one face of the sample disk is about 30^0 C for a few milliseconds and on the back face of the disk the temperature rise is about 1.5 °C. The relative heating rates will result in some minor differences in the observed phase transitions. To obtain a more accurate phase change profile using this technique would require data points at smaller temperature intervals. However, the data is consistent and shows that the thermal conductivity rate change is related to the phase change.

21. Section 4.5 - It is noted in this section that the differences in specific heat between Zr-4 and ZIRLO™ have no or negligible effect on non-LOCA analyses. However, there are several material property data for Optimized ZIRLO™ that are different from the model used in Westinghouse and CE evaluation models by more than 10%. Are there other accidents besides large break LOCA, e.g., small-break LOCA, Locked Rotor/Sheared Shaft, and Rod Ejection events, where an underprediction of clad thermal conductivity above 1000 °C, or an overprediction in clad emissivity, or an underprediction of clad thermal expansion have an impact on the calculated results? What is the cumulative impact of all these differences including specific heat on large break LOCA and other accident analyses?

Response 21:

As discussed in Sections 4.6.1 and 4.6.2 of the Topical Report, the differences between the emissivity models and the Standard/Optimized ZIRLO™ data are mostly attributed to the testing environment, and therefore should not be assessed against current licensing-basis analysis results. For thermal conductivity, thermal expansion, and specific heat, additional sensitivity calculations were completed using LOCBART and SBLOCTA to demonstrate the effect of differences between the models and data on results. The changes to the models are described below, followed by the sensitivity calculations which demonstrate an insignificant effect on the calculated peak cladding temperature.

For thermal conductivity, the current ZIRLO™ model shown in Figure 4.6.1-2 of the Topical Report was replaced by a table of the Optimized ZIRLO™ points from Table B.3-1 of the Topical Report. (Note that the first temperature point differs slightly due to rounding.) For diametral thermal expansion, the current expansion coefficient of [ ]^{a,c} was increased to [ ]^{a,b,c} based on the value used in the CE model sensitivity calculation described in Section 4.6.2 of the Topical Report. (Note that axial thermal expansion is not modeled in LOCBART and SBLOCTA.) For specific heat, the current ZIRLO™ model (which is now based on the Standard ZIRLO™ "heating" data from Table

B.2-1 of the Topical Report, per Reference 21-1) was replaced by a table of 26 points based on the Optimized ZIRLO™ "heating" data from Table B.2-1 of the Topical report. (See the Specific Heat part of Section 4.6.1 of the Topical Report for related information.)

The first case is a sample LOCBART transient with a burst-node-limited, early-reflood PCT. The base calculation (denoted as case (a)) modeled Standard ZIRLO™, and the sensitivity calculations modeled (b) Optimized ZIRLO™ thermal conductivity and thermal expansion, (c) Optimized ZIRLO™ specific heat, and (d) Optimized ZIRLO™ thermal conductivity, thermal expansion, and specific heat. Figure 21-1 compares the cladding temperature at the PCT elevation for the base case and case (d) and indicates a minimal effect on the overall transient behavior. Relative to the base case, the PCT increased by about [ ]^{a,b,c} for case (b), [ ]^{a,b,c} for case (c), and [ ]^{a,b,c} for case (d), all of which are insignificant despite the over-sensitivity of LOCBART to changes for this type of transient. Figure 21-2 compares the cladding temperature at the PCT elevation for all four cases near the PCT time and shows that most of the temperature increase results from the change in specific heat, which is consistent with the expected result given the relative importance of the specific heat vs. thermal conductivity/thermal expansion models in a large break LOCA transient.

The second case is a sample LOCBART transient with a late-reflood PCT. For this case, the four calculations described above resulted in a total variation in PCT of less than [ ]^{a,b,c}. Figure 21-3 compares the cladding temperature at the PCT elevation for the base case and case (d) and indicates a minimal effect on the overall transient behavior, which is consistent with the expected result for large break LOCA transients where the PCT occurs late in reflood.

The third case is a sample SBLOCTA transient. The base case was reanalyzed using the Optimized ZIRLO™ thermal conductivity, thermal expansion, and specific heat, resulting in a PCT decrease of about [ ]$^{a,b,c.}$ Figure 21-4 compares the cladding temperature at the PCT elevation and indicates a minimal effect on the overall transient behavior, which is consistent with the expected result for small break LOCA transients.

Based on these and other calculations that have been performed for the Optimized ZIRLO™ program, differences between the models and data for parameters such as thermal conductivity, thermal expansion, and specific heat have generally been found to produce a negligible effect on the analysis results. Similar effects are also expected for the CE LOCA evaluation models and non-LOCA transients such as locked rotor/sheared shaft and rod ejection, and updating the current ZIRLO™ models is generally not required to obtain an adequate prediction of Optimized ZIRLO™ performance. Somewhat larger effects were observed due to differences in specific heat for LOCBART transients with a burst-node-limited, early-reflood PCT, and were resolved as described in Reference 21-1 by updating the Standard ZIRLO™ specific heat model based on the "heating" data from Table B.2-1 of the Topical Report. (Note that the SBLOCTA specific heat model was also updated to maintain consistency with LOCBART, with a negligible effect on results as indicated in Reference 21-1.)

References

21-1. LTR-NRC-03-5, "U. S. Nuclear Regulatory Commission, 10 CFR 50.46 Annual Notification and Reporting for 2002", March 7, 2003.

Figure 21-1

a, b, c

Figure 21-2

a, b, c

Figure 21-3

a, b, c

Figure 21-4

a, b, c

22. Section 4.6 - Please describe how flow assembly blockage is determined from rupture strain along with a description of the flow blockage models used in the Westinghouse and CE Evaluation models. What cladding strain values are assumed for the evaluation of equivalent cladding reacted (ECR) for LOCA analyses and provide an example with initial oxidation and oxidation following the LOCA?

Westinghouse Response 22:
For the Westinghouse evaluation models, the following describes the modeling of assembly blockage in Appendix K Small Break LOCA, Appendix K Large Break LOCA, Best Estimate Large Break LOCA, and SECY Large Break LOCA.

Appendix K Small Break LOCA
In SBLOCTA, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled [as a uniform 20% reduction in mass velocity for all uncovered nodes starting 0.5 feet below the burst elevation]a,c.

Appendix K Large Break LOCA
In LOCBART, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled as a non-uniform reduction in mass velocity in the vicinity of the burst elevation. To account for blockage in BART, the conservation equations were modified to include a source term representing the exit of steam from or entry of steam to the flow channel due to flow redistribution. As discussed in Section 3.2 of Reference 22-1, this source term was derived using an empirical expression for the normalized mass velocity vs. normalized elevation in the flow redistribution region, and depends on the mass velocity at the inlet of the flow redistribution region, the channel hydraulic diameter, the channel blockage fraction, the nodal and burst elevations, and the steam density. With this formulation, steam exits the channel in the lower portion of the flow redistribution region and re-enters the channel in the upper portion of the flow redistribution region, with a discrete approximation of a continuous profile that produces a minimum mass velocity slightly downstream of the hot assembly average rod burst elevation.

For a given axial node I that lies within the flow redistribution region, the flow redistribution model is activated when the following conditions are satisfied: [

]a,c

The channel blockage fraction used with the flow redistribution model is based on Appendix B of NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding at or

below 1742°F; Figure 4 of Reference 22-3 for Zircaloy-4 cladding above 1742°F; or, Figure 5-4 of Reference 22-4 for ZIRLO™ cladding. Each of these references describes the conversion from burst strain to assembly blockage, all of which use the basic approach outlined in NUREG-0630.

In the LOCBART modeling of assembly blockage, no direct credit is taken for the beneficial effects of droplet atomization, flow acceleration, or turbulence intensification that have been observed experimentally (e.g., Reference 22-5). As a result, assembly blockage leads to a local reduction in cladding-to-fluid heat transfer and a corresponding local increase in cladding temperatures, which is conservative relative to experimental results and can represent a substantial conservatism in the analysis when the peak cladding temperature occurs late in reflood.

Best Estimate Large Break LOCA
In the Best Estimate version of WCOBRA/TRAC, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled as an adjustment to the appropriate continuity and momentum cell areas. (See Section 7-4-2 of Reference 22-6.) The flow area reduction due to blockage is based on Figures 7-22 (Zircaloy-4) and 7-23 (ZIRLO™) of Reference 22-6. The conversion from burst strain to assembly blockage uses the basic approach outlined in NUREG-0630, as applied to the burst strain curves from Figures 7-18 (Zircaloy-4) and 7-20 (ZIRLO™) of Reference 22-6. HOTSPOT uses fluid conditions from WCOBRA/TRAC, and therefore does not require an explicit model for assembly blockage.

SECY Large Break LOCA
In the SECY version of WCOBRA/TRAC, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled as an adjustment to the appropriate continuity and momentum cell areas. (See Section 7-1-4 of Reference 22-7 and Sections 3-3-2 and 3-4 of Reference 22-8.) The flow area reduction due to blockage is based on NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding and Table 3 of Reference 22-9 for ZIRLO™ cladding. Each of these references describes the conversion from burst strain to assembly blockage, using the basic approach outlined in NUREG-0630.

References
22-1. WCAP-8622, "Westinghouse ECCS Evaluation Model, October 1975 Version", November 1975.

22-2. NUREG-0630, "Cladding Swelling and Rupture Models for LOCA Analysis", April 1980.

22-3. ET-NRC-92-3746, "Extension of NUREG-0630 Fuel Rod Burst Strain and Assembly Blockage Models to High Fuel Rod Burst Temperatures", September 16, 1992.

22-4. WCAP-12610-P-A, "VANTAGE+ Fuel Assembly Reference Core Report", April 1995.

22-5. Erbacher, F. J., "Cladding Tube Deformation and Core Emergency Cooling in a Loss of Coolant Accident of a Pressurized Water Reactor", Nuclear Engineering and Design 103, pp. 55-64, 1987.

22-6. WCAP-12945-P-A Volume I (Revision 2) and Volumes II-V (Revision 1), "Westinghouse Code Qualification for Best Estimate Loss of Coolant Accident Analysis", March 1998.

22-7. WCAP-10924-P-A, Revision 2, "Westinghouse Large-Break LOCA Best Estimate Methodology; Volume 2: Application to Two-Loop PWRs Equipped with Upper Plenum Injection; Addendum 1: Responses to NRC Questions", December 1988.

22-8. WCAP-10924-P-A, Revision 1, "Westinghouse Large-Break LOCA Best-Estimate Methodology; Volume 1: Model Description and Validation; Addendum 4: Model Revisions", March 1991.

22-9. WCAP-13677-P-A, "10 CFR 50.46 Evaluation Model Report: WCOBRA/TRAC Two-Loop Upper Plenum Injection Model Updates to Support ZIRLO™ Cladding Option", February 1994.

What cladding strain values are assumed for the evaluation of equivalent cladding reacted (ECR) for LOCA analyses?

Westinghouse Response

For the Westinghouse evaluation models, the following describes the modeling of burst strain in Appendix K Small Break LOCA, Appendix K Large Break LOCA, Best Estimate Large Break LOCA, and SECY Large Break LOCA.

Appendix K Small Break LOCA

In SBLOCTA, the burst strain is taken as the [minimum of the pitch-over-diameter limit]a,c (see Section 3-2-1 of Reference 22-8) and the value obtained using: Figure 5-3 of Reference 22-4 for ZIRLO™ cladding; or, the following equation for Zircaloy-4 cladding:

[ ]a,c

where ΔP represents the cladding differential pressure at burst (psi).

Appendix K Large Break LOCA
In LOCBART, the burst strain is taken as the [

]^{a,c} (see Section 3-2-1 of Reference 22-8) and the value obtained using Appendix B of NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding at or below 1742°F; Figure 2 of Reference 22-3 for Zircaloy-4 cladding above 1742°F; or, Figure 5-3 of Reference 22-4 for ZIRLO™ cladding.

Best Estimate Large Break LOCA
The treatment of burst strain in HOTSPOT is described in Section 25-4-2-3 of Reference 22-6. As discussed therein, [

]^{a,c}.

SECY Large Break LOCA
In WCOBRA/TRAC, the burst strain is taken as the [minimum of the pitch-over-diameter limit]a,c (see Section 3-2-1 of Reference 22-8) and the value obtained using NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding, or Table 3 of Reference 22-9 for ZIRLO™ cladding.

Provide an example with initial oxidation and oxidation following the LOCA.

<u>Westinghouse Response</u>

Consider a sample LOCBART calculation that produced the following results:

[ ] a, b, c

[

]a,c Transient results for the hot rod PCT and burst elevations are shown in Figures 22-1 (clad average temperature), 22-2 (local ECR), and 22-3 (clad outside diameter); note that the ECR computed by LOCBART includes both the transient and pre-transient values, with the latter being approximately zero for this near-beginning-of-life calculation.

Figure 22-1

a, b, c

a, b, c

Figure 22-2

Figure 22-3

a, b, c

CE Response 22:

As described on pages 35 and 36 of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, the CE evaluation models use the same cladding rupture strain and assembly blockage models for Optimized ZIRLO™ as are used for Standard ZIRLO™. The models are described in Sections 6.3.10 and 6.3.11 of CENPD-404-P-A (Reference 22-10). They consist of tables of rupture strain and assembly blockage versus rupture temperature (Tables 6.3.10.1-1 and 6.3.11-1 in CENPD-404-P-A). As noted in Section 6.3.11 of CENPD-404-P-A, the assembly blockage model was developed from [

]a,c

The flow blockage model used in the CE LBLOCA evaluation model (i.e., the 1999 EM, Reference 22-11) is described in Enclosure 1-P-A to LD-81-095 (Reference 22-12). In the flow blockage model, the HCROSS computer code calculates the hot channel flow redistribution at and above the elevation of cladding rupture and the PARCH computer code calculates the hot rod steam cooling heat transfer coefficients. The steam cooling heat transfer coefficients are used by the STRIKIN-II computer code in the calculation of the hot rod cladding temperature at and above the elevation of cladding rupture after the core reflood rate decreases to less than 1 inch per second. Also, if cladding rupture is calculated to occur during blowdown, the blowdown hydraulics analysis performed by the CEFLASH-4A computer code is repeated to incorporate the impact of assembly blockage on the blowdown hydraulic response of the hot assembly. Note that in the 1999 EM, the HCROSS and PARCH computer codes have been integrated into the STRIKIN-II computer code (Section 2.7 of Reference 22-11). As described in Section 6.3.11 of CENPD-404-P-A, the CE SBLOCA evaluation model does not use a flow blockage model.

As part of the calculation of the cladding oxidation percentage (equivalent cladding reacted) in the CE evaluation models, the cladding rupture strain is used in the calculation of the amount of cladding oxidation at the elevation of cladding rupture (i.e., the cladding rupture node). As described in Section II.9 of the STRIKIN-II topical report (Reference 22-13) and Section 3.4.3 of the PARCH topical report (Reference 22-14), the cladding rupture strain is used to determine the inside and outside dimensions of the cladding rupture node. After rupture occurs, oxidation is calculated to occur on both the inside and outside surfaces of the cladding rupture node. Also, as noted in Section 6.3.10.1 of CENPD-404-P-A, the CE evaluation models do not [limit the rupture strain to the pitch-over-diameter limit]a,c as is done in the Westinghouse Appendix K evaluation models.

Tables 6.5.1.3-1 and 6.5.1.3-2 of CENPD-404-P-A provide results of sample LBLOCA hot rod heat-up calculations for ZIRLO™ cladding for conditions of maximum initial fuel stored energy and maximum initial rod internal pressures, respectively. It is one of these two conditions that generally produce the limiting result in a LBLOCA analysis. As described in Section 4.6.2 of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, the cladding models used for Standard ZIRLO™ are applicable to Optimized ZIRLO™. Therefore, these sample calculations are also representative of Optimized ZIRLO™. The tables identify the cladding rupture strains and maximum cladding oxidation percentages that were calculated for sample cases. For the maximum initial fuel rod stored energy case for ZIRLO™ cladding, cladding rupture occurred at a cladding temperature of 1569°F. The resultant cladding strain and assembly blockage percentages were 33.2% and 24.1%, respectively. The maximum cladding oxidation, which occurred at the cladding rupture node, was calculated to be 6.80%. The value includes an initial cladding oxidation percentage of approximately 0.05%, which corresponds to the value associated with the initial cladding oxidation thickness used in the CE evaluation models. The corresponding results for the maximum initial rod internal pressure case are as follows: rupture temperature, 1454°F; cladding strain, 53.0%; assembly blockage, 40.2%; maximum cladding oxidation, 5.11%.

References

22-2 NUREG-0630, "Cladding Swelling and Rupture Models for LOCA Analysis," April 1980.

22-10 CENPD-404-P-A, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," November 2001.

22-11 CENPD-132, Supplement 4-P-A, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," March 2001.

22-12 Enclosure 1-P-A to LD-81-095, "C-E ECCS Evaluation Model Flow Blockage Analysis," December 1981.

22-13 CENPD-135P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1974.

22-14 CENPD-138P, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," August 1974.

23. Section B.3 --- What specific heat function was used to reduce the diffusivity data to thermal conductivity? Was a different specific heat function used for heatup versus cooldown diffusivity data?

<u>Response 23:</u>
Discrete values were used, derived from the separate specific heat measurements. Changes in enthalpy attributable to phase changes were subtracted by smoothing visually across the phase transitions. Phase transition enthalpy is eliminated because the energy absorbed (or released) in phase transitions is unavailable for diffusion. Separate cooldown diffusivity data were not collected. Except for hysteresis in the phase transitions, there is no reason to expect that thermal diffusivity, specific heat, or thermal conductivity should vary as a function of whether the specimen is heating or cooling.
The values used are shown in the following table. It may be seen that the specific heat is not a strong function of temperature when enthalpy changes due to phase transitions are removed.

[ ] a, b, c

24 (a) Section B.6 - The $\alpha \rightarrow \alpha + \beta$ transformation temperature data appears to show a dependence on tin content [between 0.67% and 1.05%] such that there is a decrease in transformation temperature with a decrease in tin content. Why is this decrease not modeled?

<u>Response 24a:</u>

The $\alpha \rightarrow \alpha + \beta$ transformation temperature is not explicitly modeled in the Non-LOCA or LOCA codes and methods, and only affects the analysis

results through its influence on parameters that are explicitly modeled such as specific heat. For these parameters, the evaluations of Sections 4.5 and 4.6 have concluded that the Standard ZIRLO™ models can reasonably be applied to Optimized ZIRLO™, including any implicit effects due to the apparent reduction in the $\alpha \rightarrow \alpha + \beta$ transformation temperature.

(b) What were the heating and cooling rates for the dilatometry and DSC measurements used to determine the $\alpha \rightarrow \alpha + \beta$ transformation temperature?

<u>Response 24b:</u>

The heating and cooling rate for dilatometry was 3 °C/min.
The heating and cooling rate for specific heat (DSC) was 10 °C/min.

25. Sections B.7 & B.8 - The mechanical property data for microhardness, yield strength and ultimate yield strength of unirradiated Optimized ZIRLO™ is [ ]^{a,c} lower than for standard ZIRLO™ at normal reactor operating conditions. It is also implied that irradiation hardening will decrease this difference such that there will not be a significant difference between these two materials. It is also implied that the difference in failure strains between Optimized and standard ZIRLO™ will also be reduced with irradiation. How can this claim be substantiated if there are no mechanical property tests on irradiated Optimized ZIRLO™? Are irradiation hardening effects accounted for in the properties for Optimized ZIRLO™? If so, how is this done without irradiated data?

<u>Response 25:</u>

Irradiation hardening is a known mechanism in Zirconium based alloys. An early review of this is found in Reference 25.1 where it is shown that the majority of the irradiation hardening effects develop early in the initial cycle of fuel operation. The hardening effect occurs with the displacement of lattice atoms under the fast neutron flux. Because it is basically a displacement of the matrix atoms and subsequent formation of microstructure changes such as dislocations , the irradiation hardening mechanism is relatively independent of minor alloy element level changes or final annealing conditions.

A specific example of the generic effects of irradiation hardening is found in the comparison of irradiated and unirradiated ZIRLO™ and Zircaloy 4 materials. The following Table lists some nominal values of yield strength for these materials to show the relative changes in strength that occur in the materials with irradiation. The values may vary a small amount depending on the differing levels of fluence and hydrogen but the data still shows the similar response of Zircaloy 4 and ZIRLO™ to irradiation hardening. The relatively large differences in the un-irradiated condition are significantly reduced or equalized with irradiation hardening.

The results in the comparison table show that even with different alloys and different heat treatments that the irradiation hardening has an overriding equalizing effect on the mechanical strength of zirconium based materials which have minor differences in alloy content. In the un-irradiated condition there are differences of [ ][a, c] in yield strengths of the various materials but after irradiation the differences are less than [ ][a, b, c].

[ ] a, b, c

In addition to the irradiation hardening effects the neutron fluence can also cause changes in the precipitate microstructure that can affect the material properties. For Optimized ZIRLO™ the only change in alloy chemistry is the tin level. Tin is in solid solution and is not a precipitate in the matrix. The precipitates are formed from the niobium and iron elements which are at the same levels in Optimized and standard ZIRLO™. Therefore, there will be no difference in the precipitate structures of Optimized and standard ZIRLO™ for equivalent irradiation fluences. The equivalent mechanical property effects with irradiation and the equivalent precipitate microstructures with irradiation support the conclusion that standard ZIRLO™ irradiation data can be used to characterize the impacts of irradiation on Optimized ZIRLO™ and specific data on irradiated Optimized ZIRLO™ are not required.

As shown and discussed above, the irradiation hardening of Optimized ZIRLO™ will be same as observed for Zircaloy 4 and standard ZIRLO™; thus justifying the same accounting for these effects in the fuel design as used for standard ZIRLO™ and Optimized ZIRLO™.

Reference

25.1. " Effect of Irradiation on Strength , Ductility and Defect Sensitivity of Fully Recrystallized Zircaloy Tube"; Pettersson K. et al ; ASTM STP 681 Zirconium in the Nuclear Industry 1979, pp 155-173

26. Section B.7 - This section provides data that suggests there are [ ]a,c differences in total elongation and failure strains in the longitudinal and circumferential direction between unirradiated Optimized and standard ZIRLO™. What tests were used to determine the failure strains in the circumferential direction? If ring tensile tests were used it has been demonstrated that this test method is not valid for determining failure strains because the strains are a function of specimen size, gauge length and ring test apparatus and, therefore, not a property measurement of failure strain. It is also known that the ring tests generally result in higher failure strains than other methods. Please provide additional discussion in this area. How was circumferential Young's modulus obtained, from the ring tests?

Response 26:

Circumferential Young's modulus was obtained from a split-D type mechanical test, in which two opposite sides of the tubing are loaded in circumferential tension.

(a) Do the Westinghouse and CE evaluation models assume isotropic mechanical properties and, if so, what is used for Young's modulus for the isotropic analyses?

Westinghouse Response 26a:

In the Westinghouse evaluation models, mechanical properties are either assumed to be isotropic or treated as having a simple directional dependence. This yields considerable simplification relative to a rigorous anisotropic treatment such as that described in Section 4.6 of Reference 26-1, and is considered to be adequate for the intended purpose given the minimal importance of these parameters in evaluation model calculations. Young's modulus (Y) is specified as a function of temperature (T), with the following equation used in LOCBART and SBLOCTA (Y in psi and T in °F):

[ ]a,c

and the following equations used in WCOBRA/TRAC (Y in Pa and T in K):

T < 1094 K: [ ]a,c

1094 K ≤ T ≤ 1239 K: [ ]a,c

T > 1239 K: [ ][a,c]

References

26-1.NUREG/CR-6150, Vol. 4, Rev. 2, INEL-96/0422, "SCDAP/RELAP5/MOD 3.3 Code Manual: MATPRO - A Library of Materials Properties for Light-Water-Reactor Accident Analysis", January 2001.

CE Response 26a:

The CE evaluation models use models for mechanical properties (e.g. Young's modulus and Poisson's ratio) that are only applied in the radial direction. Sections 6.3.6 and 6.3.7 of CENPD-404-P-A (Reference 26-2) provide a general description of the use of Young's modulus and Poisson's ratio in the CE evaluation models. They are used in the calculation of the inside diameter of the cladding, which, in turn, is used in the calculation of the gap conductance and the gap pressure. Since the models for Young's modulus and Poisson's ratio are only applied in a single (i.e., radial) direction, characterization of the models as isotropic versus anisotropic is a moot point.

As described on page 33 of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, the Young's modulus model described in Section 6.3.6 of CENPD-404-P-A is used for Standard ZIRLO™ and Optimized ZIRLO™. It is also noted on page 33 that the model and the data for Young's modulus in the circumferential direction for both Standard ZIRLO™ and Optimized ZIRLO™ are in reasonable agreement over the temperature range of the data. The model consists of an equation for temperatures less than or equal to [ ][a,c] and linear interpolation from a table of values for temperatures above [ ][a,c] The equation is as follows:

[ ][a,c]

where Young's modulus is in units of kpsi and T is cladding temperature (^{o}F). The table used for temperatures above [ ][a,c] is as follows:

Cladding Temp. (°F)	Young's Modulus (kpsi)
[	
	]a,c

References

26-2 CENPD-404-P-A, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," November 2001.

27. Section 4.2 -- What are the consequences to the evaluations of Sections 4.2 if the microhardness, yield strength, ultimate tensile strength and Young's modulus are 25% lower for Optimized ZIRLO™ than for standard ZIRLO™? What are the consequences to the evaluations of Section 4.2 if the failure strains are lower by 50% than for standard ZIRLO™?

Response 27:

Microhardness is a surface property which plays a minor role in the contact gap conductance component for fuel-to-clad heat transfer in the fuel performance for Westinghouse CE models as described in Section 4.3.5.4 of CENPD-404-P-A. Microhardness is not a parameter in the Westinghouse models. A 25% lower microhardness value would result in a small increase in contact heat conductance but an insignificant increase in total gap conductance.

The yield and ultimate tensile strengths increase with irradiation. The cladding stress is calculated and compared to the yield and ultimate tensile strengths. As described in Section 4.2.1, the Westinghouse irradiated yield and ultimate strengths are used. The irradiation of the Optimized ZIRLO™ significantly increases the strength. A 25% reduction in un-irradiated strength would have little impact relative to the irradiated strength. However, Westinghouse CE uses the un-irradiated strength as a limiting clad stress criterion as described in Section 4.2.1. Although the available stress margin is reduced, sufficient conservatism exists to satisfy the criterion even if strength is reduced by 25%.

A reduction in Young's modulus would have an insignificant or a beneficial impact on clad stress which depends on the source of the loads. The clad stress is in equilibrium with clad pressure differentials and is independent of Young's modulus. Clad stress based on a rigid pellet thermal expansion is based on a known strain. Conversion of this strain into a clad stress is

proportional to Young's modulus. Therefore, a 25% reduction would result in a similar reduction in clad stress. A reduction in yield strength and Young's modulus under such conditions would compensate and result in no impact.

Failure strain data applicable to Section 4.2 is shown in Figure B.7-8. A 50% variation is consistent with the variation shown in this figure However, Optimized ZIRLO™ failure strain is higher than standard ZIRLO™. Failure strain is not used in fuel performance calculations given in Section 4.2, therefore a 50% reduction in the Optimized ZIRLO™ failure strain shown in Figure B.7-8 would have no impact on results or conclusions of Section 4.2.

28. Section B.9 - Thermal creep data are presented from unirradiated Optimized and standard ZIRLO™ at one temperature and stress demonstrating that there is little difference for these conditions. However, irradiation induced creep is significantly different from thermal creep with approximately an order of magnitude higher creep rates. In addition, there are several papers that demonstrate decreasing tin contents in Zr-4 result in a significant increase in creep rate (Reference 28.1). While thermal creep tests (out-of-reactor) sometimes give a qualitative measure of differences in irradiation induced creep rates between two materials this qualitative measure is not always a good measure of differences in irradiation creep. Therefore, please provide irradiation creep data to substantiate in-reactor performance.

References:

28.1 F.Garzarolli, H. Stehle, E. Steinberg, "Behavior and Properties in Power Reactors: A short Review of Pertinent Aspects in LWR Fuel", Zirconium in the Nuclear Industry; Eleventh International Symposium, ASTM STP 1295, 1996, pp. 12-32.

Response 28:
The use of out-reactor thermal creep data to determine in-reactor creep is based on the correlation between out-reactor and in-reactor creep. This correlation was developed using Westinghouse fuel rod data irradiated in BR-3 and confirmed with the results reported by the EPRI/B&W Zr-4 Program.

BR-3 CWSR ZIRLO
Westinghouse fabricated CWSR ZIRLO™ fuel rod tubing with different final pilger area reductions. Two lots of tubing were fabricated. One was made with a final area reduction of 77% and a second with a reduced value of 60%. The two tube lots received the same processing except for the final pilger area reduction. The only difference between the two lots was the amount of cold-work. Texture measurements indicated that the texture of the two tube lots was similar.

The material was tested out-reactor at the test conditions of [ ]a, c. The results are shown in Figure 28.1. The tubing fabricated with the higher area reduction exhibits higher creep-out (higher tension strains). Figure 28.2 presents free-standing fuel rod creep-down data with rods fabricated with the two different final pilger area reductions. The rods fabricated with the higher area reduction exhibit higher creep-down (higher compression strains). Figure 28.3 presents both the in-reactor and the out-reactor data showing the negative of in-reactor creep-down on the y-axis versus the out-reactor creep-out on the x-axis. Note that an increase in out-reactor creep directly correlates with in-reactor creep.

Oconee-2 EPRI/B&W Zr-4
The EPRI/B&W Program investigated the behavior of Zr-4 both with out-reactor and in-reactor creep tests. (Reference 28.2) Three tube lots were tested out-reactor and in-reactor. One material heat of Sandvik Zr-4 was tested in the CWSR and RXA conditions (lots S-1 and S-2, respectively). One lot of NRG tubing was tested in the CWSR condition. In the case of lots S-1 and S-2, the processing was identical except for the final anneal. The final anneal resulted in both texture and dislocation density differences. In the case of lot V-1, the processing for this lot was considered to be different from lot S-1. Lot V-1 was considered to have a lower area reduction and lower Q-ratio processing because the final tubing exhibited less grain distortion and lower radial texture.

Figures 28.4 to 28.6 present the in-reactor data at a hoop stress of -12.5 ksi (-86 MPa) (Reference 28.3). The out-reactor results were reported as equation correlations (Reference 28.2). Figure 28.7 presents both the in-reactor and the out-reactor data showing the negative of in-reactor creep-down on the y-axis versus the out-reactor creep-out on the x-axis. Note that an increase in out-reactor creep directly correlates with in-reactor creep. This confirms the CWSR ZIRLO BR-3 results.

Application to Optimized ZIRLO™
The final CWSR anneal temperature used for Standard ZIRLO™ was modified for Optimized ZIRLO such that the [ ]a, c Sn Optimized ZIRLO™ exhibited the same out-reactor creep as Standard ZIRLO. This behavior is shown in Figure B.9-1 of reference 28.4. Based on the correlation between out-reactor and in-reactor creep, the irradiation creep of Optimized ZIRLO™ will be the same as for Standard ZIRLO.

References

28.2 David L. Baty, W.A. Pavinich, M.R. Dietrich, G.S. Clevinger and T.P. Papazoglou, "Deformation Characteristics of Cold-Worked and Recrystallized Zircaloy-4 Cladding," Zirconium in the Nuclear Industry: Sixth International Symposium, ASTM STP 824, 1984, pp. 306-339.

28.3 D.G. Franklin, G.E. Lucas and A.L. Bement, "Creep of Zirconium Alloys in Nuclear Reactors," ASTM STP 815, 1983, Appendix III.

28.4 Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO, February 2003.

Figure 28.1

[ ] a, b, c

Figure 28.2

a, b, c

Figure 28.3.

a, b, c

Figure 28.4

a, b, c

Figure 28.5

[ ] a, b, c

Figure 28.6

a, b, c

Figure 28.7

a, b, c

Section D

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Direct tel: (412) 374-4643
Direct fax: (412) 374-4011
e-mail: greshaja@westinghouse.com

Our ref: LTR-NRC-05-26

Attn: J. S. Wermiel, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

May 18, 2005

Subject: Westinghouse Responses to NRC Request for Additional Information (RAIs) on "Optimized ZIRLO™" Topical – Addendum 1 to WCAP-12610-P-A and CENPD404-P-A (Non-Proprietary), TAC No. MB8041

Dear Mr. Wermiel:

Enclosed is one (1) copy of Westinghouse Responses to NRC Request for Additional Information (RAIs) on "Optimized ZIRLO™" Topical – Addendum 1 to WCAP-12610-P-A and CENPD404-P-A (Non-Proprietary) dated May 2005, TAC No. MB8041. The proprietary version of these responses were transmitted in LTR-NRC-04-44 dated August 4, 2004. A non-proprietary version of the responses is being sent as requested by the NRC.

Very truly yours,

J. S. Galembush, Acting Manager
Regulatory Compliance and Plant Licensing

Enclosures

cc: F. M. Akstulewicz/NRR
P. M. Clifford/NRR
B. J. Benney/NRR

ZIRLO™ trademark property of Westinghouse Electric Company LLC

COPYRIGHT NOTICE

Westinghouse Responses to NRC Request for Additional Information (RAIs) On Optimized ZIRLO™ Topical – Addendum 1 to WCAP12610-P-A and CENPD404-P-A

(for Proprietary Class 2 Refer to LTR-NRC-04-44, August 4, 2004)

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

Westinghouse Responses to NRC Request for Additional Information (RAIs) On Optimized ZIRLO™ Topical – Addendum 1 to WCAP12610-P-A and CENPD404-P-A

1. Section 1.2 provides a definition of ZIRLO™ material based upon descriptions presented in both the "NRC SE and Appendix A of WCAP-12610, and also accounting for descriptions of ZIRLO™ in patent documents". The table below lists the alloy content of ZIRLO™ found in these sources.

   Response 1:
   ZIRLO™ is a trademark commercially used by Westinghouse in connection with zirconium based alloys containing about 1% niobium (together with smaller amounts of iron and tin and other elements) and having a particular microstructure. The Abstract of US Patent No. 4,649,023 discusses zirconium alloys containing 0.5 to 2.0 percent niobium and "up to 1.5 percent tin". Westinghouse has the following patents relating to specific compositions and/or processing: 4,649,023; 5,112,573; 5,125,985, 5,266,131 and 5,230,758. There is not a direct correspondence between the licensed alloy range and the alloy range of a specific patent. The patents are used for commercial protection and are not used to define a basis for a license composition.

   a. Explain the differences in alloying content and why Optimized ZIRLO™ is within the definition of ZIRLO™ material.

   Response 1a:
   The difference in alloy content between the current ZIRLO™ and Optimized ZIRLO™ is the tin level. All other alloying additions remain within the current licensed ranges. ZIRLO™ is an alloy containing 98 % zirconium with added elements of niobium, tin, and iron. An important characteristic of ZIRLO™ is the type of precipitates that are formed in the alloy. Since the precipitates consist of niobium and iron with zirconium and not with tin, the small changes in tin content do not affect the precipitate structure.

b. Explain why do the nickel and chromium alloying content remain in the patented description of ZIRLO™?

<u>Response 1b:</u>
The patents do not provide a definition of ZIRLO™. As stated above, patents provide commercial protection for a broader alloy range than the licensed version of ZIRLO™.

c. Will the ZIRLO™ patent be revised to reflect the Addendum 1 alloy content?

<u>Response 1c:</u>
There is no need to revise the above mentioned patents. They will not be revised.

d. A definition of ZIRLO™ is presented in quotation marks in Section 1.2. What is the source of this quote?

<u>Response 1d:</u>
The description quoted was developed by Westinghouse to provide a clear statement of the unique characteristics that define ZIRLO™ and is consistent with WCAP 12610. Optimized ZIRLO™ will continue to be within the definition of ZIRLO™.

2. The material properties of a metal alloy are strongly dependent on its microstructure, which is influenced by both alloy content and material processing.

<u>Response 2:</u>

[

] a,c

a. Describe, in detail, each step of the current material processing employed to dictate the microstructure of ZIRLO (e.g. annealing temperature, beta quench, cold work, age hardening, etc.).

<u>**Response 2a:**</u>

ZIRLO is processed similar to Zircaloy 4. [

] a,c

b. How will the current process described above be altered for Optimized ZIRLO?

<u>**Response 2b:**</u>

The same basic processing steps used in the production of ZIRLO will be used for Optimized ZIRLO. The equivalent product can be manufactured using different processing parameters so it is important not to assume a specific process route is the only acceptable route. [

] a,c

c. Describe the Quality Control procedures on the control of microstructure (e.g. alloy content, size and distribution of second phase particles, grain size, etc.).

Response 2c:

[

] [a,c] The established process parameters are monitored by Quality Control in addition to the standard property testing of the final product required by the specifications. Typically, alloy content is verified on each ingot by chemistry measurements, and an in-direct method of monitoring the microstructure involving physical and mechanical testing of the final product is used.

d. Quantify the allowed manufacturing tolerances on alloy content and the control of microstructure?

Response 2d:

Alloy Composition

The alloy content tolerances are established and controlled by the applicable material specifications. The range in alloy chemistry for Optimized ZIRLO is listed in Table 2.D.1.

Table 2.D.1 - Optimized ZIRLO Cladding Composition

Element	Nominal value (wt%)	Allowable range (wt%)
Niobium	[ ] [a,c]	0.8 - 1.2
Iron	[ ] [a,c]	0.09 – 0.13
Tin	[ ] [a,c]	0.6 – 0.8
Oxygen	[ ] [a,c]	0.09 – 0.16
Zirconium	[ ] [a,c]	Balance
Trace element levels	Typical of Zircaloy 4 – ASTM B 811	

Mechanical Properties

The product specifications include acceptance criteria for the tensile strength and ductility of Optimized ZIRLO components. The mechanical strength of the material is controlled also by process procedures and qualifications and verified by quality control testing. Table 2.D.2 lists basic mechanical properties that encompass Optimized ZIRLO cladding. Additional data on the mechanical test results on Optimized ZIRLO is reported in Section B.7 of Addendum 1 to WCAP 12610-P-A

a,b,c

Table 2.D.2 Room Temperature Tensile Values

Physical Properties

Addendum 1 to WCAP 12610-P-A contains extensive lists of physical property data obtained from testing of Optimized ZIRLO. There are primarily two physical properties that are monitored during the production of Optimized ZIRLO cladding; hydride orientation and autoclave performance. The hydride orientation is measured using ASTM B811 as a guideline and the maximum value of [ ]a,c is applied to the test results for Optimized ZIRLO. The autoclave testing is done over a test time of three days in [ ]a,c

The precipitate microstructure is controlled by the qualified processing parameters. The anneal times and temperatures are controlled to insure adequate formation and aging of the precipitate microstructure. For ZIRLO the precipitate size is maintained relatively small compared to Zircaloy 4. Since the precipitate size and chemistry is a function of the iron and niobium levels in ZIRLO and these elements are present in Optimized ZIRLO at the same levels as in standard ZIRLO ; thus, the precipitate microstructure in Optimized ZIRLO is the same as in ZIRLO and is described below:

[

]^{a,c}

3. Irradiation experience with Optimized ZIRLO™ is discussed in Section 3.5.
   a. In light of the limited database presented, justify the material properties up to 62,000 MWD/MTU.

      <u>Response 3a:</u>
      The characterization testing reported in the addendum demonstrates that standard ZIRLO material properties currently used in various models and methodologies are applicable to analyses of Optimized ZIRLO. The primary effects of a reduced tin level in ZIRLO are a minor reduction in the un-irradiated mechanical strength and improvement in the corrosion resistance. The higher burn-up levels are associated with higher fluence levels. Since the precipitate structure remains the same for current and Optimized ZIRLO, the past performance of ZIRLO precipitate structure at high burn-ups also is similar to the Optimized ZIRLO condition.

      Likewise, with the irradiation strengthening occurring during the initial irradiation, the Optimized ZIRLO performance will be the same as the current ZIRLO performance. The irradiation strengthening that occurs with the initial fuel operation negates the starting differences in mechanical strength. This effect has been reported in the general literature. An early example is found in ASTM STP 681 in an article by K. Pettersson on the effects of irradiation on the mechanical strength of Zircaloy tubes. Figure 3.1 is a copy of one of the figures in the report that shows that irradiation strengthening occurs very early in the initial operating cycle. The data shows that there is an initial period when at relatively low fluence (3×10^{21} n/cm^2) the majority of the irradiation strengthening occurs. Data reported in ASTM STP 484 by D.H. Hardy on "The Effect of Neutron Irradiation on the Mechanical Properties of Zirconium Alloy Fuel Cladding in Uniaxial and Biaxial Tests" indicates that (a) strengthening occurs during the initial

irradiation, (b) for large differences in starting conditions the strength differences are not fully eliminated at 3 x 10^{21} n/cm^2 and (c) after about 3 x 10^{21} n/cm^2 the 0% cold worked structure has a strength similar to the un-irradiated cold worked material. Information from hot cell testing of irradiated thimble tubes and cladding confirms the effects of irradiation strengthening in reducing/negating the strength differences initially present in the starting un-irradiated material. Due to processing differences the standard ZIRLO thimble tubes have a lower un-irradiated strength [ ][a, b, c] compared to un-irradiated fuel cladding. As shown in the data table included in the response to RAI #25, measured strengths of cladding and thimble tubes show a significant difference in un-irradiated strengths but upon irradiation the mechanical strengths of both the thimble tube and the cladding are increased to similar levels. The difference in un-irradiated mechanical strengths between Standard ZIRLO and Optimized ZIRLO is much less than the corresponding difference between cladding and thimbles. The strength increase due to irradiation is generally beneficial and provides additional margin between stress and stress criteria.

Figure 3.1 Effects of Fluence Levels on Mechanical Properties (ASTM STP 681 - article by K.Pettersson)

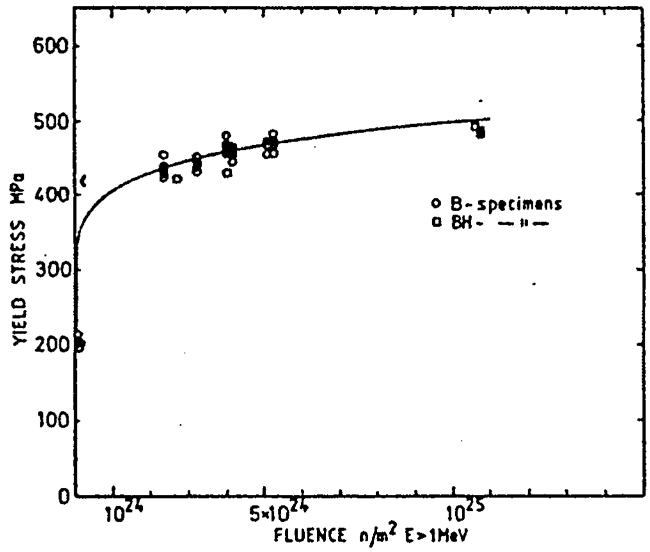


FIG. 2—*Fluence dependence of the yield stress for the B specimens.*

The difference in corrosion resistance is not changed with irradiation and is a positive result. The corrosion resistance comes primarily from both the precipitate microstructure and the tin levels. As indicated in earlier responses the precipitate structure in Optimized ZIRLO is the same as the standard ZIRLO, so there will be no difference in performance related to the precipitate structure. However, past experience with low tin Zircaloy-4 and associated alloys indicates that the tin level reduction results in a lower (beneficial) corrosion rate. This has been confirmed during the second cycle of operation in [ ] a,c where the oxide thickness on the Optimized ZIRLO cladding continues to show significant improvements over the Standard ZIRLO cladding. Oxide reductions exceeding 20% have been measured for Optimized ZIRLO compared to standard ZIRLO on the [ ] a,c LTA rods after 52 GWD/MTU.

Figure 3.2

a,b,c

b. Exemptions for LTAs containing Low-Tin ZIRLO™ have been issued for several plants. When will data be available for clad material approaching 0.60 w/o tin and 62,000 MWD/MTU?

The following is a summary of Low Tin Zirlo™ LTA programs and summary of available data from the Byron LTA program

<u>Byron</u>

Two characterized LTAs containing Optimized ZIRLO cladding were inserted into Byron Unit 1 Cycle 10. After Unit 1 Cycle 10 the LTAs were discharged to the SFP for interim examinations in December of 2000. The LTAs were subsequently reinserted into Byron Unit 2 Cycle 10 for an additional cycle. The LTAs were once again discharged for interim examinations in October 2002. After the exams the LTAs are schedule to be reinserted into Unit 1 Cycle 13 to achieve peak rod burnup in excess of 62,000 GWD/MTU.

The interim examinations for the Byron LTAs included measurements of overall assembly growth, individual fuel rod growth and structural corrosion as well as other pool-side examinations. The results of the Optimized ZIRLO measurements from the end of the first and second cycles are shown in Table 3-1 below along with Standard ZIRLO peak oxide data for comparison purposes. To date the Optimized ZIRLO cladding has exhibited excellent corrosion

performance in the Byron LTAs while fuel rod and assembly growth remain within the existing ZIRLO database.

a, b, c

At the conclusion of the Byron LTA program several Optimized ZIRLO fuel rods with varying degrees of burnup will be available for more extensive study.

Calvert Cliffs

Four LTAs containing a variety of advanced cladding alloys including Optimized ZIRLO were inserted into the Calvert Cliffs Unit 2 Cycle 15 core in 2003. These LTAs will be irradiated for two cycles to a burnup less than 60,000 GWD/MTU. The LTAs will be evaluated in a poolside exam after the second cycle and optionally inserted into Calvert Cliffs Unit 1 Cycle 19 for a third cycle to generate additional high burnup data. The first cycle of irradiation for these LTAs is currently underway.

Catawba

Eight characterized LTAs containing Optimized ZIRLO cladding were inserted in the Catawba Unit 1 Cycle 15 core at the end of 2003. The LTAs will be examined after each of three cycles. The first cycle of irradiation of these LTAs is currently underway.

Millstone

Eight characterized LTAs containing Optimized ZIRLO cladding were inserted in the Millstone Unit 3 Cycle 10 core for three cycles of irradiation. The LTAs will be examined after each cycle. The first cycle of irradiation of these LTAs began in early 2004.

Schedule for LTA PIE plans is shown in Table 3-2

Table 3-2 LTA PIE plans*

a,c

4. Byron LTAs include Optimized ZIRLO™ thimble tubes. Section 4.4 states, "the use of ZIRLO™ cladding or structural materials for the fuel assembly skeleton...". Is Westinghouse currently using or plan to use either ZIRLO™ or Optimized ZIRLO™ in fuel assembly components other than fuel clad?

   Response 4:

   Westinghouse is currently using ZIRLO™ in fuel assembly components (thimble tubes and grids). Similarly, Optimized ZIRLO™ has been in use in the Fuel Assembly thimbles and grids in the certain plants currently hosting Optimized ZIRLO™ LTAs. Westinghouse plans to use Optimized ZIRLO™ in fuel assembly components (thimble tubes and grids) upon WCAP approval.

5. With regard to the continued use of Zircaloy-4 properties in the ZIRLO™ models, the SER for CENPD-404-P-A states, "the staff notes that this practice should not be used in the future, and future applications will be expected to fully measure and develop the material properties of proposed new cladding alloys". This Topical Report supports continued use of Zircaloy-4 properties for Optimized ZIRLO™. Please provide the technical bases and relevant data to support your position.

   Response 5:

   The implementation of standard ZIRLO™ in Combustion Engineering (CE) designed PWRs (CENPD-404-P-A) involved the application of some Zircaloy-4 correlations to standard ZIRLO™ properties because it was demonstrated that the differences were insignificant. However, the Nuclear Regulatory Commission's Safety Evaluation Report (NRC SER) for CENPD-404-P-A noted that this practice should not be used in the future and future applications would be "...expected to fully measure and develop the material properties of proposed new cladding alloys." In this instance, it is important to recognize three Westinghouse considerations in the development of Optimized ZIRLO™ properties.

   1. **The first consideration is that Optimized ZIRLO™ is not a new alloy, rather it meets the established definition of ZIRLO™, albeit with a tighter specification on tin content. Consequently, Westinghouse did not consider the SER requirement in this situation to be applicable.**

2. **The second consideration is to note that although the sources of the ZIRLO™ property correlations were identified in CENPD-404-P-A (i.e., as ZIRLO™ or Zircaloy-4), the property was found to be essentially the same for both materials, and the proposed property correlation is a satisfactory correlation for both ZIRLO™ and Zircaloy-4.**

3. **Finally, and most importantly, even though Optimized ZIRLO™ is only a variation of ZIRLO™, Westinghouse developed and performed an extensive and complete test program (described in Appendix A of WCAP-12610-P-A and CENPD-404-P-A Addendum 1) to evaluate the required Optimized ZIRLO™ and standard ZIRLO™ thermal and mechanical properties and compared those properties to approved properties of ZIRLO™ (described in Appendix B of WCAP-12610-P-A and CENPD-404-P-A Addendum 1). It was concluded that the existing property correlations, whether originally from ZIRLO™ or from Zircaloy-4, are, in fact, no less applicable as Optimized ZIRLO™ property correlations. Thus, Westinghouse believes it has conformed to the referenced SER requirement that the properties should be fully measured. Westinghouse concluded, therefore, that the correlations for standard ZIRLO™ in CENPD-404-P-A are also Optimized ZIRLO™ property correlations.**

6. WCAP-12610-P-A Section 2.5.5 addresses fuel clad wear. Why is this design criterion not included for Optimized ZIRLO? Will the models maintain the 10% design wall thickness reduction?

<u>Response 6:</u>
The Fuel Rod Clad Fretting was addressed in our internal Design Review Process. The Criterion, Basis, and Verification for the Fuel Rod Clad Fretting is as follows:

Criterion: Grid assembly springs shall be designed to limit fuel rod clad fretting to less than [ ]$^{a, b, c}$ of the clad wall thickness at the end of fuel assembly life, considering all pertinent factors such as spring relaxation due to irradiation, clad creep-down, grid growth, etc. (There is no change in this criterion).

Basis: Experience has shown that by meeting these spring requirements, excessive fretting of the fuel rod clad is prevented.

Verification: Based on VIPER test results, the fuel rods of ZIRLO™ material has demonstrated fretting wear resistance that is equal to or better than the fuel rods with Zircaloy-4 material. VIPER tests conducted on Optimized ZIRLO™ also met the fretting wear resistance criteria. As the reactor starts operation, an oxide film forms on both the spring and rod surfaces. It is these surfaces that are subject to any potential fuel clad wearing. Both surfaces are zirconium oxide and there are no expected differences in the

Optimized ZIRLO™ oxide characteristic. Hence the wear rate for the Optimized ZIRLO™ fuel rods is expected to be comparable to the ZIRLO™ material. Therefore, the design criterion is satisfied.

7. The evaluation of DNB propagation in Section 4.2.1 concludes that since there is no effect on rod internal pressure, there will be no effect on DNB propagation.

a. The extent of DNB propagation would also depend on material properties (e.g., creep) and this needs to be addressed.

b. The criteria states that the internal pressure of the lead fuel rod in the reactor will be limited to a value below that which could cause extensive DNB propagation to occur. How is extensive DNB propagation quantified under normal and transient conditions? Are the potential clad failures associated with DNB propagation accounted for in the dose calculations?

<u>Response 7a:</u>

CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure", provides a more comprehensive discussion of DNB propagation than is offered in either WCAP-12610-P-A and CENPD-404-P-A, Addendum 1 or CENPD-404-P-A. Westinghouse agrees that the extent of DNB propagation depends on rod internal pressure and other material properties such as creep. It also depends on operating conditions such as linear heat rate and temperature of the cladding which, in turn, depends on the duration of the time in DNB, coolant temperature and pressure conditions, waterside corrosion and cladding loss, and the amount of rod-to-rod gap closure during a DNB transient. The evaluation in WCAP-12610-A and CENPD-404-P-A Addendum 1, Section 4.2.1, includes these dependencies as well as the potential distribution of fuel rods in DNB and above the reactor system coolant pressure. Since there is no effect of Optimized ZIRLO™ on normal plant operation, no effect on the individual DNB transient behavior relative to standard ZIRLO™, and no difference from ZIRLO™ material properties, there will be no effect on the distribution of fuel rod internal pressures relative to the distribution of fuel rods experiencing DNB during a DNB transient. As a result, there is no effect on the extent of DNB propagation. The only effect would be from reduced waterside corrosion and, therefore, reduced clad thinning and reduced creep, which would have a beneficial effect. This beneficial effect is ignored. Since this is not credited in the analyses, the result is no effect on DNB or DNB propagation.

Response 7b:

A specific limit on the fraction of rods allowed to experience DNB due to propagation is based on requiring that the total number of rods in DNB , including DNB propagation effects are within the limits for rod failure by DNB assumed in the offsite dose limit calculations. DNB propagation analyses are performed for each Condition III/IV DNB event identified. Typically, these events include: Single Rod Withdrawal at Power, Ejected Rod, and Locked Rotor. The actual number of rods allowed in DNB for each analysis is confirmed in the evaluation. Therefore, the clad failures associated with DNB propagation are bounded by the dose calculations.

8. WCAP-12610-P-A Section 2.5.3 lists a temperature limit for Condition I which differs from the corresponding value in Addendum 1. Is this a planned change to the criteria or a typo?

Response 8:

Yes, this is a typographical error; WCAP-12610-P-A Section 2.5.3 lists the correct temperature limit of 780 °F for Condition I. A correction will be made to the approved report WCAP-12610-P-A and CENPD-404-P-A Addendum 1.

9. Section 4.2.2 makes a statement concerning the "...continued use of Standard ZIRLO™ properties and models for Optimized ZIRLO™...". Identify when properties and models are based upon which clad material (e.g., Standard ZIRLO™, Optimized ZIRLO™, Zircaloy-4).

Response 9:

The Optimized ZIRLO™ measured properties and, therefore, model correlations, have been demonstrated to be equivalent to standard ZIRLO™ in Appendix B of WCAP-12610-P-A and CENPD-404-P-A Addendum 1. The implementation of standard ZIRLO™ in CE designed PWRs (see CENPD-404-P-A) involved the application of some Zircaloy-4 correlations to standard ZIRLO™ properties because it was demonstrated to be appropriate. This approach was accepted by the NRC as part of the review and approval of CENPD-404-P-A, as documented in the SER. The identification of when the source of property and model correlations were ZIRLO™ or Zircaloy-4 (OPTIN™) is summarized in CENPD-404-P-A Appendix A, Tables 7 through 25.

As stated in Response 5, however, it is concluded that the existing property correlations, whether originally from ZIRLO™ or from Zircaloy-4, are, in fact, directly applicable for use as Optimized ZIRLO™ properties.

10. Section 4.2.2 states that the calculation of DNB propagation depends on internal rod pressure, high temperature creep, and high temperature burst stress. Do DNB propagation calculations predict clad burst under non-LOCA transient conditions? If so, provide information on how the potential impacts of this failure mechanism have been addressed within the respective events dose calculation.

Response 10:

Under certain non-LOCA transient conditions, DNB propagation calculations may predict cladding burst. If clad burst is predicted, the fuel rod internal pressure is relieved and no further cladding strain occurs. The dose contribution from the burst fuel rod is automatically accounted for in the dose calculation because it was already in DNB and, consequently, conservatively assumed to fail regardless of whether or not burst was actually predicted.

11. With regard to potential differences between tensile and compressive creep rates and the "relatively small creep database for ZIRLO™", the SER for CENPD-404-P-A states, "WEC committed to acquire more in-reactor creep data under both tensile and compressive stress conditions for ZIRLO™ material". The SER concludes, "On the basis of the approved creep model and the commitment to acquire additional data, the staff considers that the creep model for the NCLO criterion is acceptable for FATES3B".

a. What is the current status of the "detailed irradiation program for ZIRLO™"?

Response 11a:
A detailed irradiation growth and creep program initiated irradiation in Vogtle unit 2 cycle 10 in November 2002. The first test assembly is scheduled to be discharged at the end of cycle 10 in May 2004.

b. Addendum 1 states, "An evaluation demonstrated that the application of Standard ZIRLO™ properties and models to Optimized ZIRLO™ will have no impact on maximum internal pressure and will have a conservative impact on the NCLO critical pressure limit". Did this evaluation consider in-reactor creep data from the above commitment?

Response 11b:
The in-reactor creep data from the above commitment is not yet available and thus was not used in the evaluation. The evaluation was based on the same out-reactor thermal creep behavior of Optimized ZIRLO™ and Standard ZIRLO™

12. Section 4.5 of Addendum 1 documents the potential affect of changes in specific heat on Non-LOCA transients.

a. For all licensees, were all events which experience DNB or elevated clad temperatures evaluated for the further decrease in phase transition temperature (relative to both Zircaloy-4 and Standard ZIRLO™)?

b. Provide a list of the events considered and the calculated peak clad temperature for each event.

c. Was FACTRAN and/or STRIKIN-II used to calculate peak clad temperature for Locked Rotor/Sheared Shaft as well as any other event which experienced DNB or elevated clad temperatures?

Westinghouse Plants
Response:
The Peak Cladding Temperatures (PCT) calculated in a number of FSAR analyses for 2, 3, and 4-loop plants were reviewed as part of the Standard ZIRLO™ licensing effort. It was found that the cladding temperature remains below the phase transition temperature (~1400°F) for the following events:

- **RCCA Withdrawal from Subcritical**
- **RCCA Withdrawal at Power**
- **Dropped RCCA/RCCA Bank Event**
- **Boron Dilution (all modes)**
- **Startup of an Inactive Reactor Coolant Loop**
- **Loss of Electrical Load and Turbine Trip**
- **Loss of Normal Feedwater and Station Blackout**
- **Excessive Heat Removal Due to Feedwater Malfunction**
- **Excessive Load Increase**
- **Accidental Depressurization of the Reactor Coolant System**
- **Steamline Break (core response and mass & energy release, at all power levels)**
- **Complete Loss of Flow**
- **Partial Loss of Flow**
- **Main Feedline Rupture**

The only events that result in PCTs higher than the phase transition temperature are Locked Rotor and RCCA Ejection (Hot Full Power and Hot Zero Power cases).

For these events, sensitivity studies using the FACTRAN code were completed to quantify the effect of the change in specific heat between Standard ZIRLO™ and Zircaloy-4. The sensitivity studies showed that the difference in specific heat between Zircaloy-4 and Standard ZIRLO™ has very little effect (~2°F in PCT) on the results. These results were judged to be applicable to Optimized ZIRLO™ since the specific heats of Standard and Optimized ZIRLO™ are the same within the accuracy of the data.

The PCTs calculated in the Locked Rotor and Rod Ejection analyses considered in the sensitivity studies are shown in Table 1 below.

a, b, c

CE Plants

<u>Response 12a:</u>
CENPD-404-P-A, Rev 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs", November 2001, concluded that, with respect to cladding materials, only specific heat was of importance to one computer code used for non-LOCA analysis. Other computer codes are not sensitive to clad material properties, or the models used are adequate for modeling ZIRLO™. This was true for thermal conductivity where it was shown that Zircaloy-4 and ZIRLO™ have the same thermal conductivity equations. The one computer code that was impacted was the STRIKIN-II code used to perform CEA Ejection analysis. As discussed in CENPD-404-P-A, CEA Ejection is impacted because it is the only event that has the potential for exceeding the ZIRLO™ lower alpha-beta phase change temperature. Up to the phase change temperature, ZIRLO™ and Zircaloy-4 have virtually identical specific heat curves. After passing through the phase change temperature, the specific heats change and this could impact STRIKIN-II predicted total hot spot deposited energy (the acceptance criteria for CEA Ejection). For this reason STRIKIN-II and CEA Ejection were investigated. Analysis was performed for CENPD-404-P-A to quantify the impact on CEA Ejection results using ZIRLO™ specific heat inputs to STRIKIN-II. This was done for both CE 14x14 and 16x16 fuel designs. The conclusion presented in CENPD-404-P-A is that the impact is negligible

For the Optimized ZIRLO™ report, an evaluation was performed to determine the impact of the slightly lower phase change temperature of Optimized ZIRLO™. The evaluation (which relied on STRIKIN-II results using Zircaloy-4 and ZIRLO™ properties) found that the Optimized ZIRLO™ and ZIRLO™ specific heat are very similar up to the alpha-beta phase change temperature of Optimized ZIRLO™ (approximately 1250 °F vs 1380 °F for ZIRLO™). Additionally, the data indicates that Optimized ZIRLO™ and Zircaloy-4 are much more nearly equal than are Zircaloy-4 and ZIRLO™ during the phase change. Consequently, it was concluded that the impact of Optimized ZIRLO™ relative to ZIRLO™ was again negligible.

Response 12b:

CENPD-404-P-A, Table 7.3-1 provides a list of events considered. Since the Optimized ZIRLO™ properties are the same as ZIRLO™, the peak clad temperatures will be the same as CENPD-404-P-A, Section 7.3.

Response 12c:

FACTRAN and STRIKIN-II are used to calculate peak clad temperature for DNB events. FACTRAN is used by Westinghouse on Westinghouse designed PWRs and STRIKIN-II is used by Westinghouse on CE designed PWRs.

13. ZIRLO™ alloy is described as having a "...microstructure comprising second phase precipitates (specifically, a body-centered cubic beta-niobium-zirconium phase and a hexagonal zirconium-niobium-iron inter-metallic phase) homogeneously distributed throughout the zirconium matrix."

a. Describe how the reduction in tin will influence the shape, size, distribution, and weight fraction of the second phase precipitates (beta-ZrNb and hcp-ZrNbFe).

Response 13a:
The two precipitate phases do not contain tin and thus their shape, size, distribution and weight fractions are not affected by the reduction in tin.

b. Describe how planned changes to the material processing will influence the shape, size, distribution, and weight fraction of the second phase precipitates (beta-Zr-Nb and hcp-Zr-Nb-Fe).

Response 13b:
The second phase or precipitate characteristics are a function primarily of the relative levels of niobium and iron in the alloy. The impacts of the process are focused on the reaching a near equilibrium condition in the precipitate microstructure. The Optimized ZIRLO™ processing follows the past ZIRLO™ processing and minor change in past ZIRLO™ annealing temperatures will not impact shape, distribution, size and weight fraction of the precipitates in Optimized ZIRLO™ compared to past ZIRLO™ production.

14. Sections 2.2 and 3.1 – It appears the mean tin content for Optimized ZIRLO™ will be around [ ] a,c? Is this interpretation correct? To what tolerance limit will the [ ] a,c value be applied in the fabrication of Optimized ZIRLO™?

Response 14:
The target tin content in Optimized ZIRLO™ will be [ ] a, b, c with lower limit of 0.6% and [ ] a, b, c. The test lot was fabricated with a target tin content of 0.6% to respond to NRC's concern to make certain that the characterization data bounds the desired [ ] a, b, c tin lower limit for Optimized ZIRLO™

15. Please provide the fabrication differences between the standard ZIRLO™, standard Zr-4, low tin Zr-4, and Optimized ZIRLO™ for cladding and guide tubes. This includes the intermediate cold-work and annealing steps but of particular interest is the final cold-work, annealing temperatures and times. If the annealing times have changed between the materials please provide the average grain size for the Standard and Optimized ZIRLO™ and any texture differences. Also what are the fabrication specifications for the Standard and Optimized ZIRLO™.

Response 15:
The basic fabrication difference in the production cycle for these materials is at the alloy additions for the ingot melting. At this stage all of the materials have different mixes of elements added to the electrode. This is the stage where the different tin levels between standard and Optimized ZIRLO are controlled. The processing of thimble tubes and cladding is the same until near the final pilger reductions. At the final stages there are differences in size reduction (cold working during pilgering and dash pot forming in the thimble tubes). For Zircaloy-4 cladding the final anneal has included both SRA and partial recrystallization anneals depending on the particular design requirements. Changes inherent in process improvements have occurred over time with both the ZIRLO and Zircaloy-4 tube production.
Tubing has been produced by four different vendors and each of the suppliers have had a mildly different process. The initial ZIRLO ingot was made by a Wah Chang process. Subsequent ingots have been made by Western Zirconium. At the Westinghouse Specialty Metals Plant the ZIRLO processing has gone through multiple optimizations, and the current process

modification is referred to as the sixth route. Sandvik Special Metals has also produced ZIRLO tubing using their specific process. The tubing characteristics from the various processes were controlled to meet the design requirements by specifications, drawings, process controls, and quality control testing.

Annealing of Intermediate and Final Tubes:

Because Optimized ZIRLO has a reduced tin level and tin is an alpha stabilizer, there is a resultant small reduction in the phase transition temperature as reported in WCAP-12610-P-A and CENPD-404-P-A Addendum 1. The transition temperature effect combined with the data that shows improved corrosion resistance with lower temperature intermediate annealing indicates that improved corrosion performance of ZIRLO alloys can be achieved with minor modifications to the annealing parameters while still maintaining the required material design characteristics. Process changes of this type are implemented per normal practice when fully qualified. Also since tin provides a degree of creep strengthening, the reduced tin alloy has lower creep strength. A recovery of creep strength can be gained by anneal and/or cold working changes. For the current Optimized ZIRLO process the final anneal temperature has been increased by [ ][a, b, c] to offset the creep strength reduction from the lower tin.

Cold Work and Grain Size:

[

][a,c]

Tubing Texture:

CSR is a measure of the tubing texture and the same CSR limits apply for ZIRLO and Optimized ZIRLO™ in the current tubing specifications. Texture measurements for Optimized ZIRLO are also reported in WCAP-12610-P-A and CENPD-404-P-A Addendum 1.

Process Specifications:

More important than the specific process a variable is that the final product is within the required alloy property ranges that are reflected in the models and design codes. These properties are monitored and controlled by the process qualifications, the design drawings and the product specifications along with other characterization tests. Westinghouse does not have a process specification for fuel cladding. The cladding specification identifies most of the key material characteristic ranges, and the production facilities develop process plans that define a set of process parameters that will be used to fabricate the cladding to meet the specification and drawing requirements.

16. Section 4.6 (Page 20) – It is stated both the ZIRLO™ specific heat model used in WCOBRA/TRAC and the specific heat approximation used in HOTSPOT compared to the differences in the new specific heat data have a negligible affect on large break LOCA analyses even though there is a [ ] a,c difference between the models and the data within a [ ] a,c range. Please discuss further how the sensitivity analysis was performed and the results of the analysis that compare the ZIRLO™ model to the Optimized ZIRLO™ data. Also, explain the differences between the specific heat model in WCOBRA/TRAC and the approximation used in HOTSPOT. (Page 28) An argument is made for the CE evaluation model such that the [ ] a,c higher specific heat for the model compared to the Optimized ZIRLO™ data within the [ ] a,c range will not have a significant impact on peak cladding temperature for LBLOCA but no sensitivity analysis is provided to substantiate this claim. Please provide a sensitivity analysis that demonstrates that the overprediction of specific heat has no or an insignificant effect on LBLOCA results.

Westinghouse Response 16:

The model used in WCOBRA/TRAC for ZIRLO™ cladding specific heat is given in Table 10-18 of Reference 16-1, and is approximated as follows in HOTSPOT:

[ ] a,b,c

Linear extrapolation of the first two points is used below 300 K, and linear interpolation of the neighboring points is used for intermediate values. As shown in Figure 16-1, there are only minor differences between the two models, indicating that the simplified model used in HOTSPOT is adequate for the intended purpose.

Figure 16-1

[ ] a, b, c

For the HOTSPOT sensitivity calculation described in Section 4.6.1 of the Topical Report, the ZIRLO™ specific heat model was replaced with a table of 25 points representing the Optimized ZIRLO™ data. These points span the range of the "heating" data from Table B.2-1 of the Topical Report [ ][a,b,c] with temperature values chosen to provide a close approximation of the data. Linear extrapolation was used for temperatures outside the data range, and linear interpolation was used for intermediate temperatures. As shown in Figure 16-2, the main differences between the Standard ZIRLO™ model and the 25-point representation of the Optimized ZIRLO™ data occur for temperatures between 1400°F and 1600°F.

Figure 16-2

a, b, c

The transient selected for the HOTSPOT sensitivity calculation has a peak cladding temperature (PCT) near the 10 CFR 50.46 limit of 2200°F that occurs early in the reflood phase of the transient. Relative to the Standard ZIRLO™ case, the Optimized ZIRLO™ case showed a 2.7°F increase in average PCT (from 2191.0°F to 2193.7°F) and a 1.7°F decrease in standard deviation (from 54.1°F to 52.4°F) that are considered to be negligible. This is consistent with the expected result, since the differences in specific heat are relatively minor over most of the temperature range of interest for large break LOCA, and since limiting licensing transients spend little time in the temperature range where the most significant differences are observed.

References

16-1. WCAP-12945-P-A Volume I (Revision 2) and Volumes II-V (Revision 1), "Westinghouse Code Qualification for Best Estimate Loss of Coolant Accident Analysis", March 1998.

CE Response 16:

[

]a,b,c

a, b, c

[

]a,c

These results substantiate the argument on page 28 and demonstrate that the overprediction of the specific heat data [ ]a,c by the ZIRLO™ specific heat model has an insignificant effect on the LBLOCA PCT. In particular, the sensitivity analysis showed that, when the specific heat data is represented, there is an increase in cladding temperature during blowdown when the cladding temperature is passing through the subject temperature range. [

]a,c

References

16-2 CENPD-132, Supplement 4-P-A, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," March 2001.

17. Section 4.6 (Page 24) – The measurements of high temperature creep rate plotted in Figure B.14.1 are implied to be determined from the secondary or steady-state creep rate. However, page A-6 in Appendix A explanation of how the creep rates were determined at and below 1183 °K for this figure appear to suggest that the creep rates are based on primary creep, i.e., tangential slope of strain versus time plot starting at zero strain. Please provide an example of how the strain rates were determined from an actual strain versus time plot for temperatures equal to and below 1183 °K and those at 1273 °K.

<u>**Response 17:**</u>

[

]a,c

Figure 17.1 – Optimized ZIRLO™ Creep Test – 1093 K 20 MPa

a,b,c

Figure 17.3 – Optimized ZIRLO™ Creep Test – 1273 K 4 MPa

a,b,c

18. Appendix B -- The tin concentrations of the Optimized ZIRLO™ data were not always provided in Appendix B. What were the tin concentrations of the Optimized ZIRLO™ properties data provided in Appendix B for emissivity, thermal expansion, high and low temperature thermal creep, fatigue, single rod burst, high temperature oxidation, and ring compression tests.

<u>Response 18:</u>
Refer to Response 14. As reported in section 3.1, [

]^{a,c}. Both the lots were for tested for emissivity, diametral thermal expansion, low and high temperature thermal creep, fatigue, high temperature oxidation and ring compression tests. For single rod burst tests, lot Q40-1113 was used. For axial thermal expansion, lot Q40-1114 was used.

19. Appendix B.14 - The high temperature creep data demonstrate that the current high temperature creep model overpredicts cladding strain [
]^{a,c} in a steam atmosphere. What are the consequences if cladding strains are overpredicted in the large and small break analysis? Is this always conservative or are there instances where this could result in non-conservative results?

<u>Response 19:</u>

It cannot be stated that over-predicting the cladding strain prior to burst is always conservative for large and small break LOCA analyses. But the degree of over-prediction observed at [ ] a,b,c is not indicative of the expected effect on large and small break LOCA analysis results, and it was decided to conduct some additional tests under conditions more typical of a licensing-basis LOCA transient. [

] a,b,c

Predictions of the tests were obtained using a computer program adapted from the LOCBART swelling and rupture models for ZIRLO™ cladding. These models calculate the change in clad diameter vs. time due to thermal expansion, mechanical strain, and high-temperature creep, and can be readily compared against the test results which include transient measurements of the clad outside diameter. [

] a,b,c

Figure 19-1

a,b,c

The swelling and burst data obtained with [

]a, b, c The following discusses, in general, how the high temperature creep model is integrated within the Westinghouse Appendix K LOCA evaluation models, using LOCBART as an example.

LOCBART is used to calculate the hot rod and hot assembly thermal responses during the large break transient. The largest axial noding used is 6 inches, with the blockage region and the limiting PCT regions modeled using 3-inch axial noding. The rod internal pressure is calculated as a function of time, accounting for changes in temperature in the various gas regions (plenum, gap and stack), and fuel rod dimensions (e.g., cladding plastic deformation due to high temperature creep). Plastic deformation, or swelling, is allowed to occur at any elevation where the cladding temperature and differential pressure are high enough to cause high temperature creep. [

]a, c When cladding burst occurs, the rod internal pressure is relieved, and the high temperature creep process is terminated.

[

]a, c

20. Section 4.6 - The non-linear increase in ZIRLO™ thermal conductivity observed [

] a,c Please explain. What were the heating rates of the laser diffusivity measurements?

<u>Response:</u>
The thermal conductivity does have a non-linear change near the temperature of 900 C [ ] a, b, c. To better understand the temperatures related to the change a plot was made of the incremental slope of the lines between the data points of the thermal conductivity data in Table B.3-1 of Appendix B to WCAP-12610-P-A. The following figure 20.1 shows the results of that calculation that focuses on the temperatures at which the thermal conductivity rate is changing. The chart indicates that the thermal conductivity rate with temperature starts to change at about [ ] a, b, c. This temperature range is similar to the start of the alpha to alpha + beta temperature range reported in section B.6 and observed in the specific heat measurements in section B.2.

Figure 20.1

[ ] a,b,c

The method used for the thermal conductivity/diffusivity measurements follows ASTM E1461 and involves relatively fast incremental heating rates. The sample is preheated to the test temperature and then pulsed with a laser of known energy. The temperature rise on one face of the sample disk is about 30^{0} C for a few milliseconds and on the back face of the disk the temperature rise is about 1.5 °C. The relative heating rates will result in some minor differences in the observed phase transitions. To obtain a more accurate phase change profile using this technique would require data points at smaller temperature intervals. However, the data is consistent and shows that the thermal conductivity rate change is related to the phase change.

21. Section 4.5 - It is noted in this section that the differences in specific heat between Zr-4 and ZIRLO™ have no or negligible effect on non-LOCA analyses. However, there are several material property data for Optimized ZIRLO™ that are different from the model used in Westinghouse and CE evaluation models by more than 10%. Are there other accidents besides large break LOCA, e.g., small-break LOCA, Locked Rotor/Sheared Shaft, and Rod Ejection events, where an underprediction of clad thermal conductivity above 1000 °C, or an overprediction in clad emissivity, or an underprediction of clad thermal expansion have an impact on the calculated results? What is the cumulative impact of all these differences including specific heat on large break LOCA and other accident analyses?

Response

As discussed in Sections 4.6.1 and 4.6.2 of the Topical Report, the differences between the emissivity models and the Standard/Optimized ZIRLO™ data are mostly attributed to the testing environment, and therefore should not be assessed against current licensing-basis analysis results. For thermal conductivity, thermal expansion, and specific heat, additional sensitivity calculations were completed using LOCBART and SBLOCTA to demonstrate the effect of differences between the models and data on results. The changes to the models are described below, followed by the sensitivity calculations which demonstrate an insignificant effect on the calculated peak cladding temperature.

For thermal conductivity, the current ZIRLO™ model shown in Figure 4.6.1-2 of the Topical Report was replaced by a table of the Optimized ZIRLO™ points from Table B.3-1 of the Topical Report. (Note that the first temperature point differs slightly due to rounding.) For diametral thermal expansion, the current expansion coefficient of [ ]^{a,c} was increased to [ ]^{a,b,c} based on the value used in the CE model sensitivity calculation described in Section 4.6.2 of the Topical Report. (Note that axial thermal expansion is not modeled in LOCBART and SBLOCTA.) For specific heat, the current ZIRLO™ model (which is now based on the Standard ZIRLO™ "heating" data from Table B.2-1 of the Topical Report, per Reference 21-1) was replaced by a table of 26 points based on the Optimized ZIRLO™ "heating" data from Table B.2-1 of the

Topical report. (See the Specific Heat part of Section 4.6.1 of the Topical Report for related information.)

The first case is a sample LOCBART transient with a burst-node-limited, early-reflood PCT. The base calculation (denoted as case (a)) modeled Standard ZIRLO™, and the sensitivity calculations modeled (b) Optimized ZIRLO™ thermal conductivity and thermal expansion, (c) Optimized ZIRLO™ specific heat, and (d) Optimized ZIRLO™ thermal conductivity, thermal expansion, and specific heat. Figure 21-1 compares the cladding temperature at the PCT elevation for the base case and case (d) and indicates a minimal effect on the overall transient behavior. Relative to the base case, the PCT increased by about [ ]^{a,b,c} for case (b), [ ]^{a,b,c} for case (c), and [ ]^{a,b,c} for case (d), all of which are insignificant despite the over-sensitivity of LOCBART to changes for this type of transient. Figure 21-2 compares the cladding temperature at the PCT elevation for all four cases near the PCT time and shows that most of the temperature increase results from the change in specific heat, which is consistent with the expected result given the relative importance of the specific heat vs. thermal conductivity/thermal expansion models in a large break LOCA transient.

The second case is a sample LOCBART transient with a late-reflood PCT. For this case, the four calculations described above resulted in a total variation in PCT of less than [ ]^{a,b,c}. Figure 21-3 compares the cladding temperature at the PCT elevation for the base case and case (d) and indicates a minimal effect on the overall transient behavior, which is consistent with the expected result for large break LOCA transients where the PCT occurs late in reflood.

The third case is a sample SBLOCTA transient. The base case was reanalyzed using the Optimized ZIRLO™ thermal conductivity, thermal expansion, and specific heat, resulting in a PCT decrease of about [ ]$^{a,b,c.}$ Figure 21-4 compares the cladding temperature at the PCT elevation and indicates a minimal effect on the overall transient behavior, which is consistent with the expected result for small break LOCA transients.

Based on these and other calculations that have been performed for the Optimized ZIRLO™ program, differences between the models and data for parameters such as thermal conductivity, thermal expansion, and specific heat have generally been found to produce a negligible effect on the analysis results. Similar effects are also expected for the CE LOCA evaluation models and non-LOCA transients such as locked rotor/sheared shaft and rod ejection, and updating the current ZIRLO™ models is generally not required to obtain an adequate prediction of Optimized ZIRLO™ performance. Somewhat larger effects were observed due to differences in specific heat for LOCBART transients with a burst-node-limited, early-reflood PCT, and were resolved as described in Reference 21-1 by updating the Standard ZIRLO™ specific heat model based on the "heating" data from Table B.2-1 of the Topical Report. (Note that the SBLOCTA specific heat model was also updated to maintain consistency with LOCBART, with a negligible effect on results as indicated in Reference 21-1.)

Calculations using the Appendix K large break LOCA hot rod heat-up code LOCBART indicated an exaggerated sensitivity to specific heat for the small subset of plants with a peak cladding temperature (PCT) that occurs at the hot rod burst elevation coincident with the onset of entrainment in early reflood. This behavior is attributed primarily to excessive conservatism in the licensed method of transferring the core inlet flooding rate from BASH to LOCBART, and is exacerbated by the application of the overly-conservative Baker-Just correlation for zirconium-water reaction to both the inside and outside surfaces of the cladding at the hot rod burst elevation. [

Table 21-1: Optimized ZIRLO™ Specific Heat Model

a,b,c

]a,b,c

A question has also been raised regarding the effect of variations in cladding specific heat on uncertainties for Best Estimate LOCA. Page 25-4-14 of Reference 21-2 states that "Uncertainty in cladding specific heat and conductivity is negligible relative to fuel uncertainties, and is ignored." In addition, the response to RAI #16 states that a HOTSPOT sensitivity calculation replacing the Standard ZIRLO™ specific heat model with a model based on the Optimized ZIRLO™ data "showed a 2.7°F increase in average PCT (from 2191.0°F to 2193.7°F) and a 1.7°F decrease in standard deviation (from 54.1°F to 52.4°F)", resulting in nearly identical 95th percentile PCTs of 2280.0°F and 2279.9°F for Standard and Optimized ZIRLO™ (respectively). Based on this information, no changes to the uncertainties for Best Estimate LOCA are required to account for the minor differences between the specific heats of Standard and Optimized ZIRLO™.

A question has also been raised regarding the effect of differences between OPTIN and Optimized ZIRLO™ properties on the swelling and rupture behavior for CE mechanistic DNB propagation analyses. For a plant that is transitioning from OPTIN to Optimized ZIRLO™, these effects would be adequately captured by completing mechanistic DNB propagation calculations using the swelling and rupture models described in Reference 21-3. This is consistent with information presented in Section 4.6 of the Topical Report, which has concluded that the swelling and rupture models for Standard ZIRLO™ can reasonably be applied to Optimized ZIRLO™ and need not be modified to reflect the new Standard ZIRLO™ data.

References

21-1. LTR-NRC-03-5, "U. S. Nuclear Regulatory Commission, 10 CFR 50.46 Annual Notification and Reporting for 2002", March 7, 2003.

21-2. WCAP-12945-P-A Volume I (Revision 2) and Volumes II-V (Revision 1), "Westinghouse Code Qualification for Best Estimate Loss of Coolant Accident Analysis", March 1998.

21-3. CENPD-404-P-A, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs", November 2001.

Figure 21-1

a,b,c

Figure 21-2

a,b,c

Figure 21-3

a,b,c

Figure 21-4

a,b,c

22. Section 4.6 - Please describe how flow assembly blockage is determined from rupture strain along with a description of the flow blockage models used in the Westinghouse and CE Evaluation models. What cladding strain values are assumed for the evaluation of equivalent cladding reacted (ECR) for LOCA analyses and provide an example with initial oxidation and oxidation following the LOCA?

Westinghouse Response 22:

For the Westinghouse evaluation models, the following describes the modeling of assembly blockage in Appendix K Small Break LOCA, Appendix K Large Break LOCA, Best Estimate Large Break LOCA, and SECY Large Break LOCA.

Appendix K Small Break LOCA

In SBLOCTA, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled [

]^{a,c}.

Appendix K Large Break LOCA

In LOCBART, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled as a non-uniform reduction in mass velocity in the vicinity of the burst elevation. To account for blockage in BART, the conservation equations were modified to include a source term representing the exit of steam from or entry of steam to the flow channel due to flow redistribution. As discussed in Section 3.2 of Reference 22-1, this source term was derived using an empirical expression for the normalized mass velocity vs. normalized elevation in the flow redistribution region, and depends on the mass velocity at the inlet of the flow redistribution region, the channel hydraulic diameter, the channel blockage fraction, the nodal and burst elevations, and the steam density. With this formulation, steam exits the channel in the lower portion of the flow redistribution region and re-enters the channel in the upper portion of the flow redistribution region, with a discrete approximation of a continuous profile that produces a minimum mass velocity slightly downstream of the hot assembly average rod burst elevation.

For a given axial node I that lies within the flow redistribution region, the flow redistribution model is activated when the following conditions are satisfied: [

]^{a,c}

The channel blockage fraction used with the flow redistribution model is based on Appendix B of NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding at or below 1742°F; Figure 4 of Reference 22-3 for Zircaloy-4 cladding above 1742°F; or, Figure 5-4 of Reference 22-4 for ZIRLO™ cladding. Each of these references

describes the conversion from burst strain to assembly blockage, all of which use the basic approach outlined in NUREG-0630.

In the LOCBART modeling of assembly blockage, no direct credit is taken for the beneficial effects of droplet atomization, flow acceleration, or turbulence intensification that have been observed experimentally (e.g., Reference 22-5). As a result, assembly blockage leads to a local reduction in cladding-to-fluid heat transfer and a corresponding local increase in cladding temperatures, which is conservative relative to experimental results and can represent a substantial conservatism in the analysis when the peak cladding temperature occurs late in reflood.

Best Estimate Large Break LOCA
In the Best Estimate version of WCOBRA/TRAC, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled as an adjustment to the appropriate continuity and momentum cell areas. (See Section 7-4-2 of Reference 22-6.) The flow area reduction due to blockage is based on Figures 7-22 (Zircaloy-4) and 7-23 (ZIRLO™) of Reference 22-6. The conversion from burst strain to assembly blockage uses the basic approach outlined in NUREG-0630, as applied to the burst strain curves from Figures 7-18 (Zircaloy-4) and 7-20 (ZIRLO™) of Reference 22-6. HOTSPOT uses fluid conditions from WCOBRA/TRAC, and therefore does not require an explicit model for assembly blockage.

SECY Large Break LOCA
In the SECY version of WCOBRA/TRAC, assembly blockage is assessed based on burst of the hot assembly average rod, and is modeled as an adjustment to the appropriate continuity and momentum cell areas. (See Section 7-1-4 of Reference 22-7 and Sections 3-3-2 and 3-4 of Reference 22-8.) The flow area reduction due to blockage is based on NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding and Table 3 of Reference 22-9 for ZIRLO™ cladding. Each of these references describes the conversion from burst strain to assembly blockage, using the basic approach outlined in NUREG-0630.

References
22-1. WCAP-8622, "Westinghouse ECCS Evaluation Model, October 1975 Version", November 1975.

22-2. NUREG-0630, "Cladding Swelling and Rupture Models for LOCA Analysis", April 1980.

22-3. ET-NRC-92-3746, "Extension of NUREG-0630 Fuel Rod Burst Strain and Assembly Blockage Models to High Fuel Rod Burst Temperatures", September 16, 1992.

22-4. WCAP-12610-P-A, "VANTAGE+ Fuel Assembly Reference Core Report", April 1995.

22-5. Erbacher, F. J., "Cladding Tube Deformation and Core Emergency Cooling in a Loss of Coolant Accident of a Pressurized Water Reactor", Nuclear Engineering and Design 103, pp. 55-64, 1987.

22-6. WCAP-12945-P-A Volume I (Revision 2) and Volumes II-V (Revision 1), "Westinghouse Code Qualification for Best Estimate Loss of Coolant Accident Analysis", March 1998.

22-7. WCAP-10924-P-A, Revision 2, "Westinghouse Large-Break LOCA Best Estimate Methodology; Volume 2: Application to Two-Loop PWRs Equipped with Upper Plenum Injection; Addendum 1: Responses to NRC Questions", December 1988.

22-8. WCAP-10924-P-A, Revision 1, "Westinghouse Large-Break LOCA Best-Estimate Methodology; Volume 1: Model Description and Validation; Addendum 4: Model Revisions", March 1991.

22-9. WCAP-13677-P-A, "10 CFR 50.46 Evaluation Model Report: WCOBRA/TRAC Two-Loop Upper Plenum Injection Model Updates to Support ZIRLO™ Cladding Option", February 1994.

What cladding strain values are assumed for the evaluation of equivalent cladding reacted (ECR) for LOCA analyses?

Westinghouse Response 22 (Cont'd):
For the Westinghouse evaluation models, the following describes the modeling of burst strain in Appendix K Small Break LOCA, Appendix K Large Break LOCA, Best Estimate Large Break LOCA, and SECY Large Break LOCA.

Appendix K Small Break LOCA
In SBLOCTA, the burst strain is taken as the [ ]^{a,c} (see Section 3-2-1 of Reference 22-8) and the value obtained using: Figure 5-3 of Reference 22-4 for ZIRLO™ cladding; or, the following equation for Zircaloy-4 cladding:

[ ]^{a,c}

where ΔP represents the cladding differential pressure at burst (psi).

Appendix K Large Break LOCA
In LOCBART, the burst strain is taken as the [ ]^{a,c} (see Section 3-2-1 of Reference 22-8) and the value obtained using Appendix B of NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding at or below 1742°F; Figure 2 of Reference 22-3 for Zircaloy-4 cladding above 1742°F; or, Figure 5-3 of Reference 22-4 for ZIRLO™ cladding.

Best Estimate Large Break LOCA

The treatment of burst strain in HOTSPOT is described in Section 25-4-2-3 of Reference 22-6. As discussed therein, [

]a,c.

SECY Large Break LOCA

In WCOBRA/TRAC, the burst strain is taken as the [

]a,c (see Section 3-2-1 of Reference 22-8) and the value obtained using NUREG-0630 (Reference 22-2) for Zircaloy-4 cladding, or Table 3 of Reference 22-9 for ZIRLO™ cladding.

Provide an example with initial oxidation and oxidation following the LOCA.

<u>Westinghouse Response 22 (Cont'd)</u>

Consider a sample LOCBART calculation that produced the following results:

[a,b,c

]

[

]a,c Transient results for the hot rod PCT and burst elevations are shown in Figures 22-1 (clad average temperature), 22-2 (local ECR), and 22-3 (clad outside diameter); note that the ECR computed by LOCBART includes both the transient and pre-transient values, with the latter being approximately zero for this near-beginning-of-life calculation.

Figure 22-1

a,b,c

Figure 22-2

a,b,c

Figure 22-3

a,b,c

CE Response 22:

As described on pages 35 and 36 of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, the CE evaluation models use the same cladding rupture strain and assembly blockage models for Optimized ZIRLO™ as are used for Standard ZIRLO™. The models are described in Sections 6.3.10 and 6.3.11 of CENPD-404-P-A (Reference 22-10). They consist of tables of rupture strain and assembly blockage versus rupture temperature (Tables 6.3.10.1-1 and 6.3.11-1 in CENPD-404-P-A). As noted in Section 6.3.11 of CENPD-404-P-A, the assembly blockage model was developed from [

]a,c

The flow blockage model used in the CE LBLOCA evaluation model (i.e., the 1999 EM, Reference 22-11) is described in Enclosure 1-P-A to LD-81-095 (Reference 22-12). In the flow blockage model, the HCROSS computer code calculates the hot channel flow redistribution at and above the elevation of cladding rupture and the PARCH computer code calculates the hot rod steam cooling heat transfer coefficients. The steam cooling heat transfer coefficients are used by the STRIKIN-II computer code in the calculation of the hot rod cladding temperature at and above the elevation of cladding rupture after the core reflood rate decreases to less than 1 inch per second. Also, if cladding rupture is calculated to occur during blowdown, the blowdown hydraulics analysis performed by the CEFLASH-4A computer code is repeated to incorporate the impact of assembly blockage on the blowdown hydraulic response of the hot assembly. Note that in the 1999 EM, the HCROSS and PARCH computer codes have been integrated into the STRIKIN-II computer code (Section 2.7 of Reference 22-11). As described in Section 6.3.11 of CENPD-404-P-A, the CE SBLOCA evaluation model does not use a flow blockage model.

As part of the calculation of the cladding oxidation percentage (equivalent cladding reacted) in the CE evaluation models, the cladding rupture strain is used in the calculation of the amount of cladding oxidation at the elevation of cladding rupture (i.e., the cladding rupture node). As described in Section II.9 of the STRIKIN-II topical report (Reference 22-13) and Section 3.4.3 of the PARCH topical report (Reference 22-14), the cladding rupture strain is used to determine the inside and outside dimensions of the cladding rupture node. After rupture occurs, oxidation is calculated to occur on both the inside and outside surfaces of the cladding rupture node. Also, as noted in Section 6.3.10.1 of CENPD-404-P-A, the CE evaluation models do not [

]a,c as is done in the Westinghouse Appendix K evaluation models.

Tables 6.5.1.3-1 and 6.5.1.3-2 of CENPD-404-P-A provide results of sample LBLOCA hot rod heat-up calculations for ZIRLO™ cladding for conditions of maximum initial fuel stored energy and maximum initial rod internal pressures, respectively. It is one of these two conditions that generally produce the limiting result in a LBLOCA analysis. As described in Section 4.6.2 of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, the cladding models used for Standard ZIRLO™ are applicable to Optimized ZIRLO™. Therefore, these sample calculations are also representative of Optimized ZIRLO™. The tables identify the cladding rupture strains and maximum cladding oxidation percentages that were calculated for sample cases. For the maximum initial fuel rod stored energy case for ZIRLO™ cladding, cladding rupture occurred at a cladding temperature of 1569°F. The resultant cladding strain and assembly blockage percentages were 33.2% and 24.1%, respectively. The maximum cladding oxidation, which occurred at the cladding rupture node, was calculated to be 6.80%. The value includes an initial cladding oxidation percentage of approximately 0.05%, which corresponds to the value associated with the initial cladding oxidation thickness used in the CE evaluation models. The corresponding results for the maximum initial rod internal pressure case are as follows: rupture temperature, 1454°F; cladding strain, 53.0%; assembly blockage, 40.2%; maximum cladding oxidation, 5.11%.

References

22-2 NUREG-0630, "Cladding Swelling and Rupture Models for LOCA Analysis," April 1980.

22-10 CENPD-404-P-A, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," November 2001.

22-11 CENPD-132, Supplement 4-P-A, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," March 2001.

22-12 Enclosure 1-P-A to LD-81-095, "C-E ECCS Evaluation Model Flow Blockage Analysis," December 1981.

22-13 CENPD-135P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1974.

22-14 CENPD-138P, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," August 1974.

23. Section B.3 --- What specific heat function was used to reduce the diffusivity data to thermal conductivity? Was a different specific heat function used for heatup versus cooldown diffusivity data?

<u>Response 23</u>:
Discrete values were used, derived from the separate specific heat measurements. Changes in enthalpy attributable to phase changes were subtracted by smoothing visually across the phase transitions. Phase transition enthalpy is eliminated because the energy absorbed (or released) in phase transitions is unavailable for diffusion. Separate cooldown diffusivity data were not collected. Except for hysteresis in the phase transitions, there is no reason to expect that thermal diffusivity, specific heat, or thermal conductivity should vary as a function of whether the specimen is heating or cooling.
The values used are shown in the following table. It may be seen that the specific heat is not a strong function of temperature when enthalpy changes due to phase transitions are removed.

[ ] **a,b,c**

24. Section B.6 - The $\alpha \rightarrow \alpha + \beta$ transformation temperature data appears to show a dependence on tin content [ ] a,c such that there is a decrease in transformation temperature with a decrease in tin content. Why is this decrease not modeled?

Response 24:

The $\alpha \rightarrow \alpha + \beta$ transformation temperature is not explicitly modeled in the Non-LOCA or LOCA codes and methods, and only affects the analysis results through its influence on parameters that are explicitly modeled such as specific heat. For these parameters, the evaluations of Sections 4.5 and 4.6 have concluded that the Standard ZIRLO™ models can reasonably be applied to Optimized ZIRLO™, including any implicit effects due to the apparent reduction in the $\alpha \rightarrow \alpha + \beta$ transformation temperature.

What were the heating and cooling rates for the dilatometry and DSC measurements used to determine the $\alpha \rightarrow \alpha + \beta$ transformation temperature?

Response:

The heating and cooling rate for dilatometry was 3 °C/min.
The heating and cooling rate for specific heat (DSC) was 10 °C/min.

25. Sections B.7 & B.8 - The mechanical property data for microhardness, yield strength and ultimate yield strength of unirradiated Optimized ZIRLO™ is [ ] a,c lower than for standard ZIRLO™ at normal reactor operating conditions. It is also implied that irradiation hardening will decrease this difference such that there will not be a significant difference between these two materials. It is also implied that the difference in failure strains between Optimized and standard ZIRLO™ will also be reduced with irradiation. How can this claim be substantiated if there are no mechanical property tests on irradiated Optimized ZIRLO™? Are irradiation hardening effects accounted for in the properties for Optimized ZIRLO™? If so, how is this done without irradiated data?

Response 25:

Irradiation hardening is a known mechanism in Zirconium based alloys. An early review of this is found in Reference 1 where it is shown that the majority of the irradiation hardening effects develop early in the initial cycle of fuel operation. The hardening effect occurs with the displacement of lattice atoms under the fast neutron flux. Because it is basically a displacement of the matrix atoms and subsequent formation of microstructure changes such as dislocations , the irradiation hardening mechanism is relatively independent of minor alloy element level changes or final annealing conditions.

A specific example of the generic effects of irradiation hardening is found in the comparison of irradiated and un-irradiated ZIRLO and Zircaloy 4 materials. The following Table lists some nominal values of yield strength for these materials to show the relative changes in strength that occur in the materials with irradiation. The values may vary a small amount depending on the differing levels of fluence and hydrogen but the data still shows the similar response of Zircaloy 4 and ZIRLO to irradiation hardening. The

relatively large differences in the un-irradiated condition are significantly reduced or equalized with irradiation hardening.

The results in the comparison table show that even with different alloys and different heat treatments that the irradiation hardening has an overriding equalizing effect on the mechanical strength of zirconium based materials which have minor differences in alloy content. In the un-irradiated condition there are differences of 50 % to 200 % in yield strengths of the various materials but after irradiation the differences are less than 10 %.

a,b,c

In addition to the irradiation hardening effects the neutron fluence can also cause changes in the precipitate microstructure that can affect the material properties. For Optimized ZIRLO the only change in alloy chemistry is the tin level. Tin is in solid solution and is not a precipitate in the matrix. The precipitates are formed from the niobium and iron elements which are at the same levels in Optimized and standard ZIRLO. Therefore, there will be no difference in the precipitate structures of Optimized and standard ZIRLO for equivalent irradiation fluences. The equivalent mechanical property effects with irradiation and the equivalent precipitate microstructures with irradiation support the conclusion that standard ZIRLO irradiation data can be used to characterize the impacts of irradiation on Optimized ZIRLO and specific data on irradiated Optimized ZIRLO are not required.

As shown and discussed above, the irradiation hardening of Optimized ZIRLO will be same as observed for Zircaloy 4 and standard ZIRLO. For applications in beginning of life fuel rod design analysis that are sensitive to un-irradiated properties the un-irradiated mechanical properties will be used for Optimized ZIRLO fuel. For example un-irradiated properties will be used in evaluating early life limiting cases such as clad free standing.

Reference

25.1. " Effect of Irradiation on Strength , Ductility and Defect Sensitivity of Fully Recrystallized Zircaloy Tube"; Pettersson K. et al ; ASTM STP 681 Zirconium in the Nuclear Industry 1979, pp 155-173

26. Section B.7 - This section provides data that suggests there are [ ] a,c differences in total elongation and failure strains in the longitudinal and circumferential direction between unirradiated Optimized and standard ZIRLO™. What tests were used to determine the failure strains in the circumferential direction? If ring tensile tests were used it has been demonstrated that this test method is not valid for determining failure strains because the strains are a function of specimen size, gauge length and ring test apparatus and, therefore, not a property measurement of failure strain. It is also known that the ring tests generally result in higher failure strains than other methods. Please provide additional discussion in this area. How was circumferential Young's modulus obtained, from the ring tests?

<u>Response 26:</u>
Circumferential Young's modulus was obtained from a split-D type mechanical test, in which two opposite sides of the tubing are loaded in circumferential tension.

Do the Westinghouse and CE evaluation models assume isotropic mechanical properties and, if so, what is used for Young's modulus for the isotropic analyses?

<u>Westinghouse Response 26:</u>
In the Westinghouse evaluation models, mechanical properties are either assumed to be isotropic or treated as having a simple directional dependence. This yields considerable simplification relative to a rigorous anisotropic treatment such as that described in Section 4.6 of Reference 26-1, and is considered to be adequate for the intended purpose given the minimal importance of these parameters in evaluation model calculations. Young's modulus (Y) is specified as a function of temperature (T), with the following equation used in LOCBART and SBLOCTA (Y in psi and T in °F):

[ ]a,c

and the following equations used in <u>W</u>COBRA/TRAC (Y in Pa and T in K):

T < 1094 K: [ ]a,c

1094 K ≤ T ≤ 1239 K: [ ]a,c

T > 1239 K: [ ]a,c

A concern was raised regarding the adequacy of the LOCBART/SBLOCTA and WCOBRA/TRAC models for cladding elastic modulus at temperatures above 400°C. (Note that the LOCBART/SBLOCTA model is also used in the other Westinghouse Appendix K large and small break LOCA codes that consider cladding deformation, while the WCOBRA/TRAC model is not used in any of the other Westinghouse or CE LOCA or Non-LOCA codes.) The fuel rod swelling and burst processes in a licensing basis LOCA transient are driven primarily by plastic deformation and, to a lesser extent, thermal expansion. Elastic deformation of the cladding is a lower-order effect, and variations in the cladding elastic modulus would be expected to produce a negligible effect on the analysis results. As such, the models used in LOCBART/SBLOCTA and WCOBRA/TRAC are considered to be adequate for the intended purpose, and need not be modified for application at cladding temperatures above 400°C.

References

26-1.NUREG/CR-6150, Vol. 4, Rev. 2, INEL-96/0422, "SCDAP/RELAP5/MOD 3.3 Code Manual: MATPRO - A Library of Materials Properties for Light-Water-Reactor Accident Analysis", January 2001.

CE Response:

The CE evaluation models use models for mechanical properties (e.g. Young's modulus and Poisson's ratio) that are only applied in the radial direction. Sections 6.3.6 and 6.3.7 of CENPD-404-P-A (Reference 26-2) provide a general description of the use of Young's modulus and Poisson's ratio in the CE evaluation models. They are used in the calculation of the inside diameter of the cladding, which, in turn, is used in the calculation of the gap conductance and the gap pressure. Since the models for Young's modulus and Poisson's ratio are only applied in a single (i.e., radial) direction, characterization of the models as isotropic versus anisotropic is a moot point.

As described on page 33 of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A, the Young's modulus model described in Section 6.3.6 of CENPD-404-P-A is used for Standard ZIRLO™ and Optimized ZIRLO™. It is also noted on page 33 that the model and the data for Young's modulus in the circumferential direction for both Standard ZIRLO™ and Optimized ZIRLO™ are in reasonable agreement over the temperature range of the data. The model consists of an equation for temperatures less than or equal to [ ]a,c and linear interpolation from a table of values for temperatures above [ ]a,c The equation is as follows:

[ ]a,c

where Young's modulus is in units of kpsi and T is cladding temperature (°F). The table used for temperatures above [ ]a,c is as follows:

a,b,c

References

26-2 CENPD-404-P-A, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," November 2001.

27. Section 4.2 -- What are the consequences to the evaluations of Sections 4.2 if the microhardness, yield strength, ultimate tensile strength and Young's modulus are 25% lower for Optimized ZIRLO™ than for standard ZIRLO™? What are the consequences to the evaluations of Section 4.2 if the failure strains are lower by 50% than for standard ZIRLO™?

Response

Microhardness is a surface property which plays a minor role in the contact gap conductance component for fuel-to-clad heat transfer in the fuel performance for Westinghouse CE models as described in Section 4.3.5.4 of CENPD-404-P-A. Microhardness is not a parameter in the Westinghouse models. A 25% lower microhardness value would result in a small increase in contact heat conductance but an insignificant increase in total gap conductance.

The yield and ultimate tensile strengths increase with irradiation. The cladding stress is calculated and compared to the yield and ultimate tensile strengths. As described in Section 4.2.1, the Westinghouse irradiated yield and ultimate strengths are used. The irradiation of the Optimized ZIRLO™ significantly increases the strength. A 25% reduction in un-irradiated strength would have little impact relative to the irradiated strength. However, Westinghouse CE uses the un-irradiated strength as a limiting clad stress criterion as described in Section 4.2.1. Although the available stress margin is reduced, sufficient conservatism exists to satisfy the criterion even if strength is reduced by 25%.

A reduction in Young's modulus would have an insignificant or a beneficial impact on clad stress which depends on the source of the loads. The clad stress is in equilibrium with clad pressure differentials and is independent of Young's modulus. Clad stress based on a rigid pellet thermal expansion

is based on a known strain. Conversion of this strain into a clad stress is proportional to Young's modulus. Therefore, a 25% reduction would result in a similar reduction in clad stress. A reduction in yield strength and Young's modulus under such conditions would compensate and result in no impact.

Failure strain data applicable to Section 4.2 is shown in Figure B.7-8. A 50% variation is consistent with the variation shown in this figure However, Optimized ZIRLO™ failure strain is higher than standard ZIRLO™. Failure strain is not used in fuel performance calculations given in Section 4.2, therefore a 50% reduction in the Optimized ZIRLO™ failure strain shown in Figure B.7-8 would have no impact on results or conclusions of Section 4.2.

28. Section B.9 - Thermal creep data are presented from unirradiated Optimized and standard ZIRLO™ at one temperature and stress demonstrating that there is little difference for these conditions. However, irradiation induced creep is significantly different from thermal creep with approximately an order of magnitude higher creep rates. In addition, there are several papers that demonstrate decreasing tin contents in Zr-4 result in a significant increase in creep rate (Reference 28.1). While thermal creep tests (out-of-reactor) sometimes give a qualitative measure of differences in irradiation induced creep rates between two materials this qualitative measure is not always a good measure of differences in irradiation creep. Therefore, please provide irradiation creep data to substantiate in-reactor performance.

References:

28.1 F.Garzarolli, H. Stehle, E. Steinberg, "Behavior and Properties in Power Reactors: A short Review of Pertinent Aspects in LWR Fuel", Zirconium in the Nuclear Industry; Eleventh International Symposium, ASTM STP 1295, 1996, pp. 12-32.

Response 28:

The use of out-reactor thermal creep data to determine in-reactor creep is based on the correlation between out-reactor and in-reactor creep. This correlation was developed using Westinghouse fuel rod data irradiated in BR-3 and confirmed with the results reported by the EPRI/B&W Zr-4 Program.

BR-3 CWSR ZIRLO

Westinghouse fabricated CWSR ZIRLO™ fuel rod tubing with different final pilger area reductions. Two lots of tubing were fabricated. One was made with a final area reduction of 77% and a second with a reduced value of 60%. The two tube lots received the same processing except for the final pilger area reduction. The only difference between the two lots was the amount of cold-work. Texture measurements indicated that the texture of the two tube lots was similar.

The material was tested out-reactor at the test conditions of [

][a, b, c].

The results are shown in Figure 28.1. The tubing fabricated with the higher area reduction exhibits higher creep-out (higher tension strains). Figure 28.2 presents free-standing fuel rod creep-down data with rods fabricated with the two different final pilger area reductions. The rods fabricated with the higher area reduction exhibit higher creep-down (higher compression strains). Figure 28.3 presents both the in-reactor and the out-reactor data showing the negative of in-reactor creep-down on the y-axis versus the out-reactor creep-out on the x-axis. Note that an increase in out-reactor creep directly correlates with in-reactor creep.

Oconee-2 EPRI/B&W Zr-4
The EPRI/B&W Program investigated the behavior of Zr-4 both with out-reactor and in-reactor creep tests. (Reference 28.2) Three tube lots were tested out-reactor and in-reactor. One material heat of Sandvik Zr-4 was tested in the CWSR and RXA conditions (lots S-1 and S-2, respectively). One lot of NRG tubing was tested in the CWSR condition. In the case of lots S-1 and S-2, the processing was identical except for the final anneal. The final anneal resulted in both texture and dislocation density differences. In the case of lot V-1, the processing for this lot was considered to be different from lot S-1. Lot V-1 was considered to have a lower area reduction and lower Q-ratio processing because the final tubing exhibited less grain distortion and lower radial texture.

Figures 28.4 to 28.6 present the in-reactor data at a hoop stress of -12.5 ksi (-86 MPa) (Reference 28.3). The out-reactor results were reported as equation correlations (Reference 28.2). Figure 28.7 presents both the in-reactor and the out-reactor data showing the negative of in-reactor creep-down on the y-axis versus the out-reactor creep-out on the x-axis. Note that an increase in out-reactor creep directly correlates with in-reactor creep. This confirms the CWSR ZIRLO BR-3 results.

Application to Optimized ZIRLO™
The final CWSR anneal temperature used for Standard ZIRLO™ was modified for Optimized ZIRLO such that the [ ]$^{a, b, c}$ Sn Optimized ZIRLO™ exhibited the same out-reactor creep as Standard ZIRLO. This behavior is shown in Figure B.9-1 of reference 28.4. Based on the correlation between out-reactor and in-reactor creep, the irradiation creep of Optimized ZIRLO™ will be the same as for Standard ZIRLO.

References

28.2 David L. Baty, W.A. Pavinich, M.R. Dietrich, G.S. Clevinger and T.P. Papazoglou, "Deformation Characteristics of Cold-Worked and Recrystallized Zircaloy-4 Cladding," Zirconium in the Nuclear Industry: Sixth International Symposium, ASTM STP 824, 1984, pp. 306-339.

28.3 D.G. Franklin, G.E. Lucas and A.L. Bement, "Creep of Zirconium Alloys in Nuclear Reactors," ASTM STP 815, 1983, Appendix III.

28.4 Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO, February 2003.

Figure 28.1

a,b,c

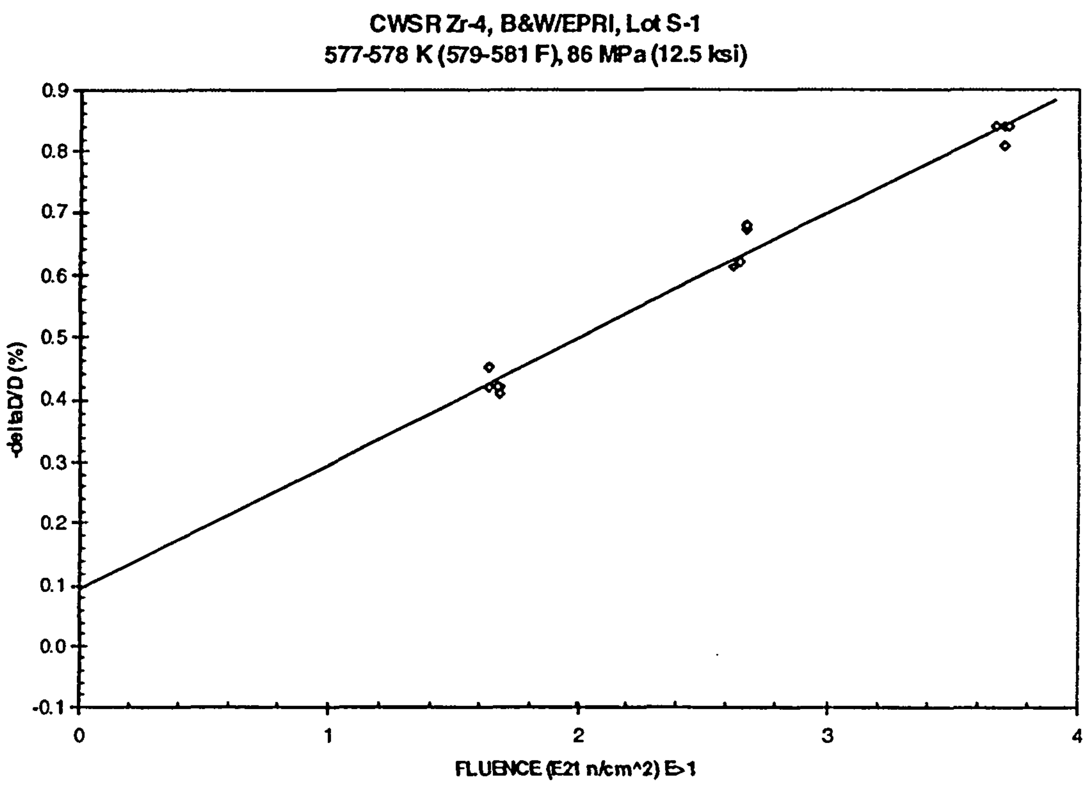
Figure 28.2

a,b,c

Figure 28.3

a,b,c

Figure 28.4



CWSR Zr-4, B&W/EPRI, Lot S-1
577-578 K (579-581 F), 86 MPa (12.5 ksi)
-deltaD/D (%)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0
1
2
3
4
FLUENCE (E21 n/cm^2) E>1

Figure 28.5

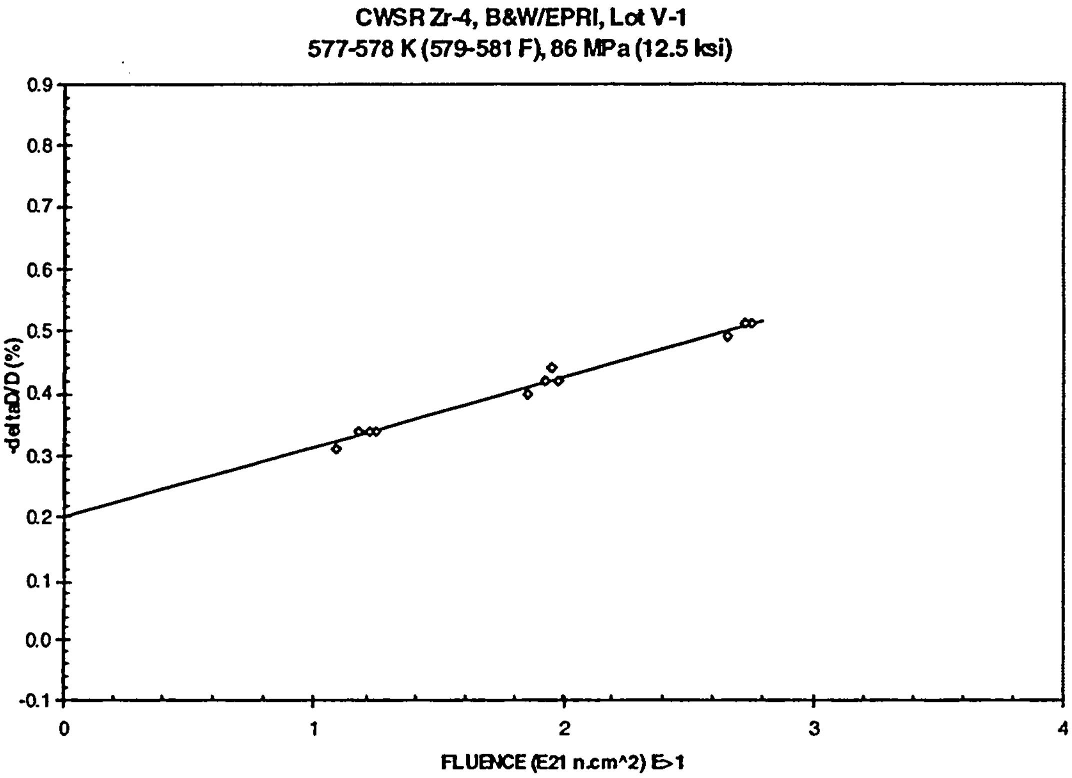

CWSR Zr-4, B&W/EPRI, Lot V-1
577-578 K (579-581 F), 86 MPa (12.5 ksi)
-deltaD/D (%)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0
1
2
3
4
FLUENCE (E21 n.cm^2) E>1

Figure 28.6

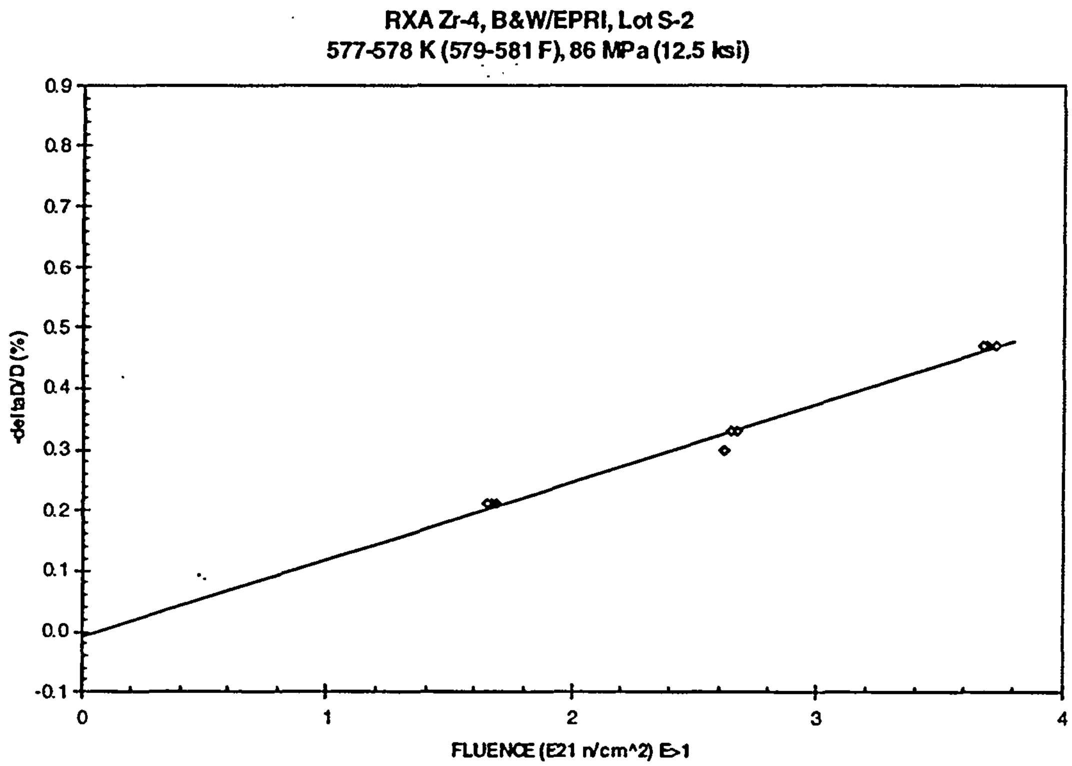
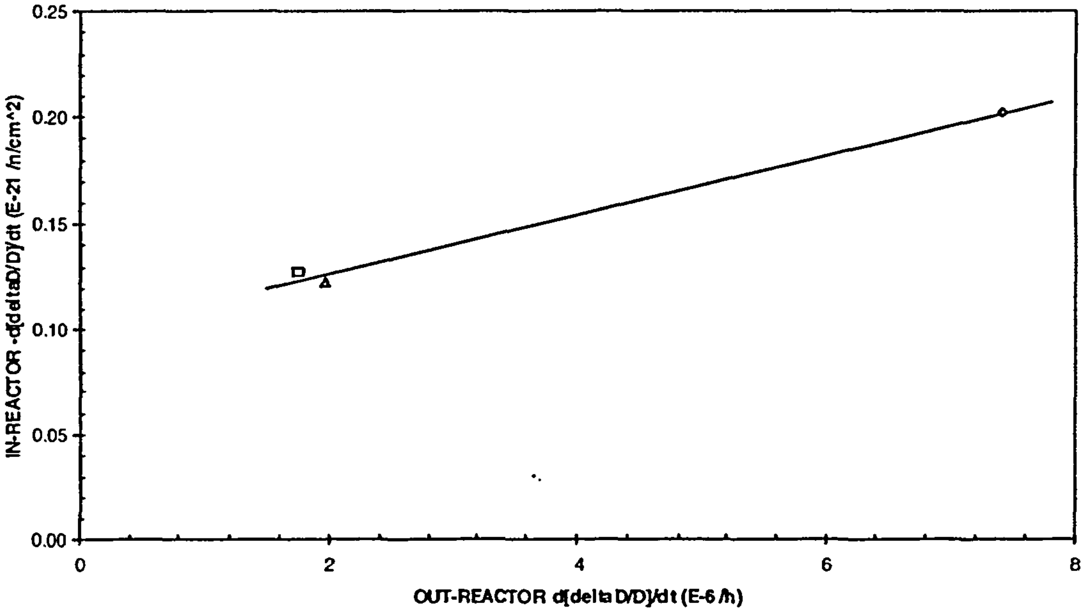

RXA Zr-4, B&W/EPRI, Lot S-2
577-578 K (579-581 F), 86 MPa (12.5 ksi)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-deltaD/D (%)
0
1
2
3
4
FLUENCE (E21 n/cm^2) E>1

Figure 28.7

Comparison of In-Reactor and Out-Reactor Creep Rates
B&W/EPRI Zr-4, 86 MPa (12.5 ksi)



Section E

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Direct tel: (412) 374-4643
Direct fax: (412) 374-4011
e-mail: greshaja@westinghouse.com

Our ref: LTR-NRC-04-63

Attn: J. S. Wermiel, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

October 29, 2004

Subject: "Response to NRC request for Additional Information #3 for Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™" (Proprietary/Non-Proprietary)

Dear Mr. Wermiel:

Enclosed is a copy of "Response to NRC request for Additional Information #3 for Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™" (Proprietary/Non-Proprietary).

Also enclosed is:

1. One (1) copy of the Application for Withholding, AW-04-1918 (Non-Proprietary) with Proprietary Information Notice.
2. One (1) copy of Affidavit (Non-Proprietary).

This submittal contains proprietary information of Westinghouse Electric Company LLC. In conformance with the requirements of 10 CFR Section 2.390, as amended, of the Commission's regulations, we are enclosing with this submittal an Application for Withholding from Public Disclosure and an affidavit. The affidavit sets forth the basis on which the information identified as proprietary may be withheld from public disclosure by the Commission.

Correspondence with respect to this affidavit or Application for Withholding should reference AW-04-1918 and should be addressed to J. A. Gresham, Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

J. A. Gresham, Manager
Regulatory Compliance and Plant Licensing

Attachments

cc: F. M. Akstulewicz/NRR
P. Clifford/NRR
W. A. Macon Jr./NRR
E. S. Peyton/NRR

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Direct tel: (412) 374-4643
Direct fax: (412) 374-4011
e-mail: greshaja@westinghouse.com

Our ref: AW-04-1918

October 29, 2004

APPLICATION FOR WITHHOLDING PROPRIETARY INFORMATION FROM PUBLIC DISCLOSURE

Subject: "Response to NRC request for Additional Information #3 for Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™" (Proprietary)

Reference: Letter from J. A. Gresham to J. S. Wermiel, LTR-NRC-04-63, dated October 29, 2004

The Application for Withholding is submitted by Westinghouse Electric Company LLC (Westinghouse), pursuant to the provisions of Paragraph (b) (1) of Section 2.390 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject report. In conformance with 10 CFR Section 2.390, Affidavit AW-04-1918 accompanies this Application for Withholding, setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.390 of the Commission's regulations.

Correspondence with respect to this Application for Withholding or the accompanying affidavit should reference AW-04-1918 and should be addressed to J. A. Gresham, Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

J. A. Gresham, Manager
Regulatory Compliance and Plant Licensing

Attachments

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared J. A. Gresham, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC (Westinghouse), and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

J. A. Gresham

J. A. Gresham, Manager
Regulatory Compliance and Plant Licensing

Sworn to and subscribed
before me this 29th day
of October, 2004

Sharon L. Fiori

Notary Public

Notarial Seal
Sharon L. Fiori, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires January 29, 2007
Member, Pennsylvania Association Of Notaries

(1) I am Manager, Regulatory Compliance and Plant Licensing, in Nuclear Services, Westinghouse Electric Company LLC (Westinghouse), and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rule making proceedings, and am authorized to apply for its withholding on behalf of Westinghouse.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.390 of the Commission's regulations and in conjunction with the Westinghouse "Application for Withholding" accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by Westinghouse in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.390 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of

Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information that is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.390, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in, "Response to NRC request for Additional Information #3 for Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™", (Proprietary), for submittal to the Commission, being transmitted by Westinghouse letter (LTR-NRC-04-63) and Application for Withholding Proprietary Information from Public Disclosure, to the Document Control Desk. The proprietary information as submitted by Westinghouse is that associated with Westinghouse's requests for NRC approval of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™.

This information is part of that which will enable Westinghouse to:

(a) Obtain NRC approval of Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLOTM.

(b) Assist customers to obtain license changes resulting from application of Optimized ZIRLOTM.

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of the information to its customers for the purpose of meeting NRC requirements for licensing documentation.

(b) Westinghouse can ause this information to further enhance their licensing position with their competitors.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar materials and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended.

Further the deponent sayeth not.

Proprietary Information notice

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.390 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.390(b)(1).

COPYRIGHT NOTICE

Response to NRC Request for Additional Information #3 for Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™

RAI #3 Irradiation experience with Optimized ZIRLO™ is discussed in Section 3.5
(a) In light of the limited database presented, justify the material properties up to 62,000 MWD/MTU.

Response:

Physical property data presented in this topical are summarized in Table 3.3-1. Various final anneal conditions were tested and presented in the topical for comparison as follows: Material Type A is nominal [ ]a,c Optimized ZIRLO [ ]a,c; Type B is nominal [ ]a,c Optimized ZIRLO [ ]a,c; Type C is standard ZIRLO [ ]a,c in the stress-relief anneal condition; and type D is Zircaloy-4 in the stress-relief anneal condition.

In the future when Westinghouse reports data to the NRC on the performance of Optimized ZIRLO LTAs we will include the final anneal condition of the material for information.

The starting unirradiated properties are affected by the final anneal and the properties are accounted for in the appropriate design models. For high temperature conditions, above 600° - 650° C, the microstructure is changed by recrystallization which erases the effects of the final anneal. Thus, the high temperature properties are not affected by the final anneal condition.

The characterization testing reported in the addendum demonstrates that standard ZIRLO material properties currently used in various models and methodologies are applicable to analyses of Optimized ZIRLO. The primary effect of a reduced tin level in Optimized ZIRLO is a minor reduction in the un-irradiated mechanical strength and improvement in the corrosion resistance. Since the precipitate structure remains the same for Optimized ZIRLO, the past performance of Standard ZIRLO precipitate structure at high burn-ups also is applicable.

Likewise, with irradiation strengthening occurring early on in the first cycle of irradiation, the mechanical strength properties of Optimized ZIRLO performance will be the same as the current ZIRLO. Justification for this assessment comes from an examination of the metallurgical conditions that primarily leads to the observed lower un-irradiated Optimized ZIRLO strength and numerous published and internal Westinghouse irradiation data sets that support the assertion that the metallurgical differences are essentially erased by irradiation.

There are [ ]a,c differences between the Optimized and Standard ZIRLO. [

]a,c

ZIRLO™ trademark property of Westinghouse Electric Company LLC.

[

]a,c

The effect of Sn will be discussed first, because it is directly supported by existing data. For these discussions, comparison of only the yield strength will be made for the sake of simplicity. The trends for ultimate strength follow those for yield strength, with the elongation and reduction of area having inverse relations with yield strength. The tensile data presented in the original Submittal were averaged, and the yield strengths of the Optimized and Standard ZIRLO at room temperature and 385°C are tabulated in Table 1.

Table 1 – A comparison of typical Optimized and Standard tin ZIRLO yield strengths.

( ) a,b,c

The un-irradiated properties of the two variants of ZIRLO given in the original submittal shows a decrease of approximately [ ]a,c at room temperature and [ ]a,c at 385°C for the Optimized alloy compared to the Standard alloy. However, these differences include the effects of both the tin and the microstructure. When both alloys are in equivalent microstructures, such as SRA and RXA, the strengths are much closer together. Such data were created in the development programs for the cladding and thimble tubes. When both alloys were given the identical stress-relief-anneal-treatment, the RT yield stress of Optimized ZIRLO was [ ]a,c, slightly less than the [ ]a,c for the Standard ZIRLO tubing used in that development program, but within the variability of Standard ZIRLO and the same as the average yield stress used of the lot of Standard ZIRLO tubing given in the Submittal. Furthermore, when both standard and Optimized ZIRLO are fully re-crystallized the yield strengths of the two alloys are essentially identical. The data on the re-crystallized materials were determined in the Thimble Tube Development Program and are given in the above table. These data strongly indicate that the effect of lowering the tin from [$]^{a,c}$ has only a very small effect, if any, on the yield stress of the Optimized ZIRLO alloy. The effect is estimated to be less than [$]^{a,c}$ at room temperature, and [$]^{a,c}$ at 316°C. The small impact of tin on the yield strength of irradiated material is also apparent in hot-cell measurements of conventional and low tin Zircaloy-4[1], in which the low tin version of the alloy showed yield strength bounded by the scatter of the conventional tin Zircaloy-4 at a fluence around $7x10^{21}$n/cm^2. The same reference also showed irradiation strengthening to saturate at a low fluence of less than $2x10^{21}$n/cm^2. A plot of the data is shown in Figure 1.

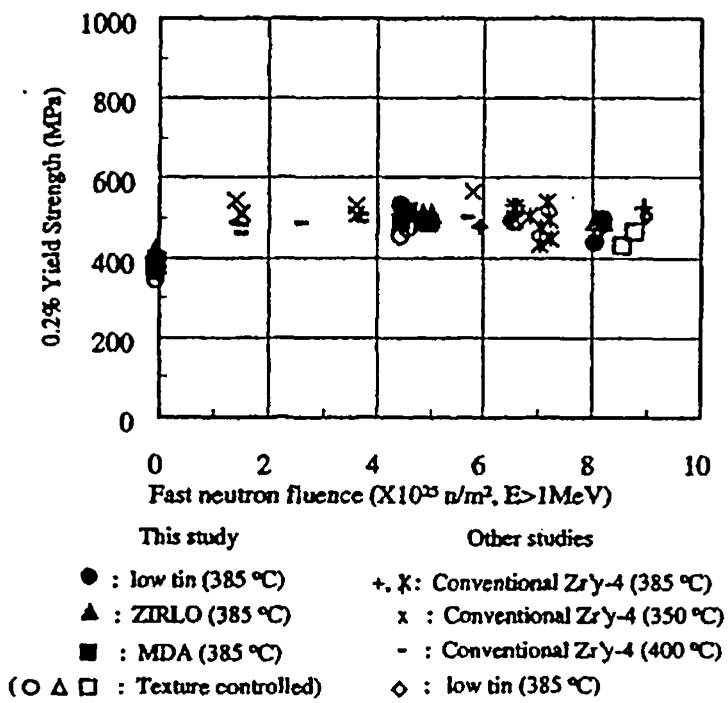


Figure 1 – Change of 0.2% yield strength by fluence[1].

Therefore, it is the effect of the [

$]^{a,c}$. The basis for this is provided in Westinghouse hot-cell data and two publications[2&3] on the properties of the Zircaloy alloys. Information from hot-cell testing of irradiated ZIRLO thimble tubes and cladding confirms the effects of irradiation strengthening in reducing/negating the strength differences initially present in the starting un-irradiated material. Due to processing differences the standard ZIRLO thimble tubes have a lower un-irradiated strength, by approximately [$]^{a,c}$, compared to un-irradiated fuel cladding. As shown in the data table included in the response to RAI#25, measured strength of cladding and thimble tubes show a significant difference in un-irradiated strength but upon irradiation the mechanical strength of both the thimble tube and the cladding are increased to similar levels. The difference in un-irradiated mechanical strengths between Standard and Optimized ZIRLO is much less than the corresponding difference between cladding and thimbles.

Bement[2] reported on the effect of irradiation on the mechanical behavior of Zircaloy-2 plate samples before irradiation and after irradiation at 280°C. Tensile testing was performed at room temperature and 300°C. Materials tested were as-recrystallized, 20% cold worded, and 40% cold worked. Review of the data show much greater irradiation hardening in the annealed material than in the cold worked materials, to the extent that the longitudinal yield stresses of all samples were nearly equivalent at fluences of 1.5 and $2.5x10^{21}n/cm^2$. Furthermore, the irradiated yield strengths at 300°C after $2.5x10^{21}$n/cm2 were somewhat less than those at $1.5x10^{21}n/cm^2$, suggesting that saturation damage had already been achieved by $1.5x10^{21}n/cm^2$. Some of the Bement data are shown in Figure 2 and re-plotted as a function of fluence in Figure 3. A quote from the abstract of the Bement paper is "At high neutron doses at 280°C, yield strength becomes nearly independent of cold work indicating that radiation-induced hardening overrides strain-induced hardening."

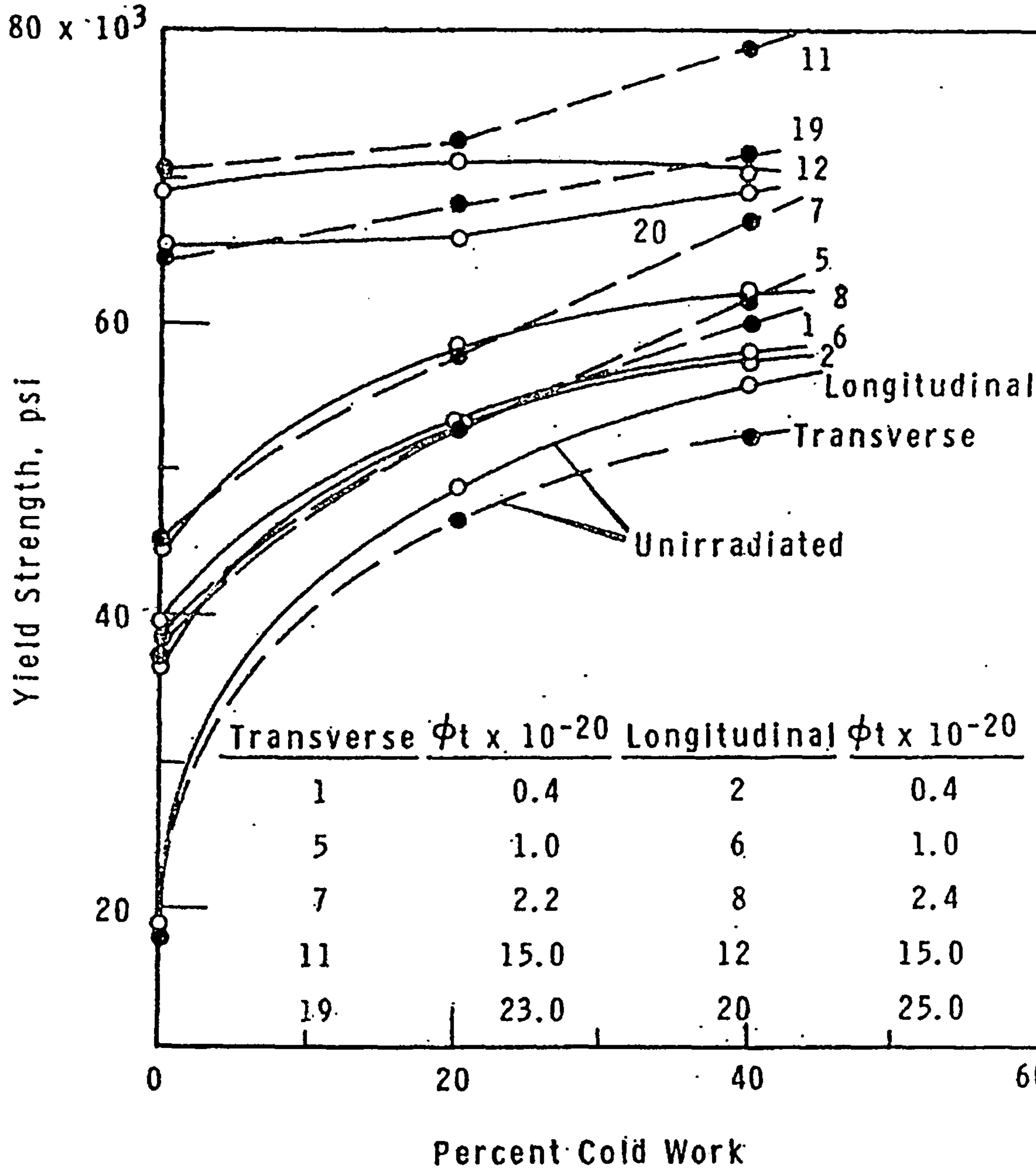


Figure 2 - The effects of cold Work on the 300°C Yield Strength of Zircaloy-2 both before and after irradiation at 280°C.[1]

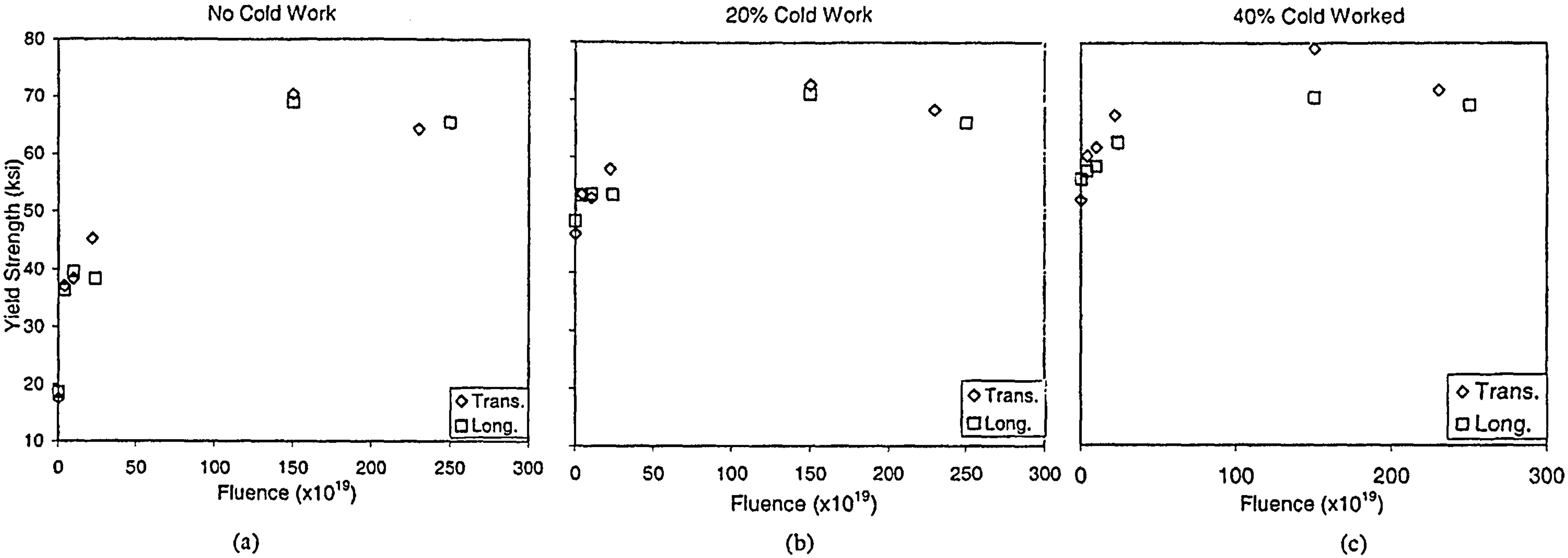


Figure 3 - Zircaloy-2 strip yield strength as a function of fluence (a) fully annealed, (b) 20% cold worked, and (c) 40% cold worked. Data re-plotted from Reference 2.

The Bement data and other data on the effect of irradiation on mechanical properties of Zircaloy-2 and -4 were reviewed by Salvaggio and documented along with new data in a Bettis Atomic Power Laboratory report edited by Woods[3]. It was concluded "...that the strength increment due to irradiation is less for cold-worked plate material than for annealed material and that at high exposure levels (2.5 x 10^{21} nvt), little difference in yield strength exists among 0, 20, or 40% cold-worked material." Additional data from SRA tubing indicates that irradiation saturation of mechanical behavior may occur at as low 5×10^{20}n/cm^2, as the properties at this fluence were essentially the same as those at 5×10^{21}n/cm^2. This saturation of mechanical properties of SRA tubing at 5×10^{20}n/cm^2 is similar to the near saturation of the yield strength of annealed Zircaloy tubing at that fluence reported by Pettersson, et. Al.[4], shown in Figure 4. It is noted that Pettersson did not fit his data to a saturation model, but rather expressed them in an exponential form.

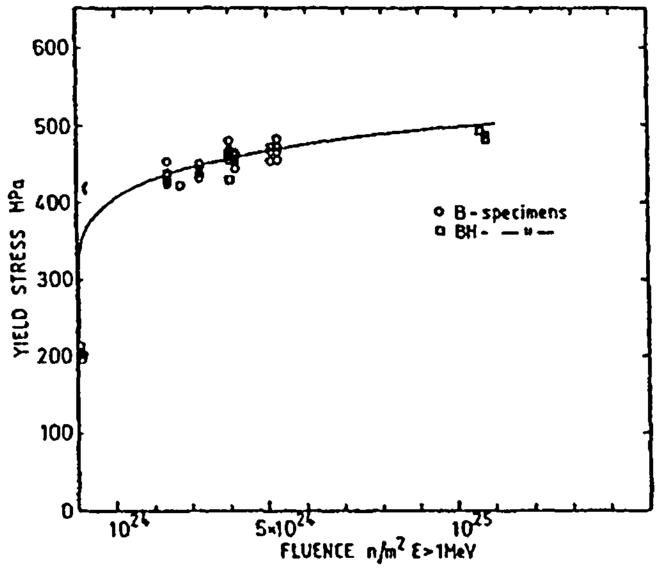


Figure 4 – Yield strength as a function of fluence for re-crystallized Zircaloy tubing[4].

Another evidence of more rapid hardening in annealed versus cold-worked or SRA material is provided by Hardy[5], although his fluences were too low for saturation. Hardy's annealed material, which was irradiated to 2.0×10^{20}n/cm^2, displays about the same irradiation-induced increment of yield strength (Hardy's σ_r) as does his cold-worked (CW) and CW+SRA materials, which were irradiated to 2.7×10^{20} and 2.9×10^{20}n/cm^2. Thus, these CW and CW+SRA materials had fluences of 35 to 45% higher than did the annealed material. It is to be noted that the data for the annealed material is erroneously plotted in reference 5. The yield stress for these samples was incorrectly plotted at the higher fluence of 2.9×10^{20}n/cm^2, instead of at the correct value of 2.0×10^{20}n/cm^2. It is noted that the correct fluence was used in the NRC basis for response to the Westinghouse response to RAI #25.

While the bulk of the irradiated mechanical properties discussed thus far are based on Zircaloy-2 and Zircaloy-4, similar irradiated data on the Russian E635 in the literature - an alloy similar composition to ZIRLO, also showed full irradiation hardening at a fluence of around 2.7×10^{21}n/cm^2 with majority of the hardening occurring less than 5×10^{20}n/cm^2.[6] A plot of their data is shown in Figure 5. A conversion factor of 0.27 was used to convert the neutron energy of >=0.5 MeV to >=1 MeV.

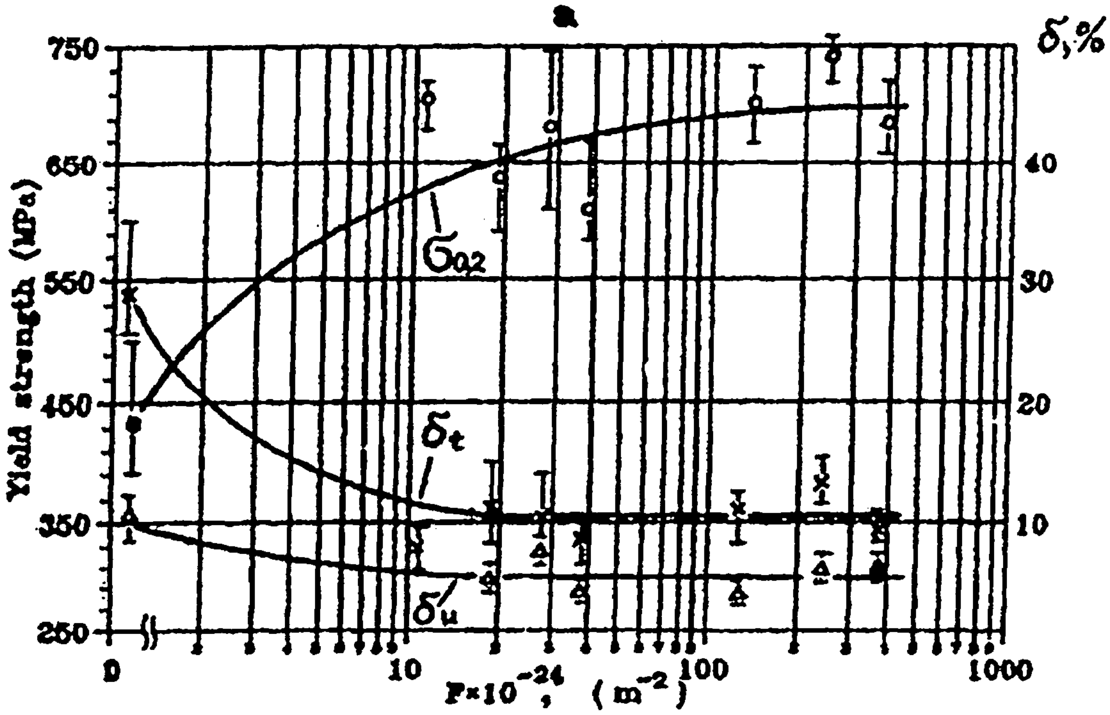


Figure 5 – E635 yield strength at 20°C plotted as a function of fluence (>=0.5 MeV).

Summary

[

]a,c.

In view of the new data presented and discussed, Westinghouse includes the following items in the design of Optimized ZIRLO cladding:

[

]a,c

[

]^{a,c}

(3) As additional irradiation mechanical data is generated, the reductions in design strength levels for Optimized ZIRLO as addressed in (2) above will be evaluated and the design strength levels may be revised as justified by the generated data.

(4) For applications in beginning of life fuel rod design analyses that are sensitive to un-irradiated properties the un-irradiated mechanical properties will be used for Optimized ZIRLO fuel. For example un-irradiated properties will be used in evaluating early life limiting cases such as clad free standing.

References

[1] H. Uchida, K. Goto, R. Sabate, S. Abeta, T. Baba, E. De Matias, J.M. Alonso, "Segmented Fuel Irradiation Program Investigation on Advance Materials", Proceedings of the TopFuel '99 Conference, September 1999, Avignon Popes'Place France.

[2] A.L. Bement, Jr., "Radiation Damage in Hexagonal Close-Packed Metals and Alloys," in *Symposium on Radiation Effects*, Asheville, NC, Sept. 1965, AIME Vol 37, American Institute of Mining Metallurgical, and Petroleum Engineers, Gordon and Breach, p671, 1967.

[3] G. J. Salvaggio, "Effect of Irradiation on Mechanical Properties," in *Properties of Zircaloy-4 Tubing*, C. R. Woods, Ed., WAPD-TM-585, p 172, December 1966.

[4] K. Pettersson, G. Vesterlund, and T. Andersson, "Effect of Irradiation on the Strength, Ductility, and Defect Sensitivity of Fully Recrystallized Zircaloy Tube," *Zirconium in the Nuclear Industry (Fourth Conference), ASTM STP 681*, ASTM, p155, 1979.

[5] D. Hardy, "The Effect of Neutron Irradiation on the Mechanical Properties of Zirconium Alloy Fuel Cladding in Uniaxial and Biaxial Tests," *Irradiation Effects on Structural Alloys for Nuclear Reactor Applications, ASTM STP 484*, ASTM, p215, 1970.

[6] Antonina V. Nikulina, Vladimir A. Markelov, Mikhail M. Peregud, Yury K. Bibilashvili, Vladimir A. Kotrekhov, Anatoly F. Lositsky, Nikolay V. Kuzmenko, Yuriy P. Shevnin, Valentin K. Shamardin, Gennady P. Koylyansky, Andrey E. Novoselov, "Zirconium Alloy E635 as a Material for Fuel Rod Cladding and Other Components of VVER and RBMK Cores", Proceedings of the 11th International Symposium on Zirconium in the Nuclear Industry, ASTM STP 1295, p785.