7.0 Non-LOCA Accidents

7.1 Introduction

This section discusses the effect of using CENP fuel designs clad with ZIRLO™ on non-LOCA safety analyses (typically FSAR Chapter 15). The methods and computer codes currently used in the analysis of the non-LOCA licensing basis events remain valid for fuel rods clad with ZIRLO™ . It has been shown that licensing basis criteria continue to be met and the margin to safety is not reduced.

7.2 Summary of Cladding-Related Models in the Non-LOCA Transient Evaluation Models

An investigation has determined the ZIRLO™ material properties important to non-LOCA transient analyses, with the objective of providing experimental data for comparison with Zircaloy-4 material properties. Experimental data and subsequent evaluations demonstrate that the properties of Zircaloy-4 and ZIRLO™ are essentially the same with the exception of the differences in the phase change temperature and its related effect on the thermophysical properties.

The phase change temperature shift affects the relationship of specific heat as a function of temperature. Zircaloy-4 and ZIRLO™ specific heats are essentially identical up to a temperature of approximately 1380°F, (750°C) at which temperature ZIRLO™ begins to undergo an alpha-beta phase change and its specific heat (which is defined to include the phase change heat of transformation) rises to a plateau value. Then, as the temperature continues to increase, the specific heat is reduced to near its original value. Zircaloy-4 exhibits a behavior similar to that of ZIRLO™, except that the phase change occurs at a higher temperature range (1504 - 1717°F). The difference in the specific heat versus temperature relationship between ZIRLO™ and Zircaloy-4 potentially affects the clad temperature response, as the clad temperature reaches the ZIRLO™ phase change temperature.

7.2.1 STRIKIN-II Code

The STRIKIN-II computer code (Reference 7-1) is used for the hot channel heatup calculations in licensing safety analyses. STRIKIN-II is used to calculate the transient heat flux, transient DNBR, coolant enthalpy and hot rod fuel temperatures in the hot assembly, using nuclear power and local coolant conditions (i.e., pressure, flow, temperature) as input. STRIKIN-II is used to predict transient heat fluxes, average and peak fuel pellet and clad temperatures for non-LOCA transients. These analyses are used to demonstrate compliance with DNBR, fuel melt, and fuel pellet enthalpy licensing basis criteria.

STRIKIN-II code accounts for the effect of thermal and mechanical properties of both the fuel pellet and clad. In order to model the ZIRLO™ cladding properties, changes were made to the clad specific heat versus temperature property data block used by STRIKIN-II. These changes are implemented in STRIKIN-II as user inputs. The cladding thermal conductivity model was not changed for the reasons discussed in Section 6.3.3. As discussed earlier, all other ZIRLO™ properties used in Non-LOCA analysis are essentially identical to Zircaloy-4, and thus, no other changes are necessary to effectively model the influence of ZIRLO™ in non-LOCA licensing basis analyses.

7.2.2 CENTS Code

The CENTS computer code (Reference 7-2) is an interactive, faster than real time computer code for the simulation of the NSSS and related systems. It is capable of calculating the behavior of a PWR for both normal and abnormal conditions, including accidents.

A review of CENTS indicated that the cladding material properties employed are cladding thermal conductivity and specific heat. The correlation used by CENTS to model Zircaloy-4 thermal conductivity was compared to the ZIRLO™ thermal conductivity correlation. The result of this comparison is that there is a negligible difference in thermal conductivity over the expected range of fuel operating temperature. The CENTS code's modeling of Zircaloy-4 specific heat is essentially identical to that of ZIRLO™ up to a temperature of approximately 1380°F. As this temperature, 1380°F, is beyond the expected operating temperature range of the cladding (for Non-LOCA transients modeled by CENTS), the difference between the

Zircaloy-4 specific heat used by CENTS and the ZIRLO™ specific heat correlation is negligible. Consequently, no change to accommodate a ZIRLO™ specific heat material property is needed.

As discussed earlier, all other ZIRLO™ properties used in Non-LOCA analysis are essentially identical to Zircaloy-4, and thus, no changes are necessary to model the effect of ZIRLO™ in non-LOCA licensing basis analyses.

7.2.3 CESEC Code

Like CENTS, the CESEC computer code (References 7-3) is used for the simulation of the NSSS and related systems. CESEC is capable of calculating the behavior of a PWR for both normal and abnormal conditions, including accidents.

A review of CESEC indicated that the cladding material properties employed are thermal conductivity and specific heat. The correlation CESEC uses for Zircaloy-4 thermal conductivity was compared to the ZIRLO™ thermal conductivity correlation. This comparison showed that there is negligible difference in thermal conductivity over the expected range of fuel operating temperature. CESEC's modeling of Zircaloy-4 cladding specific heat is essentially identical to that of ZIRLO™ up to a temperature of approximately 1380°F. As this temperature, 1380°F, is beyond the expected range of cladding operating temperature (for transients modeled by CESEC), the difference between the Zircaloy-4 specific heat used by CESEC and the ZIRLO™ specific heat correlation is negligible. Consequently, no change to accommodate a ZIRLO™ specific heat material property is needed.

As discussed earlier, all other ZIRLO™ properties used in Non-LOCA analysis are essentially identical to Zircaloy-4, and thus, no changes are necessary to model the effects of ZIRLO™ in non-LOCA licensing basis analyses.

7.2.4 HERMITE Code

HERMITE (Reference 7-4) is a space-time kinetics computer code. HERMITE was developed for the analysis of design and off-design transients in PWRs by means of a numerical solution to the multi-dimensional, few-group, time-dependent neutron diffusion equation including feedback effects of fuel temperature, coolant temperature, coolant density and control rod motion. The heat conduction equation in the fuel pellet, gap and clad is solved by a finite difference method. Continuity and energy conservation equations are solved for the coolant enthalpy and density.

A review of HERMITE indicated that the cladding material properties employed are thermal conductivity and specific heat. The correlation HERMITE uses to model Zircaloy-4 thermal conductivity was compared to that of ZIRLO™. The result of this comparison is that there is a negligible difference in thermal conductivity over the expected range of fuel operating temperature. The HERMITE code's modeling of the Zircaloy-4 specific heat is essentially identical to that of ZIRLO™ up to a temperature of approximately 1380°F. As this temperature, 1380°F, is beyond the expected range of cladding operating (as modeled for non-LOCA transients), the difference between the Zircaloy-4 specific heat used in HERMITE and the ZIRLO™ specific heat correlation is negligible. Consequently, no change to accommodate a ZIRLO™ specific heat material property is needed.

As discussed earlier, all other ZIRLO™ properties used in Non-LOCA analysis are essentially identical to Zircaloy-4, and thus, no changes are necessary to model the effects of ZIRLO™ in the non-LOCA licensing basis analyses.

7.3 ZIRLO™ Impact on Accident Parameters

This section discusses the effect of ZIRLO™ on non-LOCA licensing basis analyses. As previously discussed, the thermophysical properties of ZIRLO™ and Zircaloy-4 are essentially identical except for the effect of the phase change temperature shift on the specific heat versus temperature relationship. The ZIRLO™ phase change begins at a temperature of approximately 1380°F. Below this temperature, the specific heat of Zircaloy-4 and ZIRLO™ are essentially identical. Therefore, for those non-LOCA accident analyses in which the clad temperature does not reach or exceed a value of 1380°F, the use of ZIRLO™ cladding will have no effect on analysis results relative to results obtained for Zircaloy-4 clad fuel rods.

A review was conducted of non-LOCA licensing basis analyses typically performed for CENP designed nuclear power plants (see Table 7.3-1). This review included fuel assembly array sizes of 14x14 and 16x16. Based on this review, it was concluded that only two non-LOCA licensing basis analyses resulted in clad temperatures which were predicted to reach 1380°F or greater. These analyses are 1) Control Element Assembly (CEA) ejection, and 2) Locked Rotor/Shaft Break analysis. For other non-LOCA analyses, clad temperatures remain below approximately 1000°F. Therefore, the use of ZIRLO™ cladding has no effect on the results of these licensing basis analyses.

Each of the two potentially affected non-LOCA licensing basis analyses were evaluated to determine what effect the use of ZIRLO™ may have on analysis results and the margin to acceptance criteria.

7.3.1 CEA Ejection

The CEA ejection accident is defined as the mechanical failure of a control element drive mechanism (CEDM) pressure housing or CEDM nozzle, resulting in the ejection of a CEA and drive shaft. The consequences of such a mechanical failure are a rapid positive reactivity insertion and system depressurization together with an adverse core power distribution, possibly leading to localized fuel rod damage.

Licensing Criteria

The CEA ejection event is analyzed at hot full power (HFP) and hot zero power (HZP) conditions. The analyses demonstrate that any consequential damage to the core or the reactor coolant system does not prevent long-term core cooling and that off-site doses remain within the guidelines of 10CFR100. More specific and restrictive criteria are applied to ensure that fuel dispersal into the coolant, gross lattice distortion, or severe shock waves do not occur. These criteria are:

1. The average fuel pellet energy at the hot spot remains below 200 cal/gm (alternately, DNB is used as a criteria for fuel failure at some CENP plants. Section 4.4 discusses the application of ZIRLO and DNB and Section 4.7 concludes that the effect is insignificant.
2. Fuel centerline temperature is limited to less than the incipient melting temperature of the fuel.

3. Peak RCS pressure is less than that which would cause clad stresses to exceed the faulted condition stress limits.

The FATES3B computer code (discussed in Section 4.0) is used to analyze the fuel performance properties. The fuel performance properties are used as input to the STRIKIN-II code, which in turn calculates fuel and clad temperatures versus time, as well as thefuel stored energy. A detailed discussion of the analysis methodology may be found in Reference 7-5.

Evaluation

Sensitivity analyses of the HFP and HZP CEA ejection events were performed, accounting for the specific heat versus temperature relationship of ZIRLO™. These analyses demonstrate that the use of ZIRLO™ cladding results in a [ ] in both the fraction of fuel melted at the hot spot as well as the peak fuel stored energy when compared to the results for Zircaloy-4.

7.3.2 Locked Rotor/Shaft Break

The Locked Rotor/Shaft Break accident is an instantaneous seizure of the reactor coolant pump (RCP) rotor or a break of the RCP shaft. Flow through the affected reactor coolant loop is rapidly reduced, leading to the initiation of a reactor trip on low loop flow. Following reactor trip, heat stored in the fuel rods continues to be transferred to the coolant causing the coolant to expand, resulting in an insurge into the pressurizer and an increase in the RCS pressure. The rapid flow reduction also results in a reduction in the minimum DNBR and potentially results in some fuel rods experiencing DNB.

Licensing Criteria

The Locked Rotor/Shaft Break event is analyzed using the following computer codes. The CENTS or CESEC computer code is used to calculate nuclear power, RCS flow and pressure during the transient. The TORC computer code (Reference 7-6) is then used to calculate the DNB vs. Integrated Radial Peaking Factor (Fr) for the limiting conditions. The ABBFFEC utility code is then used to calculate the number of fuel pins experiencing DNB and the number that subsequently fail based on both statistical convolution and deterministic methods. Two separate analyses are performed. The first analysis is performed to determine the limiting coolant conditions (i.e., pressure, flow, temperature), and the associated DNB vs. Fr pairs. A second analysis is performed to predict the number of fuel rods experiencing DNB. The second analysis is not affected by the use of ZIRLO™ because the ABBFFEC code results are not dependent on the type of cladding.

Evaluation

Sensitivity analyses have been performed to determine the effect of ZIRLO™ on the limiting coolant conditions (i.e., pressure, flow, and temperature), and the associated DNB vs. Fr pairs. Conservative analyses have determined that use of ZIRLO™ results in a [ ] when compared to Zircaloy-4.

7.4 Conclusions

Based on a review of typical non-LOCA licensing basis analyses performed for CENP designed nuclear power plants, it has been determined that only two non-LOCA events resulted in clad temperatures which were predicted to reach a clad temperature of 1380°F or greater. These analyses are 1) CEA ejection, and 2) Locked Rotor/Shaft Break accident. For other non-LOCA analyses, the clad temperatures remain below approximately 1000°F. Therefore, the introduction of ZIRLO™ cladding has no effect on these analyses.

Each of the two potentially affected non-LOCA licensing basis analyses were evaluated to determine what effect the use of ZIRLO™ may have on analysis results. This evaluation showed that use of ZIRLO™ clad material in CENP designed fuel produces acceptable results.

7.5 References

7-1 CENPD-135-P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program", August 1974

7-2 CENPD-282-P-A, "Technical Manual for the CENTS Code", February 1991.

7-3 LD-82-001 (dated 1/6/82) "CESEC Digital Simulation of a Combustion Engineering Nuclear Steam Supply System", Enclosure 1-P to letter from A. E. Scherer to D. G. Eisenhut, December 1981.

7-4 CENPD-188-A, "A Multi-Dimensional Space-Time Kinetics Code for PWR Transients", July 1976.

7-5 CENPD-190-A, "C-E METHOD FOR CONTROL ELEMENT ASSEMBLY EJECTION ANALYSIS", January 1976.

7-6 CENPD-161-P-A, "TORC Code, A Computer Code for Determining the Thermal Margin of a Reactor Core", April 1986.

Table 7.3-1

Non-LOCA events Typically analyzed for CENP Designed Nuclear Power Plants

Event name / description	Type of event	Primary code used in modeling the event	Secondary code used in modeling the event
Decrease Feedwater Temperature	Cool down	CESEC/CENTS	none
increasing Feedwater Flow	Cool down	CESEC/CENTS	none
Increase Steam Flow	Cool down	CESEC/CENTS	none
Inadvertent Atmospheric Dump Valve opening	Cool down	CESEC/CENTS	none
Post –Trip Main Steam Line Break	Cool down	CESEC/CENTS	HRISE
Pre-Trip Steam Line Break	Cool down	CESEC/CENTS	TORC/CETOP
Emergency Feedwater Extraction Line Break	Cool down	CESEC/CENTS	none
Chemical Volume Control System mis-operation	Cool down	CESEC/CENTS	none
Letdown Line Break	Cool down	CESEC/CENTS	none
Steam generator Tube Rupture	Cool down	CESEC/CENTS	none
Loss of Load / Turbine Trip	Heat up	CESEC/CENTS	none
Loss of Condenser Vacuum	Heat up	CESEC/CENTS	none
Loss of Flow / Loss of AC Power	Heat up	HERMITE	none
Loss of Feedwater	Heat up	CESEC/CENTS	none
Feedwater Line Break	Heat up	CESEC/CENTS	none
CEA Withdrawal (Bank, Group, subgroup, & Single)	Heat up	CESEC/CENTS	TORC/CETOP
Seized Rotor / Sheared Shaft	Heat up	CESEC/CENTS	TORC/CETOP
Asymmetric steam Generator Transient	Heat up	CESEC/CENTS	TORC/CETOP
CEA Ejection	Heat up	STRIKIN-II	none
CEA Drop		Hand calculation	none
CEA mis-operation		CESEC/CENTS	TORC/CETOP
Boron Dilution		Hand calculation	none

8.0 Nuclear Design

8.1 Impact of ZIRLO™ Implementation on Nuclear Design

The implementation of ZIRLO™ has negligible effect on the nuclear performance (i.e., physics) of the reactor core. The primary change, with regard to nuclear performance relative to OPTIN™ is the increased concentration of niobium. This increased niobium concentration results in a small increase in neutron absorption (approximately 20 pcm for a fully loaded core) relative to OPTIN. An increase of this magnitude in neutron absorption has no significant effect on nuclear performance relative to cores containing OPTIN clad fuel. Thus, nuclear engineering parameters used in licensing design and safety analyses, including neutron flux and power distributions, reactivity coefficients, and control rod worths are not significantly effected.

The density of ZIRLO™ is essentially the same as the density of OPTIN. Thus the fraction of fission energy deposited directly in the fuel rod (Energy Redistribution Factor) for ZIRLO™ will be essentially the same as those calculated for OPTIN clad fuels. Thus, the OPTIN Energy Redistribution Factors are directly applicable for ZIRLO™ analyses.

Overall, the implementation of ZIRLO™ in CENP fuel designs has an insignificant effect on nuclear engineering aspects of core design. Furthermore, implementation of ZIRLO™ does not require modification of any nuclear engineering methodologies or computer codes. The negligible differences between ZIRLO™ and OPTIN make its implementation essentially transparent for nuclear engineering purposes.

9.0 Summary and Conclusions on ZIRLO ™ Cladding Implementation

The purpose of this report is to provide the justification and description of the implementation of ZIRLO™ cladding in CENP designed fuel. ZIRLO™ cladding properties and irradiation behavior characteristics have been measured by Westinghouse, compared with Zircaloy-4, and submitted to, reviewed by, and accepted by the NRC. These NRC approved ZIRLO™ material properties were incorporated into NRC approved Westinghouse design and licensing safety analysis methodologies. CENP has pursued a similar course. That is, using the Westinghouse developed and NRC accepted ZIRLO™ material properties, CENP has incorporated those ZIRLO™ material properties in its design and licensing safety analysis methodologies. CENP has reached the following conclusions regarding its implementation of ZIRLO™:

1. Implementation of ZIRLO™ is very beneficial to the reduction of waterside corrosion and elimination of the potential for spallation which has been observed in OPTIN™ cladding when operating under high duty cycles currently being imposed on CENP fuel designs.

2. Considerable successful operating experience has been accumulated in Westinghouse designed PWRs with ZIRLO™ cladding and Zircaloy-4 structural components. This experience includes duty cycles that are similar to and bound the duty cycles experienced in CENP designed PWRs. Thus, Westinghouse's experience is directly applicable to CENP designed PWRs. CENP also has its own LTA experience with ZIRLO™-like alloys and Zircaloy-4 structural components that have operated in both CENP's 14x14 and 16x16 fuel designs for several operating cycles. Consequently, Westinghouse's operational experience with ZIRLO™ in conjunction with CENP's ZIRLO™-like alloys LTA experience supports CENP implementation of ZIRLO™ in full batch reloads without the need for a standalone CENP ZIRLO™ specific LTA program.

3. Incorporation of the analytical capability to model ZIRLO™ cladding in the NRC approved CENP design and safety analyses is straightforward. ZIRLO™ properties and correlations are consistent with CENP's application, existing

models, methodology, design criteria and regulatory acceptance criteria (e.g., the NRC has already incorporated ZIRLO™ in the applicable sections of Title 10 of the Code of Federal Regulations).

4. The impact of ZIRLO™ on fuel thermal performance, mechanical performance, LOCA analyses, and non-LOCA accident analyses has been thoroughly evaluated. Results of design and safety analyses with ZIRLO™ clad fuel rods are, as expected, well behaved and are generally benign and/or insignificant.

5. Therefore, CENP concludes that implementation of ZIRLO™ cladding will provide an improvement to its fuel designs when incorporated into reloads for CENP designed nuclear power plants.

CENPD-404-NP-A

U.S. Nuclear Regulatory Commission

Safety Evaluation Report

Required Materials

3. Letter, LD-2001-0028, "Assessment of Ft. Calhoun Fuel Rod Fretting History and Root Cause As It Relates to Implementation of ZIRLO™ Cladding Material in Fuel Designed By CE Nuclear Power"

WESTINGHOUSE ELECTRIC COMPANY LLC

2000 Day Hill Road
Windsor, CT 06095
USA

3 May, 2001
LD-2001-0028

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

SUBJECT: **ASSESSMENT OF FT. CALHOUN FUEL ROD FRETTING HISTORY AND ROOT CAUSE AS IT RELATES TO IMPLEMENTATION OF ZIRLO™ CLADDING MATERIAL IN FUEL DESIGNED BY CE NUCLEAR POWER**
[CONTAINS PROPRIETARY INFORMATION]

Reference(s):
1) Letter, P. W. Richardson (CENP) to USNRC Document Control Desk, "Submittal of CENPD-404-P, Rev. 0 Regarding Implementation of ZIRLO™ Cladding Material in CENP Fuel Assembly Designs", LD-2001-0005, January 22, 2001
2) Letter, J. S. Cushing (NRC) to P.W. Richardson (WEC), Acceptance of CENPD-404-P, Rev. 0, 'Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs' for Review (TAC No. MB1035)", February 27, 2001
3) Memorandum, J. S. Cushing (NRC) to S. A. Richards (NRC), "Summary of Meeting Held on February 8, 2001, With CE Nuclear Power to Discuss CENPD-404-P, Rev. 0 – 'Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs'", April 4, 2001

On January 22, 2001 (Reference 1), Westinghouse Electric Company LLC (WEC) submitted CENPD-404-P, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs", to the Nuclear Regulatory Commission (NRC) for review and acceptance for referencing in licensing analyses. Subsequently, WEC and NRC staff members met on February 8, 2001 (Reference 2), to further discuss this initiative. During the course of the meeting, Ralph Caruso (NRC) requested information regarding fretting of fuel (some of which was ZIRLO™ clad) at the Omaha Public Power District Ft. Calhoun nuclear power plant. The information requested is provided in Enclosure 1-P to this letter.

WEC has determined that the information contained in Enclosure 1-P is proprietary in nature. Consequently, it is requested that Enclosure 1-P be withheld from public disclosure in accordance with the provisions of 10 CFR 2.790 and that these copies be appropriately safeguarded. The reasons for the classification of this information as proprietary are delineated in the affidavit provided in Enclosure 2. Enclosure 3 provides a non-proprietary version of Enclosure 1-P for your information and use.

If you have any questions regarding this matter, please do not hesitate to call Chuck Molnar of my staff at (860) 285-5205.

Very truly yours,
Westinghouse Electric Company LLC

Philip W. Richardson
Licensing Project Manager
Windsor Nuclear Licensing

Enclosure(s): As stated

xc: R. Caruso (NRC)
M. S. Chatterton (NRC)
J. S. Cushing (NRC)

Enclosure 3 to LD-2001-0028

WESTINGHOUSE ELECTRIC COMPANY LLC

FT. CALHOUN NUCLEAR POWER PLANT
FUEL ROD FRETTING HISTORY AND ROOT CAUSE
NON-PROPRIETARY VERSION

MAY 2001

Westinghouse Electric Company LLC
Proprietary Information

FT. CALHOUN NUCLEAR POWER PLANT
FUEL ROD FRETTING HISTORY AND ROOT CAUSE

BACKGROUND:

Westinghouse Electric Company LLC (WEC) first supplied fuel to Ft. Calhoun in 1991, and the spacer grid design was an adaptation of the [ ] design that had been used in ten (10) plants and eleven (11) regions by that period. The [ ] Subsequent regions delivered to Ft. Calhoun included changes in the cladding material, as well as modifications to the grid design, as shown in Table 1. The history of leaking fuel rods resulting from fretting and the mix of fuel assemblies in reactor Cycles 14 through 18 at Ft. Calhoun is shown in Table 2.

ROOT CAUSE:

The leaking fuel rods at Ft. Calhoun in [ ] were due to fretting through of the clad at the [ ] An extensive study was performed to determine the root cause, with the determination being that the [ ] compared with other designs. Based on recent data obtained for the [ ], it is now known that [ ] are due to:

[ ]

It is important to note that these fretting induced failures occurred [ ] A [revised grid spring design] was developed that showed some improvement in [ ] The [ ]

However, as shown in Table 2, there was [ ] In hindsight, based on more recent tests, [ ]

Also as shown in Table 2, the [ ] As shown in Table 1, [ ] As shown in Table 2, the number of [ ]

In summary, the Ft. Calhoun fuel failures are due to [ ] As pointed out in the ZIRLO™ Topical Report (CENPD-404-P, Rev. 0), cladding material as it affects mechanical properties does play a role in grid to rod fretting. For example, a different rod growth characteristic will affect how the cladding is exposed to the wearing surface of the grid support. However, [ ]

TABLE 1

FT. CALHOUN - REGION FEATURE COMPARISON

TABLE 2

LEAKING FUEL ROD HISTORY FOR WESTINGHOUSE FUEL AT FT. CALHOUN

CENPD-404-NP-A

U.S. NUCLEAR REGULATORY COMMISSION

SAFETY EVALUATION REPORT

REQUIRED MATERIALS

4. Letter, LD-2001-0045, "Response to Requests for Additional Information on Topical Report CENPD–404-P, Rev. 0"

Westinghouse Electric Company, LLC

2000 Day Hill Road
Windsor, CT 06095
USA

LD-2001-0045, Rev. 0
August 10, 2001

Mr. John S. Cushing, Project Manager
U. S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Subject: Response to Requests for Additional Information on Topical Report CENPD-404-P, Rev. 0
(Contains Proprietary Information)

Dear Mr. Cushing:

Enclosure 1-P provides responses to the NRC's Requests for Additional Information (RAIs) on CENPD-404-P, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs." Each RAI is stated in its entirety followed by Westinghouse's response. Enclosure 1-P thus documents the formal set of RAIs to which Westinghouse is responding.

A non-proprietary version of the RAI responses in Enclosure 1-P is provided in Enclosure 2. Three copies of each enclosure are provided.

Westinghouse requests that the proprietary information in Enclosure 1-P be withheld from public disclosure in accordance with the provisions of 10 CFR 2.790 and that it be appropriately safeguarded. The reasons for classifying this information proprietary are delineated in the enclosed affidavit (Enclosure 3).

If you have any questions, please contact George Hess at (860) 731-6285 or Chuck Molnar at (860) 731-6286.

Sincerely yours,

G. Hess for

P. W. Richardson, Project Manager
Windsor Nuclear Licensing

cc: M. Chatterton (NRC, w/attachment)
R. Caruso (NRC, w/o attachment))

Enclosure 2 to LD-2001-0045, Rev. 0

Responses (Non-Proprietary) to RAIs on CENPD-404-P, Rev. 0

QUESTIONS ON CENPD-404-P ZIRLO™ CLADDING IN CE FUEL ASSEMBLY DESIGNS♦

Question #1:

Figure 3.4-2 on page 18 of CENPD-404-P, shows modified fuel duty index vs. measured oxide thickness. Please provide the details of the measurements shown. Will the CE plants limit fuel duty index until actual corrosion data is obtained for ZIRLO™ in CE plants?

Response:

Table 1-1 provides a summary of the fuel rods for the ZIRLO™ corrosion database shown in CENPD-404-P Figure 3.4-2. For each fuel rod, a modified Fuel Duty Index (mFDI) was calculated at the location of the measured maximum oxide thickness in each grid span. Therefore, for a given fuel rod several points may be plotted in Figure 3.4-2 based on the number of grid spans measured for oxide thickness. The mFDI model is described in CENPD-404-P Section 3.4 and in the response to Question 11.

Westinghouse's current calculations show that the maximum mFDI experienced to date for CE designed 14x14 and 16x16 fuel is well within the ZIRLO™ database defined in Figure 3.4-2. Typical maximum mFDI values given in CENPD-404-P Section 3.5 are [ ] for 14x14 fuel and [ ] for 16x16 fuel. These maximum mFDI values are not operating limits but were calculated to demonstrate where CE designed fuel falls within the ZIRLO™ database for Westinghouse designed fuel. The engineering implementation of ZIRLO™ cladding for CE designed fuel will demonstrate that the mFDI and best estimate oxide thickness stays within the bounds of the ZIRLO™ database defined in Figure 3.4-2.

Oxide thickness will be measured on selected rods with the highest mFDIs to assure that actual corrosion performance is following the expected behavior shown in Figure 3.4-2. These measurements will be made on typical high duty fuel assemblies after second and third cycles of operation. For the initial batch implementation of ZIRLO™ the mFDI will be restricted until further data is obtained to verify corrosion performance. The interim mFDI restriction will be set so there is adequate corrosion margin with the use of ZIRLO™ compared to the use of OPTIN cladding and there is sufficient margin in the mFDI restriction to accommodate for uncertainties in core design (e.g. cycle length, plant operating conditions, etc). The mFDI restriction will be established by each licensee and addressed in the site specific submittal to implement the ZIRLO™ topical. The interim fuel duty restriction will be dropped or modified after measurements are obtained. The mFDI model may also be modified to assure accurate behavior for future fuel duty predictions after data is obtained.

♦ RAI phraseology based on memorandum from J. Cushing to S. A. Richards, dated June 5, 2001, "Summary of Meeting Held on May 21, 2001, With Westinghouse Regarding ZIRLO™ Topical Report".

Table 1-1 Summary of ZIRLO™ Cladding Database

Question #2:

Page 3-6, first sentence – "Full batch implementation of ZIRLO™ may be implemented for the following CENP 14X14 and 16X16 fuel designs". Is this application for use of ZIRLO™ cladding in CE fuel assembly designs for the designs listed or for all designs, present and future?

Response:

CENPD-404-P lists the present fuel designs being manufactured for all Westinghouse CE PWR 14x14 and 16x16 fuel designs. Consequently, ZIRLO™ will be available and possibly implemented in the listed designs. However, Westinghouse intends to make ZIRLO™ cladding material an option for all future fuel designs as well. As such, the intended application of CENPD-404-P is for the use of ZIRLO™ cladding on all fuel types, present and future.

Question #3:

Section 3.6.1 clearly states that approval is sought to 60MWd/kgU, thus this review will be limited to burnups to 60MWd/kgU, and the SER will limit burnups to 60MWd/kgU.

Response:

Westinghouse concurs with the observation that CENPD-404-P, Section 3.6.1 requests approval for the application of ZIRLO™ to a burnup limit of 60 MWd/kgU. This is necessary and consistent with the current burnup limit of 60 MWd/kgU for 14x14 and 16x16 Zircaloy-4 (i.e., OPTIN™) fuel assembly designs.

However, as described in CENPD-404-P, Section 3.6.2, the review of the justification for a peak burnup limit of 62 MWd/kgU for OPTIN™ fuel assembly designs is in progress via CENPD-388-P. Continuation of the CENPD-388-P review requires additional information from Westinghouse that is being prepared and will be submitted to the NRC. Beyond the OPTIN™ cladding itself, CENPD-388-P also provides the justification for operation to 62 MWd/kgU and beyond for all other fuel assembly components (i.e., fuel, spacer grids, guide tubes, end fittings, etc.).

ZIRLO™ cladding material is already accepted for up to 62 MWd/kgU for Westinghouse fuel designs. Based on NRC approval of the Westinghouse Fuel Criteria Evaluation Process (WCAP-12488-A, Appendix R), the fuel assembly may operate to a peak rod burnup of 62 MWd/kgU. In addition, the NRC approval (i.e., SER) of the Westinghouse PAD 4.0 fuel performance code (WCAP-15063-P-A, Revision 1, with Errata) explicitly approves application to a peak rod burnup of 62 MWd/kgU. It is also to be noted that ZIRLO™ has been shown to be robust enough to eventually achieve even higher peak rod burnups. Westinghouse intends to ultimately request a peak pin burnup limit of up to 62 MWd/kgU for all ZIRLO™ clad CE fuel assembly designs.

Consequently, it is requested that the burnup limit for CE ZIRLO™ clad fuel designs be restricted to a peak rod burnup of 60 MWd/kgU only until the burnup limit of 62 MWd/kgU is approved for the CE OPTIN™ fuel design via the CENPD-388-P topical report approval. The linkage to the OPTIN™ topical report is necessary because that topical report also justifies the extension of the non-clad components and design and licensing methodology to 62 MWd/kgU. Westinghouse believes this linkage to CENPD-388-P is advantageous in that the information in CENPD-388-P does not need to be repeated in CENPD-404-P and the NRC does not need to repeat the review of this information a second time for application of ZIRLO™ to 62 MWd/kgU. Furthermore, this approach also facilitates a more expeditious review of the ZIRLO™ topical report by not requiring review of material not necessary for the immediate implementation of ZIRLO™ cladding; since burnups approaching 62 MWd/kgU would not be achieved until the third cycle of operation.

In summary, Westinghouse concurs that the SER for CENPD-404-P should restrict the peak pin burnup to 60 MWd/kgU until such time as approval of CENPD-388-P is obtained. Furthermore, the Westinghouse response to the NRC request for additional information on CENPD-388-P will include an appropriate linkage to CENPD-404-P to include application of ZIRLO™ to 62 MWd/kgU.

Westinghouse offers for NRC consideration potential wording of a SER constraint that could serve as a vehicle for automatic extension of CE ZIRLO™ clad fuel to 62 MWd/kgU:

"Based on information provided by Westinghouse in CENPD-404-P, the NRC finds the use of CE fuel designs employing ZIRLO™ cladding material in conjunction with Zircaloy-4 structural components acceptable for burnups up to but not exceeding 60 MWd/kgU. Following approval of topical report CENPD-388-P, which is expected to provide justification for a burnup extension to 62 MWd/kgU for non-clad, Zircaloy-4 fuel assembly structural components (i.e., spacer grids, guide tubes, end fittings, etc.), fuel assemblies employing ZIRLO™ cladding material and Zircaloy-4 structural components may be acceptable for use to burnups up to but not exceeding 62 MWd/kgU."

Question #4:

Page 4-4, last sentence before Section 4.3.1; specifically what dimensional characteristics will differ from those of OPTN?

Response:

ZIRLO™ cladding is procured by Westinghouse from the Westinghouse Blairsville cladding manufacturing facility. OPTIN™ has been procured by Westinghouse from the Zircaloy-4 supplier Sandvik Special Metals. Although the fuel rod design specifications do not differ, the manufacturing processes at these facilities are not identical. Thus, the statistical distribution of specific dimensional characteristics, such as tube diameter, thickness, ovality, surface roughness, etc., may differ between ZIRLO™ and OPTIN™ in response to an identical range of fuel rod design specifications (i.e., nominal dimension plus or minus tolerances). Design and safety analyses which utilize such distributions, for example, Engineering Factor on surface heat flux, or mechanical response leading to cladding collapse, will account for the characteristics of ZIRLO™ or OPTIN™, as appropriate to the particular cladding in use. Little, if any, impact on design or safety analyses is expected because the dimensional manufacturing characteristics of ZIRLO™ are expected to be quite similar to OPTIN™. In conclusion, the reload analysis process will account for dimensional manufacturing differences for ZIRLO™ cladding should they be observed.

Question #5:

Page 4-14. Equations 4-23 and 4-24 do not appear to be "nearly identical" as stated. Please provide justification for the statement.

Response:

Equation 4-23 provides the thermal conductivity for ZIRLO™ as a [ ] Equation 4-24 provides the established thermal conductivity for OPTIN™. The functional form of these equations are identical (i.e., both are [ ] Although the constants in each of these equations differ a small amount, the value of thermal conductivity at temperatures that are of interest (i.e., 500°F to 700°F) in a fuel performance analysis are nearly identical. That is, the thermal conductivity at room temperature is [ ] However, the increase with temperature is [ ] The values for thermal conductivity are [ ] This can be seen in Figure 6-1. The impact of the noted difference in equations is insignificant. In other words, the differences in temperatures in the fuel rod are insignificant.

The difference in thermal conductivity at 700°F is about [ ] Considering an extreme example of 10 kw/ft from a fuel rod 0.382 inches in diameter with a 25 mil wall (16x16 design), the difference in the fuel rod temperature operating at an average clad temperature of 700°F is [ ] This difference for a core average fuel rod would, of course, be much less, on the order of [ ] (because both LHR and thermal conductivity differences would be smaller). Thus, Westinghouse concluded that the application of the OPTIN™ thermal conductivity equation is acceptable for ZIRLO™ fuel performance analyses.

Figure 6-1
Thermal Conductivity

Question #6:

Page 4-15 through 4-17, please provide additional justification for using Equation 4-27, 4-30, and 4-32.

Response:

Response 6a:Equations 4-26 and 4-27

Equations 4-26 and 4-27 have been used for OPTIN™ (Zircaloy-4) axial and radial thermal expansion in FATES3B for many years. Similarly, the Westinghouse axial and radial thermal expansion for Zircaloy-4 is given by Equations 4-25 and 4-26. Westinghouse axial and radial thermal expansion for ZIRLO™ was concluded to be the same as Westinghouse Zircaloy-4. Since the anisotropy effect of the Westinghouse Blairsville cladding (Zircaloy-4 and ZIRLO™) and the Sandvik Special Metals cladding (OPTIN™) [

] A comparison of the radial thermal expansion Equations 4-27 and 4-25 is provided in Figure 6-1. It can be seen that the total thermal expansion is a small strain, [ ] at 700°F, the difference in total expansion is also small, and the slope of the thermal expansion versus temperature (i.e., the conventional coefficient of thermal expansion, is [
]

The difference in radial thermal expansion at an operating temperature of 700°F for a fuel rod diameter of 0.382 inches is [ ] This represents only [ ] of an as-fabricated radial gap of 3.5 mils and is concluded to be insignificant. Typically, the temperature rise across the fuel-clad gap for maximum stored energy at LOCA LHR conditions is on the order of [ ] Therefore, the impact on temperature would be no more than [ ], and is concluded to be insignificant. As gap closure occurs due to cladding creep and pellet swelling, etc., the impact is completely eliminated.

Response 6b: Equations 4-28, 4-29 and 4-30

Westinghouse concluded that the modulus of elasticity of ZIRLO™ and Zircaloy-4 were identical. The modulus of elasticity for ZIRLO™, Equations 4-28 and 4-29, and for OPTIN™, Equation 4-30, are compared in Figure 6-2. The differences such as observed from this comparison are not considered to be significant. Furthermore, anisotropic differences [
] in the CE fuel performance analyses. This can be justified by quantifying the impact on stress and strain.

For example, the maximum pressure loads on the cladding over the entire life span of the fuel rod (from minimum internal pressure to maximum internal pressure) results in a strain of [ ] (based on an approximation using stress over elastic modulus). Thus, the differences in computation of stress and strain are negligible. For the example of a fuel rod 0.382 inches in diameter and a 0.025 inch wall thickness, this represents a radial deformation of [ ] The impact on gap size and fuel rod thermal performance is [ ] using the example in Response 6a. In fact, it can be seen that the impact is in the opposite direction at beginning of life, mitigating some of the impact of thermal expansion.

Response 6c:Equation 4-32

Use of the Poisson's Ratio defined by Equation 4-32 for Zircaloy-4 is consistent with the approach used for the modulus of elasticity [

] in the approved models and methodology. Furthermore, Westinghouse has concluded that there is no difference in Zircaloy-4 Poisson's Ratio and ZIRLO™ Poisson's Ratio. Consequently, it is consistent with previously approved models and methodology to use a generic Poisson's Ratio for ZIRLO™ as represented by Equation 4-32.

Figure 6-1
Thermal Expansion

Figure 6-2
Modulus of Elasticity

Question #7:

Page 4-18, last sentence, first paragraph, please provide a table comparing thermal and mechanical properties to justify the statement.

Response:

A complete list of thermal and mechanical properties used in the FATES3B fuel performance code is provided below. The models for each of these properties are discussed in CENPD-404-P to provide justification for application to ZIRLO™. Additional justification is provided in Responses 5 and 6. The list indicates some of the models are specific to ZIRLO™ and some are applicable to both ZIRLO™ and Zircaloy-4. This table and further information is provided in Appendix A which provides a 'Roadmap' describing the relationships between the various methodologies and the representation of ZIRLO™ clad material in those methodologies.

Thermal / Mechanical Property	Model for Analyses of ZIRLO™ Cladding

ZIRLO™ specific properties identified in the above table are based on Westinghouse measurements for ZIRLO™ cladding and are incorporated into the CE design and safety analyses. In addition, Westinghouse measurements were made for thermal conductivity and axial thermal expansion for ZIRLO™ cladding. ZIRLO™ axial thermal expansion was found to be essentially identical to Westinghouse Zircaloy-4 thermal expansion (Reference 7-1, Figure A-1). Consequently, it was concluded that radial thermal expansion of ZIRLO™ and Westinghouse Zircaloy-4 would be the same. These properties are discussed in References 7-1 and 7-2. The balance of the properties were not expected to differ from Zircaloy-4 and measurements were not made for Reference 7-1 or 7-2. These properties are assumed to be the same for ZIRLO™ and Westinghouse Zircaloy-4. As discussed in CENPD-404-P, CE agrees with Westinghouse that these properties would not be expected to differ significantly, and further, has provided a demonstration that variations within the range of values obtained from the various equations used by Westinghouse and CE do not have any significant impact on design and safety analyses results. Thus, more precise measurements of these properties were not, and are not, warranted.

Thermal and mechanical properties of Zircaloy-4 were measured and reported by Westinghouse Electric Corporation in Reference 7-3 under contract to the U.S. Atomic

Energy Commission. Zircaloy-4 properties were obtained from Reference 7-3 for use in the FATES fuel performance code and remain the basis of the properties in the current version of the fuel performance code, FATES3B. FATES3B incorporated ZIRLO™ capability as described in CENPD-404-P. Properties to be used for ZIRLO™ thermal conductivity, thermal expansion, modulus of elasticity, and Poisson's Ratio were concluded to be essentially the same as CE Zircaloy-4 (OPTIN™) properties in use in FATES3B. Additional discussion of thermal conductivity, thermal expansion, modulus of elasticity, and Poisson's Ratio is provided below.

Thermal Conductivity

Thermal conductivity used by CE for Zircaloy-4 differs from the current Westinghouse thermal conductivity for Zircaloy-4. The CE Zircaloy-4 thermal conductivity is nearly identical to ZIRLO™ and CE has proposed to use the same equation for both materials. Thermal conductivity for FATES Zircaloy-4 (OPTIN™) was originally obtained from Reference 7-3 and provided again in CENPD-404-P. Equation 4-24 of CENPD-404-P can be found on Reference 7-3, page 8. Supporting data for this correlation is provided in Reference 7-3, page 9, Figure 3. The PAD 4.0 correlations and data for ZIRLO™ and Zircaloy-4, which differ, are provided in Reference 7-2 Section 3.0. The FATES Zircaloy-4 correlation is compared with the ZIRLO™ conductivity equation in Section 4.3.3 of CENPD-404-P, and discussed and shown in Figure 5-1 of the Response to Question 5. This discussion demonstrates that the differences in fuel rod temperatures resulting from use of either of these equations for ZIRLO™ are insignificant [ ]. It can also be seen that the scatter in the Zircaloy-4 data of Figure 3, page 9 of Reference 7-3 is equal to or greater than the differences in correlations shown in Figure 5-1. Since the impact of using the same thermal conductivity equation for Zircaloy-4 (OPTIN™) and ZIRLO™ is insignificant (and, in fact, conservative at operating temperatures of 600 to 750°F (i.e., low conductivity will result in conservatively higher fuel temperatures) and the scatter in measured thermal conductivity of Reference 7-3 exceeds the differences between correlations shown in Figure 5-1, it is acceptable to apply the FATES3B Zircaloy-4 thermal conductivity equation to ZIRLO™ in FATES3B.

Thermal Expansion

Thermal expansion of CE Zircaloy-4 was provided in CENPD-404-P. Axial thermal expansion data for Zircaloy-4 (OPTIN™) used to support the equation in FATES3B was obtained from Reference 7-3. Axial thermal expansion data for ZIRLO™ and Westinghouse Zircaloy-4 were found to be essentially identical as shown by the data in Reference 7-2. Furthermore, axial thermal expansions for Westinghouse Zircaloy-4, ZIRLO™, and CE Zircaloy-4 all agree. No data exist for radial thermal expansion of ZIRLO™. However, it is correctly concluded in Reference 7-2 that since the measured axial thermal expansion of ZIRLO™ is identical to Zircaloy-4, the radial should also be identical.

Radial thermal expansion measurements for the FATES3B Zircaloy-4 equation is provided in Reference 4 for heatup and cooldown similar to the Zircaloy-4 axial heatup and cooldown provided by Reference 7-3. The radial thermal expansion equation for CE Zircaloy-4 is based on Reference 7-4. Although the historical equations for FATES3B and PAD 4.0 radial thermal expansion differ in the algebraic form used and differ somewhat as shown in the Figure 6-1 of the Response to Question 6, differences in results have been shown to be insignificant [ ]. Since the axial thermal expansion of ZIRLO™ was demonstrated to be the same as Zircaloy-4, it is reasonable to conclude that the FATES3B radial thermal expansion equation should also be applied to ZIRLO™.

Modulus of Elasticity

The modulus of elasticity data and correlation for CE Zircaloy-4 (OPTIN™) was obtained from Reference 7-3, Figure 8 and is assumed to be isotropic. No measurements of the modulus of elasticity for ZIRLO were submitted in References 7-1 and 7-2 as Westinghouse previously concluded that the modulus of elasticity for ZIRLO was essentially the same as Zircaloy-4. Since the impact of differences between Westinghouse Zircaloy-4 and the CE Zircaloy-4 correlations was shown to be insignificant in the Response to Question 6 [ ], it is reasonable to conclude that the CE Zircaloy-4 modulus of elasticity can also be used for ZIRLO™.

Poisson's Ratio

The CE Zircaloy-4 data and correlation for Poisson's Ratio was obtained from Reference 7-3, page 17 and is assumed to be isotropic. No measurements of the Poisson's Ratio for ZIRLO were submitted in References 7-1 and 7-2 as Westinghouse previously concluded that the Poisson's Ratio for ZIRLO was essentially the same as Zircaloy-4. Thus, it is reasonable to conclude that the CE Zircaloy-4 Poisson's Ratio can also be used for ZIRLO™.

References:

7-1 WCAP-12610-P-A, "VANTAGE+ Fuel Assembly Reference Core Report", April 1995.

7-2 WCAP 15063-P-A Revision 1, with Errata, "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)", July 2000.

7-3 WCAP-3269-41, UC-80, "Physical and Mechanical Properties of Zircaloy 2 and 4", May 1965.

7-4 CENPD-136, "High Temperature Properties of Zircaloy and UO_2 for Use in LOCA Evaluation Models", July 1974.

Question #8:

At the May 16, 2001, Westinghouse Fuel Performance Update Meeting, results of the LOCA Basis Testing of ZIRLO™ Cladding were presented. Please provide more details of these tests including the optical metallography and hydrogen concentration measurements.

Response:

A copy of the Westinghouse report supporting the conclusions drawn regarding the 17% ECR issue with respect to ZIRLO™ cladding material is summarized in the referenced Westinghouse letter to the NRC.

Reference:

8-1 "Ductility of ZIRLO™ and Zircaloy-4 after High Temperature Oxidation in Steam", LD-2001-0046, August 10, 2001.

Question #9:

Please provide details of the root cause investigation of the Ft. Calhoun fuel fretting. In particular, please address why a similar problem will not occur with ZIRLO™ implementation in CE Nuclear Power fuel designs.

Response:

The cause of the fretting failures is summarized in the referenced Westinghouse letter to the NRC.

Reference:

9-1 "Assessment of Ft. Calhoun Fuel Rod Fretting History and Root Cause as it Relates to Implementation of ZIRLO™ Cladding Material in Fuel Designed by CE Nuclear Power", LD-2001-0028, May 3, 2001.

Question #10:

NRC evaluations of WCAP-12610, Appendices F and G, dated October 9, 1991, address application of approved LBLOCA and SBLOCA analysis methodologies to cores containing ZIRLO™ fuel. These SERs state that Appendix K LOCA methodologies may (should) retain the Appendix K treatment of material properties, such as the Baker-Just equation, when prescribed by Appendix K and justified as suitably conservative. The SERs did not say that it is appropriate to use properties of Zircaloy in analyses of ZIRLO™, or that it is appropriate to use the properties of ZIRLO™ in analyses of Zircaloy. The SERs also state that ZIRLO™ and Zircaloy are sufficiently alike that when performing LOCA analyses of cores containing both ZIRLO™ and Zircaloy in assemblies with like features (geometry), no mixed-core penalty need be applied.

The topical, CENPD-404-P, implies the intention to perform LOCA analyses assuming a representative fuel combining various properties from both fuel cladding types. This is not the intention of the NRC SER. Each fuel must be analyzed separately to identify the limiting fuel type, which could conceivably change in subsequent fuel cycles. Also, in the case of a change in limiting fuel type, the limiting fuel could approach the 10 CFR 50.46 reporting requirements as well. Please clarify the intention in the document referenced above.

Response:

It is not Westinghouse's intention to perform loss-of-coolant accident (LOCA) analyses assuming a representative fuel that combines various properties of ZIRLO™ and Zircaloy-4 cladding. Rather, when both ZIRLO™ and Zircaloy-4 clad fuel rods are co-resident in a core, the ZIRLO™ clad rods will be analyzed using the ZIRLO™ cladding models described in Section 6.3 of CENPD-404-P. Likewise, the fuel rods clad with Zircaloy-4 will continue to be analyzed using the Zircaloy-4 cladding models that have been previously used in the Westinghouse ECCS performance evaluation models for Combustion Engineering (CE) designed Pressurized Water Reactors (PWRs).

The document referenced in the question, herein referred to as the 'Roadmap', was provided to the NRC as an aid in reviewing CENPD-404-P. The Roadmap provides the following information for each cladding property used by each of the methodologies addressed in CENPD-404-P:

- The section in CENPD-404-P that describes the ZIRLO™ model for the cladding property.
- The NRC-accepted documentation for the Zircaloy-4 model for the cladding property.
- An indication as to whether the ZIRLO™ model is the same as the Zircaloy-4 model.

It is the last item that may have been interpreted as implying that both fuel types would be analyzed using a combination of various properties from both cladding types. As noted above, that is not the intent. Rather, the Roadmap is merely identifying those cladding properties for which, as described in CENPD-404-P, the ZIRLO™ models are the same as the Zircaloy-4 models.

As originally described in WCAP-12610-P-A and repeated in CENPD-404-P, several of the physical and mechanical properties of ZIRLO™ are sufficiently similar to those of Zircaloy-4 such that the same models are applicable to both materials. However, because the change in metallurgical phase occurs over a different temperature range for the two materials, properties that are impacted by the change in phase may require use of separate models. Consequently, ZIRLO™-specific models have been developed and are used for such properties. Examples of these properties include specific heat and cladding rupture temperature and rupture strain. This approach of using the same model for ZIRLO™ and Zircaloy-4 properties, where appropriate, and ZIRLO™-specific models where necessary is also used in the LOCA evaluation models for Westinghouse designed PWRs as described in Appendices F and G of WCAP-12610-P-A. These appendices are explicitly noted in the above question as having received an SER from the NRC.

As described in Section 6.3 of CENPD-404-P, the approach used for the implementation of ZIRLO™ cladding models in the LOCA evaluation models for CE designed PWRs is analogous to the approach used in WCAP-12610-P-A (i.e., the same models are used for ZIRLO™ as for Zircaloy-4 where appropriate and ZIRLO™-specific models are used where necessary). The following is a brief summary of the use of ZIRLO™-specific models versus non-ZIRLO™-specific models for the thirteen cladding properties used in the LOCA evaluation models for CE designed PWRs:

- ZIRLO™-specific models are used for specific heat, rupture temperature, rupture strain, and assembly blockage.
- The pre-rupture plastic strain model can also be viewed as ZIRLO™-specific since the model uses the ZIRLO™-specific models for rupture temperature and rupture strain.
- The Baker-Just metal-water reaction rate model is used for ZIRLO™. As described in Section 6.3.13, the Baker-Just model is suitably conservative for ZIRLO™ cladding.
- The models used for the remaining seven cladding parameters are the same models that are used for Zircaloy-4 cladding. The basis for the applicability of the models to ZIRLO™ for these seven parameters is provided in Section 6.3 of CENPD-404-P.

Question #10a

As noted in the Question 10 response, WCAP-12610, Appendices F and G, dealing with LBLOCA and SBLOCA were reviewed and approved by the NRC. These appendices were submitted separately from WCAP-12610, and were reviewed and approved separately. WCAP-12610 was not within the direct scope of the Appendices F and G review. The review of Appendices F and G focused primarily on the effect of ZIRLO™ on mixed-core LOCA analyses, and whether a separate mixed-core penalty would be needed for LOCA analyses. WCAP-12610 and Appendices F and G did not explicitly state that certain Zr4 properties would be used in place of the corresponding ZIRLO™ properties in LOCA calculations for ZIRLO™. One exception, use of the Baker-Just equation (and any other Appendix K-specified treatment) was granted, but only with justification that it (they) conservatively represented ZIRLO™. This was done only to avoid an unnecessary conflict with Appendix K, which would have resulted in a need to issue an exemption from elements of Appendix K to reference that regulation in showing compliance.

It was found that for Zr4 and ZIRLO™ fuels of like features (geometry, including spacers, flow mixing vanes, cladding surface texture, etc.), a mixed-core penalty need not be added for each/either fuel. However, the Safety Evaluation did not remove the obligation to evaluate each type of cladding separately using the fuel heatup model.

To fail to use cladding-specific properties would be to ignore analysis changes or errors which would affect each fuel differently, potentially accumulating to the point that the sum of the effects could exceed the mixed-core penalty, change the identification of the limiting fuel, or identify that one fuel had exceeded either the 50°F reporting criterion, or one of the safety criteria of 10 CFR 50.46(b) (without significantly affecting the other cladding). Specific properties for each cladding material should be used, when they are available.

Until all the specific properties are incorporated into the LOCA methodologies/analyses, one interim measure that could meet 10 CFR 50.46 would be to estimate the PCT impact of each property substitution separately for both LBLOCA and SBLOCA analyses, and report them for each plant under the provisions of 10 CFR 50.46. Such reporting would show compliance with the regulation, and most likely would not affect plant operating and licensing status, if the differences are as small as alleged.

Response:

Although not phrased as an unambiguous question (Question 10a appears to be more a statement of historical background and regulatory perspective), we believe that the essence of Question 10a is contained in the last sentence of the third paragraph, which states:

"Specific properties for each cladding material should be used, when they are available."

A more precise statement would be that specific models for each cladding property should be used for both cladding materials (i.e., ZIRLO™ and Zircaloy-4), when they are available.

As described in Section 6.3 of CENPD-404-P (Reference 10a-1), ZIRLO™-specific models are used for specific heat, rupture temperature, rupture strain, and assembly blockage in the Westinghouse evaluation models for CE designed PWRs. In addition, the pre-rupture plastic strain model is essentially ZIRLO™-specific since it is dependent on the ZIRLO™-specific rupture temperature and rupture strain models.

As further described in Section 6.3 of CENPD-404-P, the same models that are currently used for Zircaloy-4 are also used for ZIRLO™ for the following seven properties in the Westinghouse evaluation models for CE designed PWRs:

- density
- thermal conductivity
- thermal emissivity
- thermal expansion
- modulus of elasticity
- Poisson's ratio
- diamond pyramid hardness

Because of the similarity between ZIRLO™ and Zircaloy-4, the same models for these properties are applicable (i.e., specific) to both materials.

However, ZIRLO™-specific data are available for two of these properties, namely, thermal conductivity and thermal expansion. Despite the fact that ZIRLO™-specific data are available, Westinghouse has chosen to use the models that are currently used for Zircaloy-4 for these two properties for ZIRLO™ cladding in the Westinghouse evaluation models for CE designed PWRs.

Thermal Conductivity

Thermal conductivity data for ZIRLO™ and Zircaloy-4 are compared in Figure A-2 of WCAP-12610-P-A (Reference 10a-2). The ZIRLO™ data extends up to a maximum temperature of [ ]. This is well below the upper end of the temperature range of interest in an ECCS performance analysis (i.e., 2200°F). Consequently, the range of applicability of a ZIRLO™-specific model based on the available data would not cover the temperature required by an ECCS performance analysis. As described in Appendix A of WCAP-12610-P-A and Section 6.3.3 of CENPD-404-P, the differences between the ZIRLO™ and Zircaloy-4 thermal conductivity data are sufficiently small so as to be of no consequence. Therefore, use of the same model (which is based on Zircaloy-4 data that does cover the temperature range of interest) for both materials is appropriate. The following discussion provides a quantitative demonstration of the fact that small differences in thermal conductivity, such as the differences shown in Figure A-2 of WCAP-12610-P-A, do not have a significant impact on cladding temperature during a LOCA.

The heat transfer from the fuel pellet to the coolant during a LOCA is determined by the thermal resistances of the fuel pellet, the pellet-to-cladding gap, the cladding, and the cladding-to-coolant interface. Differences in cladding thermal conductivity will have an impact on the LOCA transient, in general, and cladding temperature, in particular, *only* if the thermal resistance of the cladding is limiting the heat transfer (i.e., if the cladding thermal resistance is large in comparison to the other resistances). This is not the case.

As shown in the following table, at the start of the LOCA transient, the thermal resistance of the pellet is limiting the heat transfer.

Approximate Thermal Resistances at the Start of a LOCA (normalized to the thermal resistance of the cladding)	
Component	**Normalized Thermal Resistance**
Fuel Pellet	[ ]
Gap	[ ]
Cladding	[ ]
Cladding-to-Coolant	[ ]

By the end of the blowdown period of a large break LOCA, the cladding-to-coolant heat transfer coefficient has decreased to the point that its corresponding thermal resistance is more than [ ] times that of the cladding. During late reflood when the reflood rate has decreased to below one inch per second (i.e., the time period when the peak cladding temperature is calculated to occur), the thermal resistance of the cladding-to-coolant heat transfer is more than [ ] times that of the cladding. Since the thermal resistance of the cladding is always significantly non-limiting during a LOCA, differences in cladding thermal conductivity of the size shown in Figure A-2 of WCAP-12610-P-A (i.e., up to approximately [ ]) will not significantly impact the thermal response of the hot rod. Consequently, use of a thermal conductivity model based on Zircaloy-4 data for ZIRLO™ cladding is acceptable and appropriate in an Appendix K ECCS performance evaluation model.

Thermal Expansion

Axial thermal expansion data for ZIRLO™ and Zircaloy-4 are compared in Figure A-1 of WCAP-12610-P-A. There are no ZIRLO™ data for radial thermal expansion. As described in Section 6.3.5 of CENPD-404-P, the Westinghouse evaluation models for CE designed PWRs only represent radial thermal expansion; they do not model axial thermal expansion. Since there is no ZIRLO™-specific data available for radial thermal expansion, the question of using ZIRLO™-specific models when they are available does not explicitly apply to radial thermal expansion. Also, in discussing the differences between the thermal expansion models that are used for Zircaloy-4/ZIRLO™ in the Westinghouse evaluation models for Westinghouse and CE designed PWRs, Section 6.3.5 of CENPD-404-P reports the result of a calculation that shows the lack of sensitivity of the peak cladding temperature to changes in the cladding thermal expansion model. For these reasons, it is concluded that use of a radial thermal expansion model based on Zircaloy-4 data for ZIRLO™ cladding is acceptable and appropriate.

The last paragraph of Question 10a suggests an interim measure that could be used until ZIRLO™-specific models are implemented for all cladding properties. As described in Section 6.3 of CENPD-404-P and augmented by information contained in the responses to Question 10 and this question, models that are appropriately applicable to

ZIRLO™ are used for all cladding properties in the Westinghouse evaluation models for CE designed PWRs. Consequently, no interim measure such as that described in the last paragraph of Question 10a is required.

Lastly, the following clarification to Question 10a is presented. The first paragraph of Question 10a states that:

"WCAP-12610 and Appendices F and G did not explicitly state that certain Zr4 properties would be used in place of the corresponding ZIRLO™ properties in LOCA calculations for ZIRLO™."

While this may be literally true, WCAP-12610-P-A does clearly identify that only a subset of the Zircaloy-4 cladding models were modified to represent ZIRLO™ (and, consequently, the remaining models were not modified). For example, page G-3 of Appendix G states that:

"Modifications were made to the large break Evaluation Model computer codes to represent the ZIRLO™ cladding as discussed in Section 5.2.1."

Section 5.2.1, in turn, identifies [ ] models that were changed:

It is also noted that the Safety Evaluation Report (SER) for Appendix F of WCAP-12610-P-A, which is contained in Section D of WCAP-12610-P-A, lists the models in the small break LOCA NOTRUMP evaluation model that were modified for ZIRLO™. In particular, the SER states:

"WCAP-12620, Appendix F, identifies the following changes in the use of the NOTRUMP model to account for ZIRLO™ material properties: clad specific heat, high-temperature creep, rupture temperatures, and circumferential strain following rupture."

1 Section 5.2.1 also lists the metal-water reaction rate model as a model that is changed. However, as described in Appendix G (and as alluded to in the first paragraph of Question 10a), the use of the Baker-Just model was ultimately retained in both the large break and small break LOCA evaluation models.

Effect of ZIRLO™ Clad Conductivity on Non-LOCA Events

Non-LOCA events which are analyzed using the CENTS or CESEC-III computer codes (References 10a-3 and 10a-4, respectively) are concerned with the calculation of core average heat flux, fuel temperature, and coolant temperature. These quantities can be affected by the fuel-clad conductivity; if it is a significant contributor to the overall heat transfer path.

Hot channel DNBR is calculated separately using the CETOP or TORC computer codes (References 10a-5 and 10a-6, respectively) based on the results of the CENTS or CESEC system simulation computer codes. Core peaking is calculated using standard hot pin synthesis methodology. For these calculations, hot pin heat flux is assumed to respond instantly to an increase in core average power or hot pin power peaking. This assumption over-predicts the rate of increase of hot pin heat flux so that the resistance of the hot channel clad thermal conductivity *is not* important to the calculation of DNBR.

The affect of varying thermal conductivity on the core average heat flux response was evaluated by considering typical values for the various resistances at a clad temperature of 1000°F. This is higher than typically reached during non-LOCA events and exaggerates the difference between the clad thermal resistance curves for ZIRLO™ vs OPTIN™.

DESCRIPTION OF RESISTANCE	TYPICAL VALUE	EQUIVALENT RESISTANCE HR-FT^2- °F/BTU
CLAD-TO-COOLANT HEAT TRANSFER		
ZIRLO™ CLAD (REFERENCE 10A-7, EQ. 4-23)		
OPTIN™ CLAD (REFERENCE 10A-7, EQ. 4-24)		
FUEL–CLAD GAP CONDUCTANCE (BOUNDING HIGH VALUE)		
FUEL		

Thus, the most important resistance is that of the fuel itself. The difference between the correlations for ZIRLO™ vs. OPTIN™ changes the total resistance by about [ ], which is negligible.

The STRIKIN-II program is used to evaluate the CEA ejection accident. For these analyses the fuel-clad gap conductance is calculated by STRIKIN-II and is significantly lower than the bounding high value used in the other analyses. Thus the difference in clad thermal resistance would have relatively less effect on the results of the CEA ejection accident.

References:

10a-1 CENPD-404-P, Revision 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," January 2001.

10a-2 WCAP-12610-P-A, "Vantage+ Fuel Assembly Reference Core Report," April 1995.

10a-3 CENPD-282-P-A, {Vols. 1 thru 4 + Suppl, 1} "Technical Manual for the CENTS Code", February 1991.

10a-4 Enclosure 1-P LD-82-001 "CESEC, Digital Simulation of a Combustion Engineering Nuclear Steam Supply System," January 6, 1982.

10a-5 CEN-191(B)-P, "CETOP-D Code Structure and Modeling Methods for Calvert Cliffs Units 1 and 2", December 1981

10a-6 CENPD-161-A, "TORC Code, A Computer Code for Determining the Thermal Margin of a Reactor Core," April 1986.

10a-7 CENPD-404-P, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs", January 2001.

Question #11:

Equation 3-1, provide detail information to show how the T_{avg} is obtained.

Response:

The methodology for calculating the mFDI is summarized below in further detail.

The Fuel Duty Index, FDI, (Reference 11-1) was developed as an alternative to representing fuel rod corrosion as a function of burnup. The corrosion was expressed as a function of the time average fuel rod surface temperature and the total irradiation time. Subsequent studies indicated that the correlation between corrosion and the FDI could be improved (Reference 11-2) if a coolant boiling term was included. The definition of the FDIB with the boiling is:

$$FDIB = [(T_{avg} - 580)/100) * (hrs/1000)]^2 + b\, m_{e,total} \qquad (1)$$

where:

T_{avg} = Time averaged rod surface temperature, °F
hrs = Total irradiation time, hrs
$m_{e,total}$ = Total mass evaporated per unit area, 10^6 lb/ft^2
b = Empirical constant = [ ]

A description of a single channel thermal model used for computing the FDI inputs is provided below. The channel considered is the flow area surrounded by four fuel rods.

Inputs required for the calculation are;

- Channel hydraulic diameter, ft
- System pressure, psi
- Inlet temperature, °F
- Core coolant mass flux, lb/hr/ft^2
- Rod power kw/ft
- Rod axial power shape

System inputs may be time dependent.

The enthalpy rise at any axial location, z, and time, t, is given by:

$$H(z,t) = H(0,t) + F_{mix} \int_0^z \frac{4 q_{avg}(z,t)\,dz}{G(t) De} \qquad (2)$$

The F_{mix} factor is determined by the ratio of the single channel hydraulic diameter to an effective core hydraulic diameter which accounts for guide thimbles and inter assembly spacing.

where;

q_{avg} = Channel average heat flux, BTU/hr/ft^2
G = Coolant mass flux, lb/hr/ft^2
D_e = Channel hydraulic diameter, ft, = 4 Area/Wetted perimeter
z = Axial location, ft

The channel average heat flux is calculated by converting Kw/ft to heat flux and taking the average heat flux of the four rods comprising the flow channel.

Equation (1) gives the enthalpy, H, at any axial location z and time t. The enthalpy is used to determine the local bulk temperature, T_b, and fluid properties from the ASME steam tables. This may be by access to the tables or from curve fits of data taken from the steam tables. The local fluid velocity is calculated from the mass flux, channel area, and local bulk density.

The Dittus-Boelter film heat transfer coefficient (Reference 11-3) is used to calculate the single phase heat transfer coefficient.

$$hD_e/k = 0.023\, Re^{0.8}Pr^{0.4} \qquad (3)$$

where:

h	= Film coefficient, BTU/hr/ft²/°F
k	= Fluid conductivity, BTU/hr/ft/°F
D_e	= Channel hydraulic diameter, ft
Re	= Reynolds number
Pr	= Prandtl number

The fuel rod surface temperature, T_{OD} at any time t, is calculated from:

$$q''(z) = h\,(T_{OD} - T_b) \qquad (4)$$

and

$$T_{OD}(z) = T_b(z) + q(z)''/h(z) \qquad (5)$$

Where q"(z) is the local heat flux on the rod of interest.

It the surface temperature calculated by Equation (5) is greater than, or equal to the fluid saturation temperature, T_{sat}, subcooled nucleate boiling is occurring and a different procedure is used to calculate the surface temperature.

The Thom (Reference 11-3) boiling heat transfer coefficient is used when subcooled nucleate boiling occurs. The surface temperature in boiling is given by:

$$T_{OD} = Tsat + (0.072\,(q'')^{0.5})/(\exp(P/1260)) \qquad (6)$$

The effective heat transfer coefficient is obtained substituting the convective heat transfer term for q" in Equation (6), and solving for the heat transfer coefficient.

$$h_{Thom} = [\exp(P/1260)\,(T_{OD} - T_{sat})/0.72]^2 \,/\, (T_{OD} - T_b) \qquad (7)$$

The total heat transfer in the mFDI thermal model is the sum of the heat transfer by forced convection plus the heat transfer by subcooled nucleate boiling.

The total heat flux is given by:

$$q'' = q_{conv} + q_{Thom} = h_{conv}\,(T_{OD} - T_b) + h_{Thom}\,(T_{OD} - T_b) \qquad (8)$$

Substitution of the equation for h_{Thom} into Equation (8) and solving for T_{OD} gives the following expression:

$$T_{OD} = T_{sat} + \{[h_{conv}{}^2 + 4\,a\,(q'' - h_{conv}(Tsat - Tb))]^{1/2} - h_{conv}\}/\,2a \qquad (9)$$

where $a = [\exp(P/1260)/0.72]^2$

The expression for T_{OD} is evaluated over time intervals, Δt, where variable values can be assumed to be constant. The time average surface temperature, T_{avg}, is determined by summing ($T_{OD}\,\Delta t$) over all the time increments and dividing by the total time, τ.

$$T_{avg} = (1/\tau) * \Sigma T_{OD}(t)\,\Delta t \qquad (10)$$

The mass evaporated per unit area during any time interval Δt is given by:

$$m_e = ((q'' - q''_{conv}) \Delta t)/h_{fg} \qquad (11)$$

where

m_e = mass evaporation, lb/ft^2
h_{fg} = latent heat of vaporization, BTU/lb

The total mass evaporated is the sum over all the time intervals.

$$m_{e,total} = \Sigma m_e \qquad (12)$$

The expressions from Equations (10) and (12) are substituted into Equation (1) to calculate the FDIB.

References:

11-1 R. S. Kaiser, W. J. Leech, and A. L. Casadei, "The Fuel Duty Index (FDI) – A New Measure of Fuel Rod Cladding Performance", An International Topical Meeting on Light water Reactor Fuel Performance, April 10-13, 2000, Park City Utah, American Nuclear Society.

11-2 W. J. Leech and K. Yueh, "The Fuel Duty Index, a Method to Assess Fuel Performance", ENS Topfuel 2001, May 27-30, 2001, Stockholm.

11-3 F. W. Dittus and L .M. K. Boelter, "Heat Transfer in Atuomobile Radiators of the Tubular Type", University of California-Publications in Engineering 12, No. 13, 443-461, 1930.

11-4 J. R. Thom, W. M. Walker, T. A. Fallon, and G. F. S. Reising, "Boiling in Sub-Cooled Water During Flow up Heated Tubes or Annuli", Proc. Inst. Mech. Engrs, 1965-1966.

Question #12:

The corrosion measurement technique and data acquisition including uncertainty can vary from vendor to vendor. Are there any differences between Westinghouse and CE; if yes, please provide both results for comparison.

Response:

Eddy current technology is utilized to measure the thickness of the oxide layer on the surface of both Westinghouse and CE designed fuel rods. Although separate measurement systems evolved, they both utilize slightly different high-frequency probes of similar geometry and design. The CE oxide measuring system is currently being converted to utilize the Westinghouse hardware, and it is anticipated that the conversion will be completed prior to the measurement of CE fuel rod designs with ZIRLO™ cladding that have been irradiated. In both approaches continuous, axial traces are utilized to acquire measurement data. Westinghouse fuel rod measurements are most often performed with the fuel rod in the assembly by translating the probe on the outer surface of a stationary assembly. However, the capability also exists to perform measurements with the fuel rod removed from the assembly, in which case the fuel rod is translated past a stationary probe similar to CE. Data acquisition using CE equipment is obtained on individual fuel rods that are removed from the fuel assembly. The fuel rod to be measured is translated past a stationary probe. Similar techniques are used for video verification of the measurement process and both approaches use a computer interface and software to facilitate data acquisition and analysis.

These similarities insure the high degree of precision required to accurately utilize the measurement capability of the eddy current systems. However, the most important aspect of the oxide measurement process is the calibration of the measurement probes. Both Westinghouse and CE measurement systems follow similar practices in this important area. System calibrations for both processes are performed using cladding specimen "standards" that have an autoclave-grown oxide layer of known thickness. The material that is used to fabricate the "standards" is the same as the material that is to be measured (e.g., Zircaloy or ZIRLO™). As a result, a precision of [ ] is applied to both systems within the [ ]. Hot cell examinations conducted on fuel rods measured by both systems confirm this precision without correction for measurement bias. [

]

The data reduction techniques used to determine the important measurement attribute of maximum oxide thickness, for each measured fuel rod, appears to result in a minor difference between the Westinghouse and CE methodologies for defining oxide thickness. For CE fuel rod designs, a maximum, circumferential-average oxide thickness is determined for each fuel rod measured. This maximum thickness is determined by combining the axial scans for the fuel rod to form a composite axial and circumferential map of oxide thickness. Typically, four axial traces that were performed at 90° azimuthal orientations are combined to generate the composite. The maximum oxide thickness is calculated from the composite matrix by determining the thickest oxide layer for any [ ] interval of cladding. [

] The maximum circumferential-averaged oxide thickness is correlated as a function of burnup and/or fuel duty index. Similarly, the data reduction process for Westinghouse fuel rod designs also determines a maximum average oxide thickness by calculating the thickest oxide layer for any [ ] interval of cladding. However, since most fuel rods measured using the Westinghouse methodology are peripheral fuel rods that are measured while residing in the fuel assembly, the maximum [ ] average thickness is determined using a single axial trace from the peripheral side of the fuel rod. [

] In the event that the Westinghouse technique is used exclusively, no difference in the reported measurement attributes will exist. However, if the CE method is used, the maximum oxide thickness on the rod will have to be defined by the maximum single trace for comparisons to the mFDI. As a result, the differences in determination of maximum thickness and mFDI either have no impact or will be conservative. This approach will be continued until a reasonable database for ZIRLO™ cladding corrosion is developed that is applicable to CE plants.

Question #13:

There is a 100 microns corrosion limit for Westinghouse design. What is the CENP corrosion limit for this report?

Response:

The Westinghouse corrosion limit for ZIRLO™ will be 100 microns as discussed in CENPD-404-P, Section 4.5. More specifically, as discussed in Section 4.5.2 and in response to Question Nos. 1 and 26, the best estimate maximum oxide thickness for ZIRLO™ cladding will be determined. In addition, fuel reload management will be designed to ensure that the mFDI remains within the Westinghouse database as described in response to Question Nos. 1 and 26. Thus, the best estimate maximum oxide thickness will remain within 100 microns.

In addition, to ensure that this oxide limit is not exceeded, waterside corrosion will initially be monitored in CE designed fuel clad with ZIRLO™ via sufficient end-of-cycle (EOC) poolside measurements to ensure that the oxide thickness vs mFDI characteristics also remain within the Westinghouse database.

Question #14:

Provide a derivation of Mt in Equation 3-2.

Response:

The response to this question was answered in the response to Question 11.

Question #15:

Sections 4.3.3 and 4.3.4 show that CENPD (sic) will use the old correlations from FATES3B rather than those from ZIRLO™ properties. Please provide comparison plots for these properties.

Response:

See the response to Question 6 for comparison plots and further discussion of these properties.

It is Westinghouse's intent to use all ZIRLO™ properties for the analysis of ZIRLO™ clad fuel assembly designs. For some properties, the same model that is used for Zircaloy-4 cladding is also used for ZIRLO™ cladding and, as such, are considered ZIRLO™ properties. The use of the same model is based on an evaluation that concludes that use of the Zircaloy-4 model is conservative or the differences, if any, are concluded to have an insignificant impact on design and licensing performance parameters. Thus, a complete set of ZIRLO™ specific properties has been qualified for implementation.

Question #16:

Provide results of FATES3B licensing calculations of fuel centerline temperature, power-to-melt, strain limit, rod and assembly growths, creep collapse, delta P beyond the system pressure, and LOCA initial conditions for both Zircaloy and ZIRLO™ claddings in typical CENPD (sic) fuel designs and maximum/nominal power histories.

Response:

Fuel performance analyses for both Zircaloy-4 (OPTIN™) and ZIRLO™ clad fuel rods were prepared and selected performance parameters presented in CENPD-404-P, Section 4.6. Results are included that are typical of a 14x14 fuel design and typical of a 16x16 fuel design. Except for the substitution of cladding material, all features of the fuel rod design, power history, and coolant conditions for each pair of cases are identical. The analyses presented in Section 4.6 are bounding licensing calculations and provide initial conditions for accident analyses (e.g., LOCA analysis). These analyses are also used to confirm that the fuel rod satisfies the power-to-centerline melt and maximum internal pressure Specified Acceptable Fuel Design Limits (SAFDL). A comparison of each pair of cases demonstrates the impact of ZIRLO™ versus Zircaloy-4 cladding.

The licensing methodology and level of conservatism is identical to that currently approved for FATES3B by the NRC. [

]

The power-to-centerline melt is shown as a function of rod burnup in Figures 4.6.1.2-1 and 4.6.1.2-2. The bounding envelope of maximum internal hot gas pressure as a function of rod burnup is shown in Figures 4.6.1.3-1 and 4.6.1.3-2. Also shown in Figures 4.6.1.3-1 and 4.6.1.3-2 are the critical no-clad-lift-off pressures. These results are discussed in further detail in CENPD-404-P.

Additional performance parameters have been extracted from these bounding licensing analyses for the 14x14 design ZIRLO™ clad fuel rod and are shown in Figures 16-1 through 16-5. Results for the comparable Zircaloy-4 fuel rod behave nearly the same as a function of rod average burnup. Additional comparisons between the performance of the ZIRLO™ clad fuel rod and the Zircaloy-4 fuel rod are provided at selected burnup points for the 14x14 design and the 16x16 design in Tables 16-1 through 16-6.

Figure 16-1 and Tables 16-1 and 16-2 provide internal hot gas pressures based on different assumed operating linear heat rate conditions. Maximum transient pressure is the maximum that can occur at any given burnup obtained by the imposition of the operating transients. Maximum steady-state pressure is the maximum that can occur at any given burnup obtained in a fuel rod at the maximum rod average long-term (steady-state) radial peaking factor. Also shown is the maximum internal pressure expected for a fuel rod at nominal, rather than bounding, linear heat rates as a function of burnup. The nominal linear heat rate can be approximated to be the long-term linear heat rate required to achieve 62 MWd/kgU peak rod burnup in three 24-month operating cycles, assuming full power operation with a typical 45 day shutdown for reload activities. It can be seen that a significant margin exists between the nominal conditions and the bounding licensing conditions.

Fuel centerline temperatures are provided by Figure 16-2 and Table 16-3. It can be seen that the centerline temperatures of the ZIRLO™ rod and of the Zircaloy-4 rod are quite similar, especially at beginning of life and end of life.

Cold void volume, which reflects the differences in creepdown and axial growth, are provided by Figure 16-3 and Table 16-4. Void volume differences are the primary cause of differences in maximum hot gas pressure.

Rod growth is provided by Figure 16-4 and Table 16-5. As expected from the rod growth correlation, ZIRLO™ does not grow as much as the Zircaloy-4 fuel rod. Rod growth and shoulder gap evaluations are discussed in CENPD-404-P in Section 5.4.5. Considerably more shoulder gap margin is available because of the lower growth of ZIRLO™ clad fuel rods.

Finally, typical hoop stress as a function of steady-state operation and rod burnup is provided by Figure 16-5. Hoop stress was selected from a single hot location near the top of the fuel rod. It can be seen that the hoop stress is compressive at beginning of life and progresses to a tensile condition after fuel-clad contact as expected. Comparisons between ZIRLO™ and Zircaloy-4 are provided in Table 16-6.

The impact of ZIRLO™ cladding on mechanical design performance - collapse, maximum stress and strain, and fatigue is described in Sections 5.4.1 through 5.4.4. ZIRLO™ provides comparable or additional margin in all of these performance parameters. For example, collapse time for Zircaloy-4 is in excess of the required time but ZIRLO™ collapse times are in excess of the Zircaloy-4 collapse times.

TABLE 16-1
MAXIMUM INTERNAL HOT GAS PRESSURE – 14X14 DESIGN

TABLE 16-2
MAXIMUM INTERNAL HOT GAS PRESSURE – 16X16 DESIGN

TABLE 16-3
MAXIMUM TRANSIENT CENTERLINE TEMPERATURE
AT HOTTEST AXIAL LOCATION (NODE 18)

TABLE 16-4
FUEL ROD INTERNAL VOID VOLUME AT COLD CONDITIONS (RT)

TABLE 16-5
FUEL ROD AXIAL GROWTH

TABLE 16-6
CLADDING HOOP STRESS
AT HOTTEST AXIAL LOCATION (NODE 18)

Figure 16-1
Maximum Internal Pressure – 14x14 ZIRLO Design

Figure 16-2
Maximum Centerline Temperature – 14x14 ZIRLO Design

Figure 16-3
Cold Internal Void Volume – 14x14 ZIRLO Design

Figure 16-4
Fuel Rod Axial Growth – 14x14 ZIRLO Design

Figure 16-5
Hoop Stress – 14x14 ZIRLO Design

Question #17:

Please provide LOCA initial condition results from the FATES3B analyses. The results should be a plot of bounding volumetric averaged fuel temperatures versus rod average burnups at various LHGRs for different fuel designs including any burnable absorber features.

Response:

Fuel rod temperature and pressure results from the FATES3B analyses for a typical CENP 16x16 fuel assembly design and a typical CENP 14x14 fuel assembly design are provided in CENPD-404-P, Section 4.6. These FATES3B analysis results presented are, in fact, the analyses used to provide hot rod initial conditions for a LOCA, as well as providing a bounding maximum internal hot gas pressure history. These results are for erbia bearing fuel rods near the maximum erbia content anticipated in future reloads of each design. Because of the degradation of thermal properties in the fuel pellets inherent with the addition of erbia, these results will also bound standard UO_2 fuel rods in a given reactor core containing both burnable absorbers and UO_2. The impact of gadolinia addition is the same as erbia.

Bounding hot rod power histories for the LOCA initial conditions are also shown in CENPD-404-P, Section 4.6. [

]. This methodology is described in Reference 17-1.

Additional data was extracted from these FATES3B analyses and presented in response to Question 16. Fuel rod data presented in Question 16 from the FATES3B analyses, applicable as initial conditions for LOCA analysis, included internal hot gas pressure, void volume, and rod growth as a function of rod average burnup. Centerline temperatures were also presented at the [ ] for the hottest node near the top of the fuel rod, node 18 (of 20 equal length nodes). LHGR at each axial node is [

]

Temperatures for other nodes along the fuel rod are lower than node 18 in these analyses. Average temperatures follow a burnup dependent behavior similar to centerline temperature with respect to burnup. The [ ] for node 18 is shown in Figures 17-1 and 17-2 for the 14x14 and 16x16 fuel designs, respectively. The resulting fuel average temperatures for node 18 are shown as a function of rod average burnup in Figures 17-3 and 17-4 for these fuel designs, comparing temperatures between Zircaloy-4 (OPTIN™) cladding and ZIRLO™ cladding. [

]

[

] This feature continues to remain valid.

References:

17-1 CEN-193(B)-P Supplement 2-P, "Partial Response to NRC Questions on CEN-161(B), Improvements to Fuel Evaluation Model", March 21, 1982.

17-2 CEN-205(B)-P, "Response to NRC Questions on FATES3 and the Calvert Cliffs 1 Cycle 6 Reload", April 23, 1982.

Figure 17-1

Linear Heat Rate

Monitored LOCA LHR (Hot Node 18) 14x14 Design

Figure 17-2

Linear Heat Rate

Monitored LOCA LHR (Hot Node 18) 16x16 Design

Figure 17-3

Fuel Average Temperature

Hot Node (Node 18) 14x14 Design

Figure 17-4

Fuel Average Temperature

Hot Node (Node 18) 16x16 Design

Question 18:

Why should correlations developed by Westinghouse for fuel used in Westinghouse plants be applicable to fuel used in CE plants? Specifically address the effects of differences in geometry and material with regard to the fuel rods and the supporting structures such as grids and guide tubes.

Response:

Correlations developed by Westinghouse for ZIRLO™ cladding have been evaluated for dependency on texture (anisotropy) and geometry (tubing), interaction with other structural components, interaction with other model correlations and/or analysis methodology, and the relationship of correlation biases, if any, on design and licensing applications.

The property measurements and correlations developed by Westinghouse take account for tube geometry and fabrication process. The result is property correlations that apply to the ZIRLO™ cladding for Westinghouse plants. Since the ZIRLO™ cladding tubes produced for both Westinghouse and CENP plants are fabricated by the same facility and process, the basic properties will be the same and, therefore, are equally applicable to CENP designed ZIRLO™ clad fuel.

The interaction of the ZIRLO™ and supporting structures, such as grids and guide tubes, were also considered for implementation in CENP fuel designs. This interaction was evaluated and addressed in CENPD-404-P, Sections 3.0 and 5.0. Correlations or behaviors which must consider this interaction are clad fretting, clad corrosion, rod growth and shoulder gap, rod and assembly bow, and guide tube design function. Considerable successful Westinghouse experience is available on the combination of ZIRLO™ clad fuel rods in combination with Zircaloy-4 structural components supporting the conclusion that this combination of materials in CENP fuel designs is acceptable. It is recognized that the grids and guide tube designs for Westinghouse fuel designs differ somewhat from CENP fuel designs. However, CENP has also experienced successful performance with the CENP Zircaloy-4 structural fuel assembly components where the fuel rods were clad with an advanced material quite similar to ZIRLO™ (see CENPD-404-P Table 3.5-1 for a comparison of material constituents). Thus, the combined Westinghouse and CENP experience is directly applicable to the implementation of ZIRLO™ in CENP fuel designs. Consequently, there is considerable experience using ZIRLO™ clad fuel in combination with Zircaloy-4 structural components and no performance issues are expected.

Although rod growth and shoulder gap are dependent on other structural components, the behavioral correlation is empirical. Rod growth and shoulder gap will be monitored to ensure that no unforeseen problems develop. [

]

Waterside corrosion is known to be a plant-specific phenomenon. The phenomenon of waterside corrosion is understood well enough that Westinghouse expects the behavior of ZIRLO™ in CENP fuel designs to be similar to that of Westinghouse fuel designs (i.e., a performance improvement). Thus, the waterside corrosion of ZIRLO™ clad fuel will be initially monitored in plants using CENP fuel designs to ensure waterside corrosion behavior is acceptable.

The cladding creep correlation was found to be dependent on the analysis methodology employed (e.g., specific definitions of driving functions such as stress and temperature, and data agreement achieved by Westinghouse using the PAD 4.0 fuel performance code). Application of the creep correlation in the CENP fuel designs, therefore, uses the same driving function definitions for the ZIRLO™ application as are used for Westinghouse fuel designs. The creep correlation applied in FATES3B was also verified by comparisons to the database (see CENPD-404-P Section 4.3.6).

Based on the above considerations, Westinghouse has concluded that ZIRLO™ material property correlations originally developed for Westinghouse fuel designs are equally applicable to CENP fuel designs.

Question 19:

Page 4-29, last two sentences of paragraph before 4.5.2. Please explain this further.

Response:

CENPD-404-P, Section 4.5.1 is intended to provide background on the evaluations of waterside corrosion for OPTIN™. The last two sentences of the last paragraph of Section 4.5.1 describes the application of the proposed benchmarked waterside corrosion model for OPTIN™ in topical report CENPD-388-P (February 1998) for extended burnups (i.e., peak pin burnups in excess of 60 MWd/kgU). However, since CENPD-388-P is not yet approved, the extended burnup limit, oxide thickness limit, and OPTIN™ waterside corrosion model have likewise not yet been approved by the NRC. Section 4.5.1 can be considered as information only.

Section 4.5.2 is intended to provide a description of CENP evaluations that will be performed for ZIRLO™ clad fuel at that point in time where extended burnup operation would occur. A description of the proposed evaluation for ZIRLO™ for CENP fuel designs is provided by the response to Question Nos. 1 and 26.

Question 20:

Were the ZIRLO™ and OPTIN models for internal hot gas pressure validated with actual data?

Response:

Hot internal gas pressure has generally not been directly validated for FATES3B. Limited comparisons to hot gas pressure have been done with FATES at the request of the NRC (Reference 20-1). These comparisons were made for fuel rods irradiated in the IFA 432 experiment in the Halden test reactor. [

]

[

] This conclusion is not impacted by substitution of ZIRLO™ cladding.

References

20-1 CEN-193(B)-P Supplement 2-P, "Partial Response to NRC Questions on CEN-161(B)-P, Improvements to Fuel Evaluation Model", March 21, 1982.

20-2 CEN-161(B)-P-A, "Improvements to Fuel Evaluation Model", August 1989.

Question 21:

Section 4.6.1.5, last sentence. Please provide a table showing the design and licensing applications referred to and the disposition of each.

Response:

Applications for FATES3B were defined in References 21-1 and 21-2, and remain the same as for the current version of FATES3B except as noted. The impact of ZIRLO™ is concluded to be insignificant for all these applications because the FATES3B input to these analysis applications does not change for ZIRLO™ implementation. Furthermore, the FATES3B results for these applications are primarily dependent on temperatures and pressures in the fuel rod which have been demonstrated to be nearly identical between Zircaloy-4 and ZIRLO™ clad fuel. These specific applications are:

1. Fuel rod initial conditions for LOCA analyses.
2. Fuel rod initial conditions for non-LOCA analyses for which initial conditions at the start of the transient are important (e.g., internal gas pressure, internal gas composition, etc.).
3. Minimum value of the steady-state power-to-centerline melt.
4. Engineering factor on linear heat generation rate.
5. Fuel column thermal expansion and densification for computation of the densification factor included in establishing Technical Specification LCO and LSSS limits on linear heat rates.
6. Stored energy for containment analysis.
7. Minimum core average gap conductance values for input to non-LOCA transient analyses
8. Fuel rod initial conditions for internal gas pressure for clad stress and strain compliance calculations.
9. Maximum end-of-life design pressure and maximum cycle-by-cycle operating pressure.
10. Maximum core average gap conductance values for input to non-LOCA transient analyses.
11. Minimum pressure histories for input to clad collapse analyses.
12. Fuel temperature-power correlation data used to establish Doppler reactivity coefficient correlations.
13. Maximum internal pressure for spent fuel pool handling accidents (added).

References

21-1 CEN-193(B)-P Supplement 2-P, "Partial Response to NRC Questions on CEN-161(B)-P, Improvements to Fuel Evaluation Model", March 21, 1982.

21-2 CEN-345(B)-P, "Responses to NRC Questions on FATES3B", October 17, 1986.

Question 22:

Section 5.3.2. Will the OPTIN growth model be used for evaluations of shoulder gap?

Response:

The OPTIN™ axial growth model is not proposed to be used for ZIRLO™ clad fuel. Axial growth of ZIRLO™ is concluded to be less than Westinghouse Zircaloy-4 (see WCAP-12610-P-A, April 1995). Never the less, Westinghouse proposed to conservatively apply the Westinghouse Zircaloy-4 growth model for shoulder gap calculations. It is the intent of CENPD-404-P, Section 5.3.2 to propose that CENP fuel designs will also conservatively apply the Westinghouse WCAP-12610-P-A Zircaloy-4 growth model.

Question 23:

Section 5.3.10. The maximum oxide limit will need to agree with the 100 micron limit that has been used on all other cladding.

Response:

Westinghouse agrees that the maximum oxide limit used in the mechanical design evaluations for CENP ZIRLO™ clad fuel designs should be 100 microns. However, it is noted that a value of [ ] is conservative relative to thermal impact and clad wastage. Thus, mechanical design results found acceptable for [ ] will remain acceptable at a 100 micron limit.

Question 24:

Sections 7.3.1 and 7.3.2 refer to sensitivity studies. Please provide the details and results of these studies.

Response:

Approximately twenty four (24) CEA Ejection cases (Hot Full Power, Hot Zero Power, erbia fuel pellets, UO_2 fuel pellets, etc.) were analyzed using the STRIKIN II simulation computer code. Half of these cases were performed for a CENP 14x14 fuel design and half for a CENP 16x16 fuel design. In each case the ZIRLO™ specific heat properties were incorporated through input to STRIKIN II. All other input remained the same. The cases considered repeated existing CEA Ejection analyses that had been performed as part of a previous reload analysis. The results of the re-analysis were compared to the analyses of record to determine the impact of the ZIRLO™ material properties. The results remained within approximate [ ] in all cases.

With respect to the Seized Rotor/Sheared Shaft event, the sensitivity study involved reviewing the clad temperature versus time response to determine the maximum inside and outside clad temperature. Given that the specific heat for ZIRLO™ and Zircaloy-4 are "identical" up to approximately 1380°F (the alpha-beta phase change temperature for ZIRLO™), and that the maximum temperature reached for this transient was typically approximately 700°F for the Seized Rotor/Sheared Shaft events surveyed, therefore, it was concluded that changing the fuel rod cladding from Zircaloy-4 to ZIRLO™ had no effect on this event.

Based on the studies it is concluded that only one event, CEA Ejection, is predicted to reach the 1380 °F ZIRLO™ phase change temperature.

Question 25:

Report on Ductility of ZIRLO™, Tables 1, 2, and 3. For ZIRLO™ please explain why there is no difference between W15 and W17 in Table 3. Also, explain why no data is available for certain measurements.

Response:

The hydrogen data in the table is plotted in the attached, Figure 26-1. Hydrogen pickup values are low, and comparable in magnitude to the scatter in the measurement method. Both ZIRLO™ and Zircaloy-4 show a linear increase of hydrogen content with the oxygen weight gain and extrapolate to the correct value [ ] The difference between the two values is due to normal data scatter.

The 'na' symbol is used to represent 'Not Available' where measurements were not made. Oxide thickness measurements were not repeated for cases where the oxide thickness data was obtained on a previous run made at the same time and temperature conditions. Also, a number of runs, particularly at low temperatures, had very low weight gains that indicated very thin oxide layers. Not all of these specimens were examined.

FIGURE 25-1

HYDROGEN CONTENT OF ZIRLO™ AND ZIRCALOY-4

FOLLOWING HIGH TEMPERATURE STEAM OXIDATION

Question #26:

What corrosion model will be used for implementation of ZIRLO™ in CE plants? Is this model different from that used for the Westinghouse plants? Please explain how uncertainties and conservatism are handled.

Response:

CENP intends to use the same waterside corrosion model for ZIRLO™ as used by Westinghouse. The Westinghouse ZIRLO™ corrosion model consists of the Westinghouse Zircaloy-4 corrosion model with a multiplier applied to correct for ZIRLO™ corrosion behavior (approved in Reference 26-1). The maximum oxide thickness on the lead fuel rods in CENP plants will be verified to be less than 100 microns.

The Westinghouse approach and the CENP approach in the development of a corrosion model is to apply best-estimate power histories and coolant conditions to predict the maximum oxide thickness observed in lead power and lead burnup fuel rods. Lead power and lead burnup rods (i.e., highest duty rods) are generally targeted for measurements and comprise the bulk of the data base. Consequently, the corrosion model represents a reasonably upper bound prediction to the oxide thickness which may exist on all of the fuel rods in the core which have achieved a given burnup. The criterion of a 100 micron limit on this "best-estimate" maximum oxide is considered to provide sufficient conservatism and the imposition of an additional uncertainty is unnecessary.

Westinghouse currently has an active program to develop an improved ZIRLO™ waterside corrosion model. This improved corrosion model will be applied to both CENP and Westinghouse designed ZIRLO™ clad fuel when completed and it will be used after review and acceptance by the NRC.

Westinghouse CENP also intends to use the modified Fuel Duty Index (mFDI) for fuel duty comparisons in addition to the waterside corrosion model evaluations. This is discussed further in response to Question Nos. 1, 19, and 27.

Reference:

26-1 WCAP-12610-P-A, "VANTAGE+ Fuel Assembly Reference Core Report", April 1995.

Question #27:

Is CENPD-404-P Revision 0 requesting approval for the modified fuel duty index for prediction of corrosion?

Response:

Westinghouse is requesting the approval to implement ZIRLO™ into CENP fuel designs because it is well established that ZIRLO™ is more robust than OPTIN™ with respect to waterside corrosion. It is expected that for the same fuel duty, ZIRLO™ will experience less oxidation than OPTIN™ and ZIRLO™ has not been observed to be susceptible to oxide spallation. Westinghouse recognizes that ZIRLO™ oxidation data must first be obtained to directly verify applicability of the mFDI to CENP ZIRLO™ clad fuel designs. It is *not* requested that mFDI be approved as a licensing model for CENP fuel designs.

It is requested, however, that the NRC consider mFDI as a viable tool to define the fuel duty in core design evaluations because mFDI takes account of nearly all plant parameters and conditions influencing waterside corrosion. While it is a concept that requires further development and verification, it is a valuable fuel cycle management design tool to evaluate projected corrosion performance and ensure oxide thickness will be acceptable.

Question #28:

Page 2–1 1st paragraph. Please supply the measured data range for the independent properties and the range required for CENP implementation. Please explain further the statement, "Measurements were made ... with the intended implementation." Please give more explanation of the statement about uncertainties. With regard to the last sentence. Please list all performance criteria or limits and how each is demonstrated to be consistent with or applicable to ZIRLO™.

Response:

Section 2.0 of CENPD-404-P is intended to give an overview of the detailed discussions, evaluations, results, justifications, and conclusions for implementation of approved ZIRLO™ properties and correlations into the Westinghouse CENP design and licensing analyses. Considerable information is provided in the CENPD-404-P Sections 3 through 7 which is intended to support this overview. However, additional explanations of the evaluation process and data and application ranges are provided below.

It has been the long-established practice within the industry to obtain fuel rod performance data and material property data at normal operating conditions, or as close as possible to accident conditions, to ensure that design and licensing analytical models provide an accurate prediction of performance parameters. Conditions of thermo-dynamic states and irradiation environments in Westinghouse PWR fuel designs and in CENP PWR fuel designs are, in fact, quite similar. For example, the range in fuel rod cladding temperatures, internal gas and external coolant pressures, core power levels, and fast and thermal neutron environments are similar. Consequently, it can be concluded that properties properly measured for application of ZIRLO™ in Westinghouse fuel designs will be applicable to CENP fuel designs.

However, it must also be recognized that properties and correlations may also be defined as a function of the independent parameters that are defined in an explicit or unique manner and/or measured and applied in a unique manner. Application of these properties and correlations in the CENP fuel designs must be consistent with the application in Westinghouse fuel designs. Considerable discussion of the ZIRLO™ properties, including identification of properties which were measured, properties which were not measured, and unique definitions of the independent correlation parameters have been presented in CENPD-404-P and additionally discussed in responses to Question Nos. 5, 6, 7, and 10. For example, the cladding thermal and mechanical properties measured by Westinghouse range from those that are simple functions of temperature (and measurements were made from room temperature, as appropriate, to operating temperatures in excess of the 550 °F to 750 °F range that the fuel rod cladding will experience in normal operation), to the more complex correlations such as cladding creep (where cladding temperatures, stresses, and neutron flux are also in about the same range over the length of the fuel rods in both Westinghouse and CENP plants). ZIRLO™ thermal conductivity was measured from [ ], thermal expansion from [ ]. 800 °C (212 °F However, the creep correlation independent parameters of temperature, stress, and fast neutron flux were defined in an explicit manner ([ ] clad model, use of specific stress and strain relationships, etc.), which was duplicated in the application in CENP analytical models. Also, the independent parameters in the creep correlation are not directly measured or controlled, but were calculated by Westinghouse using the fuel performance code PAD 4.0. Consequently, the implementation of the creep correlation in FATES3B would only be adequately verified by comparisons of FATES3B predictions to the creep data. Furthermore, it is noted that the FATES3B cladding temperatures and stresses also compared reasonably well with the PAD 4.0 temperatures and stresses. Thus, it was concluded that the ZIRLO™ creep correlation was appropriate for implementation into FATES3B. Finally, the evaluation of high temperature properties and correlations needed for ZIRLO™ behavior during accidents, such as a LOCA, was presented in detail in CENPD-404-P Section 6. Furthermore, for properties which were not measured for ZIRLO™, an evaluation of the impact was made to demonstrate that the precise values for these properties were not important, and in some cases the Zircaloy-4 property or correlation was found to be acceptable. Consequently, CENP concluded that the Westinghouse properties and correlations for ZIRLO™ were also applicable for CENP design and licensing models, and that sufficient information was available for implementation of ZIRLO™ in CENP fuel designs.

Some Westinghouse CENP design and licensing applications utilize uncertainties. CENP use of these uncertainties is not as extensive as in the Westinghouse fuel design and performance methodology. However, CENP methods require the application of (1) the uncertainty in rod growth for shoulder gap evaluations and (2) the uncertainty in clad creep for NCLO evaluations. It was concluded that both of these CENP needs were satisfied with the correlation uncertainties defined by Westinghouse.

Performance criteria and limits referred to are cladding design and licensing criteria and limits which include clad maximum stress limits, the strain limit, the fatigue limit, maximum pressure criterion (NCLO), the rod growth and shoulder gap criterion, and the clad collapse criterion. Some of these criteria and limits are based on ZIRLO™ properties (e.g., yield and ultimate stress, ductility, creep strength). Other criteria are not directly dependent (e.g., shoulder gap margin and collapse) on clad properties even though demonstration that the criteria are met requires modeling of ZIRLO™ properties. These properties and correlations are discussed in CENPD-404-P.

Question #29:

For CEA Ejection accidents, CENPD-404-P discusses the use of a 200 cal/gm limit (Section 7.3.1, Page 7-5). In today's environment this is not an acceptable approach. Provide additional discussion regarding the inherent conservatism in the CENP CEA ejection methodology with respect to using 200 cal/gm.

Response:

Current fuel failure criteria used for RIA assessments are an enthalpy insertion limit and, in some cases, DNB. These criteria result in some calculated fuel failure, but only in low to moderate burnup fuel.

Recent RIA testing has shown that high burnup fuel may fail at a relatively low enthalpy insertion threshold. The industry, NRC, and other regulatory bodies around the world are currently evaluating the potential RIA fuel failure criteria that might be applied to high burnup fuel rods.

While awaiting final rulemaking operating plants continue to evaluate the CEA ejection accident using previously approved methods and criteria. NRC has required plant-specific evaluations of the new data only for plants that have requested an extension of current burnup limits (Reference 29-1). Westinghouse recognizes that the fuel failure threshold of 200 cal/gm used for some CENP-designed plants may change when rulemaking is complete.

The lack of a definitive high burnup failure criteria for the CEA Ejection accident does not compromise plant safety because current analyses include many conservatisms which more than compensate for the uncertainty in the failure criteria. These conservatisms include the following.

- The CEA ejection analysis assumes that the ejected CEA, which is fully inserted, is the highest worth CEA allowed by the plant Technical Specifications. In practice bounding data for the ejected peaks and worth are used that greatly exceed the maximum calculated values.
- Not a single rod ejection has ever occurred in a commercial reactor. Even if a rod were to be ejected during critical operation, it would likely be a CEA which is held out of the core or is only partially inserted so that there would be little or no power excursion.
- The CABRI failure point which showed an unexpectedly low failure threshold occurred during a power excursion with a duration of about 10 ms. This is a much more rapid power excursion than would occur following the ejection of even a very high worth CEA. For CENP plants, the duration of the power excursion during a CEA ejection accident is about 50 ms for ejection of a high worth CEA and is much longer for the ejection of a lower worth CEA.
- Bounding values, including all uncertainties are used for all important input parameters including:

  Ejected CEA Worth
  Doppler Temperature Coefficient

Delayed Neutron Fraction
Moderator Temperature Coefficient
Other important initial conditions including RCS flow, pressure and temperature.

- The method of analysis is inherently conservative. The point kinetics synthesis method overestimates the core average power excursion somewhat and grossly overestimates the hot spot power excursion compared to a more detailed 3-D calculation. An ongoing study using 3-D space time methods shows that the maximum enthalpy insertion for a CENP-designed PWR is less than 100 cal/gm even when bounding values, including uncertainties, are used for all important input parameters. This result confirms the high degree of conservatism inherent in the standard methodology. This result is consistent with previous studies and with ongoing studies being performed for other reactor designs.

The evaluation of the CEA ejection accident included in CENPD-404-P is sufficient to demonstrate that the use of ZIRLO™ cladding in the analysis does not affect the results with respect to enthalpy deposition.

Reference:

29-1 NRC/NEI/Industry Meeting on High-Burnup Fuel Slides Presented by Larry Phillips (NRC). Rockville, Maryland, November 20, 1997.

APPENDIX A

CE NUCLEAR POWER LLC

METHODOLOGY REFERENCES AND ROADMAP SUPPORTING IMPLEMENTATION OF ZIRLO™ CLADDING MATERIAL IN CE NUCLEAR POWER FUEL ASSEMBLY DESIGNS

METHODOLOGY REFERENCES AND ROADMAP SUPPORTING IMPLEMENTATION OF ZIRLO™ CLADDING MATERIAL IN CE NUCLEAR POWER FUEL ASSEMBLY DESIGNS

Introduction:

CENPD-404-P, Rev. 0 collects and summarizes the ZIRLO™ cladding material properties and provides an evaluation of those properties and correlations CE Nuclear Power (CENP) intends to use in design and licensing analysis activities. Specific CENP methodologies impacted by the implementation of ZIRLO™ cladding are identified and descriptions of required substitutions for implementing ZIRLO™ are provided. The purpose of this supplemental information compilation is to provide a quick reference, a 'Roadmap', to be used in conjunction with the Nuclear Regulatory Commission (NRC) review of CENPD-404-P, Rev. 0 — "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs", dated January 2001. The 'Roadmap' links the various discussions provided in CENPD-404-P, Rev. 0, regarding clad material property usage, to the specific engineering discipline and methodology documentation previously reviewed and accepted for use by the NRC.

Discussion:

Table 1, CE Nuclear Power Methodology References, lists, by Engineering Discipline, the methodology references reviewed and accepted for use by the NRC. Following Table 1 is a sequentially numbered list of methodology references (Nos. 1 – 56) followed by a list of associated NRC Safety Evaluation Reports — SERs, references (Nos. 57 – 86). The numbers entered in Table 1, and the 'Roadmap' tables that follow, are keyed to this reference list.

Following the reference list is the beginning of the 'Roadmap' itself. The 'Roadmap' is composed of three (3) tiers of increasingly detailed information. The three tiers include:

Tier 1 - A high level overview that identifies (Table 2), by Engineering Discipline, the clad material properties having the most influence on the results of analyses performed. While other material properties may be employed, they are of secondary or lower significance with respect to influencing the ultimate answer obtained and are not addressed.

Tier 2 - Provides the next level of increased detail by looking at each of the Engineering Disciplines individually (Tables 3 – 6). The tables provided at this tier identify the computer code or type of analysis performed and which of the clad material properties are of importance. That is, the clad material properties that must be considered when using the ZIRLO™ cladding material.

Tier 3 - This final 'Roadmap' level (Tables 7 – 25) provides the actual linkage between the CENPD-404-P, Rev. 0 discussions of clad material properties identified in the preceding tables to discussions of those properties in the originally NRC accepted CENP methodology documentation references. In addition to the document linkage, these tables also identify the NRC SER associated with the original methodology reference and, more significantly, whether CENP determined it was necessary to utilize a ZIRLO™ specific property in analyses or whether continued use of a Zircaloy-4 cladding material property was acceptable. The Zircaloy-4 cladding material properties are those currently associated with the methodologies. Along these lines, OPTIN™ - is the CENP term for <u>O</u>ptimized <u>P</u>rocess Low <u>**Tin**</u> Zircaloy-4. OPTIN™ falls completely within the overall Zircaloy-4 material specification but with a tin content at the lower end of the Zircaloy-4 specification.

In the tables, an "***X*** " appears in the OPTIN™ column where the ZIRLO™ property is either the same as OPTIN™ or similar enough that actual use of the ZIRLO™ property is not warranted.

ZIRLO™ cladding material properties were developed by Westinghouse and submitted for NRC review and acceptance. The principal Westinghouse ZIRLO™ references are:

WCAP-8963-P-A	"Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis," August 1978
WCAP-10851-P-A	"Improved Fuel Performance Models for Westinghouse Fuel Rod Design and Safety Evaluations," August 1988
WCAP-12488-A	"Westinghouse Fuel Criteria Evaluation Process," October 1994
WCAP-12610-P-A	"Vantage+ Fuel Assembly Reference Core Report," April 1995
WCAP-15063-P-A, Rev. 1 w/errata	"Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)," July 2000

The methodologies of importance for ZIRLO™ implementation encompass the following engineering disciplines; 1) Fuel Mechanical Design, 2) Fuel Performance, 3) Emergency Core Cooling System (ECCS) Performance Analysis (Loss of Coolant Accident — LOCA) and 4) Non-LOCA Transient Analysis. Methodologies associated with Thermal Hydraulic Performance or Nuclear Engineering (i.e., physics) have been omitted since they are unaffected by the fuel rod cladding material. The methodologies employed by CENP within this group of disciplines are themselves individually discussed and have been reviewed and accepted for use by the NRC via more than 50 topical reports and their respective NRC Safety Evaluation Reports (SERs). One of the purposes of CENPD-404-P, Rev. 0 is to provide, in one place, the information needed for ZIRLO™ implementation, thereby precluding the need for revision by CENP, and review by the NRC, of the entire topical report record (see Reference list). It is CENP's intent that the affected individual topical reports and associated NRC SERs are, and will, remain the licensing basis for their subject methodology. Detailed report cross-references are provided in the attached 'Roadmap' (Tables 2 – 25), for both users and NRC reviewers. The 'Roadmap' delineates where the original comparable Zircaloy-4 cladding material discussions occur in the individual underlying base methodology topical reports. It is important to note that the methodology discussions provided in CENPD-404-P, Rev. 0 do not supercede the original methodology discussion and justifications found in the referenced underlying base topical reports upon which the NRC's acceptance was originally formulated. Methodology discussions provided in CENPD-404-P, Rev. 0 are only meant to provide a basic understanding of the methodology so that justification for implementation of ZIRLO™ cladding material properties into that methodology can be understood. Said more succinctly, ZIRLO™ cladding material has already been reviewed and accepted for use by the NRC in conjunction with Westinghouse design and safety analysis methodologies and nothing in CENPD-404-P, Rev. 0 should be construed to change in any way the underlying ZIRLO™ topical reports or their NRC acceptance. Likewise, CENP design and safety analysis methodologies have already been reviewed and accepted for use by the NRC, albeit for Zircaloy-4 (OPTIN™) cladding material, and nothing in CENPD-404-P, Rev. 0 should be construed to change in any way the underlying methodology topical reports or NRC acceptance. CENPD-404-P, Rev. 0 simply brings together, in one place, these previously NRC accepted topical reports and explains their linkage (i.e., ZIRLO™ into CENP fuel designs and safety analysis methodologies). Nothing in any of the previously NRC approved topical reports has been changed save the linking of the information in one to the other for the purpose of gaining NRC approval for the use of ZIRLO™ clad material in CENP designed fuel assemblies and the analysis of those fuel assemblies and the cores in which they reside.

TABLE 1
CE NUCLEAR POWER METHODOLOGY REFERENCES▲

ENGINEERING DISCIPLINE				
FUEL MECHANICAL DESIGN	FUEL PERFORMANCE	ECCS PERFORMANCE	NON-LOCA TRANSIENT ANALYSIS	HIGH BURNUP APPLICATION
4	2-3	14-18	28	12
39	5-11	19-24	44	13
42	38	25-27	45	48
43	49-50	28-31	52	54
47	53	32-34	56	
		35-37		
		41		
		46		
		51		
		55		

▲ — The methodology references provided are those that have been reviewed and accepted for use by the Nuclear Regulatory Commission. The references are predominately for performance of safety analyses or in support of the safety analysis methodologies. Since this compilation has been created in support of ZIRLO™ cladding material implementation, the list does not include methodologies associated with Thermal Hydraulic Performance or Nuclear Engineering (i.e., physics), which are unaffected by the fuel rod cladding material.

Design and Licensing Methodology References

CE Nuclear Power Methodology References

1. CEN-121(B)-P, "Methods of Analyzing Sequential Control Element Assembly Group Withdrawal Event for Analog Protected Systems", November, 1979 SER dated Sept 2, 1981
2. CEN-161(B)-P, Supplement 1-P-A, "Improvement to Fuel Evaluation Model," March 1992
3. CEN-161(B)-P-A, "Improvement to Fuel Evaluation Model," August 1989
4. CEN-183(B)-P, "Application of CENPD-198 to Zircaloy Component Dimensional Changes," September 1981
5. CEN-193(B)-P, "Partial Response to NRC Questions [Nos. 8, 10-13] on CEN-161(B)-P, Improvements to Fuel Evaluation Model," January 29, 1982
6. CEN-193(B)-P, Supplement 1-P, "Partial Response to NRC Questions [Nos. 7 and 9] on CEN-161(B)-P, Improvements to Fuel Evaluation Model," March 4, 1982
7. CEN-193(B)-P, Supplement 2-P, "Partial Response to NRC Questions [Nos. 1 - 6] on CEN-161(B)-P, Improvements to Fuel Evaluation Model," March 21, 1982
8. CEN-205(B)-P, "Response to NRC Questions on FATES-3 and the Calvert Cliffs 1 Cycle 6 Reload," April 23, 1982
9. CEN-220(B)-P, "Supplemental Information on FATES-3 Stored Energy Conservatism," October 5, 1982
10. CEN-345(B)-P, "Response to Questions on FATES3B," October 17, 1986
11. CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure," May 1990
12. CEN-382(B)-P-A, "Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 14x14 PWR Fuel," August 1993
13. CEN-386-P-A, "Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 16x16 PWR Fuel," August 1992
14. CENPD-132P, "Calculative Methods for the C-E Large Break LOCA Evaluation Model," August 1974
15. CENPD-132P, Supplement 1, "Calculational Methods for the C-E Large Break LOCA Evaluation Model," February 1975
16. CENPD-132-P, Supplement 2-P, "Calculational Methods for the C-E Large Break LOCA Evaluation Model," July 1975
17. CENPD-132, Supplement 3-P-A, "Calculative Methods for the C-E Large Break LOCA Evaluation Model for the Analysis of C-E and W Designed NSSS," June 1985
18. CENPD-132, Supplement 4-P, Revision 1, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," August 2000
19. CENPD-133P, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," August 1974
20. CENPD-133P, Supplement 1, "CEFLASH-4AS, A Computer Program for the Reactor Blowdown Analysis of the Small Break Loss of Coolant Accident," August 1974
21. CENPD-133P, Supplement 2, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis (Modifications)," February 1975

22. CENPD-133, Supplement 3-P "CEFLASH-4AS, A Computer Program for the Reactor Blowdown Analysis of the Small Break Loss of Coolant Accident," January 1977
23. CENPD-133, Supplement 4-P "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," April 1977
24. CENPD-133, Supplement 5-A "CEFLASH-4A, A FORTRAN77 Digital Computer Program for Reactor Blowdown Analysis," June 1985
25. CENPD-134P, COMPERC-II, A Program for Emergency Refill-Reflood of the Core", August 1974
26. CENPD-134P, Supplement 1, "COMPERC-II, A Program for Emergency Refill-Reflood of the Core (Modifications)," February 1975
27. CENPD-134, Supplement 2-A, "COMPERC-II, A Program for Emergency Refill-Reflood of the Core," June 1985
28. CENPD-135P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1974
29. CENPD-135P, Supplement 2, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program (Modifications)," February 1975
30. CENPD-135, Supplement 4-P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1976
31. CENPD-135-P, Supplement 5, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," April 1977
32. CENPD-137P, "Calculative Methods for the C-E Small Break LOCA Evaluation Model," August 1974
33. CENPD-137, Supplement 1-P, "Calculative Methods for the C-E Small Break LOCA Evaluation Model," January 1977
34. CENPD-137, Supplement 2-P-A, "Calculative Methods for the ABB CE Small Break LOCA Evaluation Model," April 1998
35. CENPD-138P, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," August 1974
36. CENPD-138P, Supplement 1, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," February, 1975
37. CENPD-138, Supplement 2-P, "PARCH A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," January, 1977
38. CENPD-139-P-A (includes Supplement 1-P), "C-E Fuel Evaluation Model Topical Report," April 1975
39. CENPD-178-P, Rev. 1-P, "Structural Analysis of Fuel Assemblies for Combined Seismic and Loss of Coolant Accident Loading," August 1981
40. CENPD-183-(A), "Loss of Flow, C-E Methods for Loss of Flow Analysis", May 12, 1982 (this is the date of the SER inside the cover of the Topical......although the Topical is dated June 1984)
41. CENPD-185-P-A, "Clad Rupture Behavior, LOCA Rupture Behavior of 16x16 Zircaloy Cladding," May 1975
42. CENPD-187-P, "CEPAN Method of Analyzing Creep Collapse of Oval Cladding," April 1976

43. CENPD-187-P, Supplement 1-P-A, "CEPAN Method of Analyzing Creep Collapse of Oval Cladding," June 1977

44. CENPD-188-A, "HERMITE A Multi-Dimensional Space-Time Kinetics Code for PWR Transients," July 1976

45. CENPD-190-A, "CEA Ejection, C-E Method for Control Element Assembly Ejection," July 1976

46. CENPD-213-P, "Reflood Heat Transfer, Application of FLECHT Reflood Heat Transfer Coefficients to C-E's 16x16 Fuel Bundles," January 1976

47. CENPD-225-P-A (includes Supplement s 1, 2 & 3), "Fuel and Poison Rod Bowing," June 1983

48. CENPD-269-P, Rev. 1-P, "Extended Burnup Operation of Combustion Engineering PWR Fuel," July 1984

49. CENPD-275-P, Revision 1-P-A, "C-E Methodology for Core Designs Containing Gadolinia-Urania Burnable Absorbers," May 1988.

50. CENPD-275-P, Revision 1-P, Supplement 1-P-A, "C-E Methodology for PWR Core Designs Containing Gadolinia-Urania Burnable Absorbers," April 1999.

51. CENPD-279, Supplement 6, "Annual Report on ABB CE ECCS Performance Evaluation Models," February 1995

52. CENPD-282-P-A, {Vols. 1 Thru 4 + Supplement 1}, "Technical Manual for the CENTS Code", Vols. 1,2 and 3 - February 1991 and Vol. 4 - December 1992, Supplement 1 – June 1993

53. CENPD-382-P-A, "Methodology for Core Designs Containing Erbium Burnable Absorbers," August 1993

54. CENPD-388-P, "Extension of the 1-Pin Burnup Limit to 65 MWD/kgU for ABB PWR Fuel with OPTIN™ Cladding," February 1998 {currently under NRC review}

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

56. LD-82-001, Enclosure 1-P, "CESEC, Digital Simulation of a Combustion Engineering Nuclear Steam Supply System," January 6, 1982

<u>**Nuclear Regulatory Commission Safety Evaluation Reports**</u>

57. A. C. Thadani (NRC) to A. E. Scherer (C-E), "Acceptance for Referencing C-E Topical Report CEN-372-P, Fuel Rod Maximum Allowable Gas Pressure (TAC No. 69231)", April 10, 1990

58. A. C. Thadani (NRC) to A. E. Scherer (C-E), "Generic Approval of C-E Topical Report CEN-386-P, Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 16x16 PWR Fuel", (TAC No. M82192), June 22, 1992

59. C. O. Thomas (NRC) to A. E. Scherer (C-E), "Combustion Engineering Thermal-Hydraulic Computer Program CESEC III", April 3, 1984

60. C. Thomas to A. Scherer, "Acceptance for Referencing of Topical Report CENPD-225 (P)", February 15, 1983

61. D. M. Crutchfield (NRC) to A. E. Scherer (C-E), "Safety Evaluation of Combustion Engineering ECCS Large Break Evaluation Model and Acceptance for Referencing of Related Licensing Topical Reports," July 31, 1986

62. E. J. Butcher (NRC) to A. E. Lundvall, Jr. (BG&E) regarding Safety Evaluation Report for "Extended Burnup Operation of Combustion Engineering PWR Fuel" (CENPD-269-P Revision 1-P), October 10, 1985

63. H. Bernard (NRC) to A. E. Scherer (C-E), "Acceptance for Referencing of Licensing Topical Report CENPD-178", August 6, 1982

64. K. Kniel (NRC) to A. E. Scherer (C-E), "Combustion Engineering Emergency Core Cooling System Evaluation Model," November 12, 1976

65. K. Kniel (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Report CENPD-138, Supplement 2-P," April 10, 1978

66. K. Kniel (NRC) to A. E. Scherer (C-E), August 2, 1976

67. Letter, A. C. Thadani (NRC) to A. E. Scherer (C-E), "Generic Approval of C-E Fuel Performance Code FATES3B (CEN-161(B)-P, Supplement 1-P)", November 6, 1991

68. Letter, A. C. Thadani (NRC) to S. A. Toelle (ABB-CE), "Generic Approval of the Acceptability of 1-Pin Burnup Limit of 60 MwD/Kg for C-E 14x14 PWR Fuel (CEN-382(B)-P) (TAC No. M86305)", June 11, 1993

69. Letter, K. Kniel (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Reports CENPD-133, Supplement 3-P and CENPD-137, Supplement 1-P," September 27, 1977

70. Letter, M. J. Virgilio (NRC) to S. A. Toelle (CE), "Acceptance for Referencing of Licensing Topical Report CENPD 282-P, Technical Manual for the CENTS Code (TAC No. M82718)", March 17, 1994

    R.C. Jones (NRC) to S.A. Toelle (CE), "Acceptance for Referencing of Licensing Topical Report CENPD-282-P Vol. 4, Technical Manual for the CENTS Code (TAC No. M85911)", February 24, 1995

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975

72. O. D. Parr (NRC) to A. E. Scherer (C-E), October 30, 1975

73. O. D. Parr (NRC) to A. E. Scherer (C-E), December 9, 1975

74. O. D. Parr (NRC) to A. E. Scherer (C-E), June 10, 1976

75. O. D. Parr (NRC) to A. E. Scherer (C-E), Untitled, February 10, 1976

76. O. D. Parr (NRC) to F. M. Stern (C-E), "C-E Fuel Evaluation Model Topical Report", December 4, 1974
77. R. A. Clark (NRC) to A. E. Lundvall, Jr. (BG&E), "Safety Evaluation of CEN-161 (FATES 3)," March 31, 1983
78. R. A. Clark (NRC) to A. E. Scherer (C-E), "Acceptance for Referencing of the Topical Report CEN-161, Improvements to Fuel Evaluation Model (FATES3)", May 22, 1989
79. R. L. Baer (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Report CENPD-135 Supplement No. 5," September 6, 1978
80. S. A. McNeil (NRC) to J. A. Tiernan (BG&E), "Safety Evaluation of Topical Report CEN-161(B)-P Supplement 1-P, 'Improvements to Fuel Evaluation Model'", February 4, 1987
81. S. A. Richards (NRC) to P. W. Richardson (Westinghouse CENP), "Safety Evaluation of Topical Report CENPD-132, Supplement 4, Revision 1, 'Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model' (TAC No. MA5660)," December 15, 2000
82. T. H. Essig (NRC) to I. C. Rickard (ABB CENP), "Acceptance for Referencing of the Topical Report CENPD-137(P), Supplement 2, 'Calculative Methods for the C-E Small Break LOCA Evaluation Model' (TAC No. M95687)," December 16, 1997
83. Ashok C. Thadani (NRC) to A. E. Scherer (C-E), "Acceptance for Referencing of Licensing Topical Report CENPD-275-P, Revision 1-P, "C-E Methodology for Core Designs Containing Gadolinia-Urania Burnable Absorbers"," May 14, 1988
84. Cynthia A. Carpenter (NRC) to I. C. Rickard (ABB CENP), "Acceptance for Referencing of Licensing Topical Report CENPD-275-P, Revision 1-P, Supplement 1-P,"C-E Methodology for PWR Core Designs Containing Gadolinia-Urania Burnable Absorbers" (TAC No. M99307)," April 5, 1999
85. Ashok C. Thadani (NRC) to S. A. Toelle (ABB CENP), "Acceptance for Referencing of Topical Report "Methodology for Core Designs Containing Erbium Burnable Absorbers" (TAC Nos. M79067 and M82959)," June 29, 1993
86. David H. Jaffe (NRC) to A. E. Lundvall, Jr. (BGE), Untitled, June 24, 1982

TABLE 2

CLADDING MATERIAL PROPERTIES USED IN ENGINEERING DISCIPLINES

TABLE 3

FUEL MECHANICAL DESIGN
CLADDING MATERIAL PROPERTY USAGE CATEGORIZATION

TABLE 4

FUEL PERFORMANCE
CLADDING MATERIAL PROPERTY USAGE CATEGORIZATION

TABLE 5

ECCS PERFORMANCE ANALYSES
CLADDING MATERIAL PROPERTY USAGE CATEGORIZATION

TABLE 6

NON-LOCA TRANSIENT ANALYSIS
CLADDING MATERIAL PROPERTY USAGE CATEGORIZATION

TABLE 7

FUEL MECHANICAL DESIGN – CEPAN COMPUTER CODE – CREEP COLLAPSE CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

42. CENPD-187-P, "CEPAN Method of Analyzing Creep Collapse of Oval Cladding", April 1976

43. CENPD-187-P, Supplement 1-P-A, "CEPAN Method of Analyzing Creep Collapse of Oval Cladding", June 1977

Safety Evaluation Report:

75. O. D. Parr (NRC) to A. E. Scherer (CE), Untitled, February 10, 1976

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 8

FUEL MECHANICAL DESIGN - SIGREEP COMPUTER CODE - AXIAL GROWTH - SHOULDER GAP CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

4. CEN-183(B)-P, "Application of CENPD-198 to Zircaloy Component Dimensional Changes", September 1981

Safety Evaluation Report:

86. David H. Jaffe (NRC) to A. E. Lundvall, Jr. (BGE), Untitled, June 24, 1982

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 9

FUEL MECHANICAL DESIGN – FUEL ROD BOW MODEL CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

47. CENPD-225-P-A (includes Supplements 1, 2 & 3), "Fuel and Poison Rod Bowing", June 1983

Safety Evaluation Report:

60. C. Thomas to A. Scherer, "Acceptance for Referencing of Topical Report CENPD-225 (P)", February 15, 1983

ID	Material Property	Model Utilized	CENPD-404-P	OPTIN Model Reference

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TABLE 10

FUEL MECHANICAL DESIGN – SEISMIC & LOCA LOADS MODEL CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

39. CENPD-178-P, Rev. 1-P, "Structural Analysis of Fuel Assemblies for Seismic and Loss of Coolant Accident Loading," August 1981

Safety Evaluation Report:

63. H. Bernard (NRC) to A. E. Scherer (CE), " Acceptance for Referencing of Licensing Topical Report CENPD-178," August 6, 1982

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 11

FUEL PERFORMANCE – FATES3B FUEL PERFORMANCE COMPUTER CODE CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

38. CENPD-139-P-A, "C-E Fuel Evaluation Model Topical Report," April 1975

2. CEN-161(B)-P-A, "Improvement to Fuel Evaluation Model," August 1989

11. CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure," May 1990

Safety Evaluation Report:

76. O. D. Parr (NRC) to F. M. Stern (C-E), "C-E Fuel Evaluation Model Topical Report", December 4, 1974

77. R. A. Clark (NRC) to A. E. Lundvall, Jr. (BG&E), "Safety Evaluation of CEN-161 (FATES3)," March 31, 1983

78. R. A. Clark (NRC) to A. E. Scherer (CE), "Acceptance for Referencing of the Topical Report CEN-161, Improvements to Fuel Evaluation Model (FATES3)", May 22, 1989

57. A. C. Thadani (NRC) to A. E. Scherer (CE), "Acceptance for Referencing C-E Topical Report CEN-372-P, Fuel Rod Maximum Allowable Gas Pressure (TAC No. 69231)", April 10, 1990

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 12

FUEL PERFORMANCE – INTEG DNB PROPAGATION
CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

11. CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure", May 1990

Safety Evaluation Report:

57. A. C. Thadani (NRC) to A. E. Scherer (CE), "Acceptance for Referencing C-E Topical Report CEN-372-P, Fuel Rod Maximum Allowable Gas Pressure (TAC No. 69231)", April 10, 1990

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

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TABLE 13

ECCS Performance – CEFLASH-4A
LBLOCA Blowdown Hydraulics
Cladding Material Property Cross-Reference

Topical Report:

19. CENPD-133P, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," August 1974
21. CENPD-133P, Supplement 2, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis (Modifications)," February 1975
23. CENPD-133, Supplement 4-P "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," April 1977
24. CENPD-133, Supplement 5-A "CEFLASH-4A, A FORTRAN77 Digital Computer Program for Reactor Blowdown Analysis," June 1985
18. CENPD-132, Supplement 4-P, Revision 1, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," August 2000

Safety Evaluation Report:

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975
81. S. A. Richards (NRC) to P. W. Richardson (Westinghouse CENP), "Safety Evaluation of Topical Report CENPD-132, Supplement 4, Revision 1, 'Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model' (TAC No. MA5660)," Dec. 15, 2000
61. D. M. Crutchfield (NRC) to A. E. Scherer (C-E), "Safety Evaluation of Combustion Engineering ECCS Large Break Evaluation Model and Acceptance for Referencing of Related Licensing Topical Reports," July 31, 1986

ID	Material Property	Model Utilized		CENPD-404-P	Zircaloy-4 Model Reference
		ZIRLO	Zirc-4		

TABLE 13

ECCS Performance – CEFLASH-4A
LBLOCA Blowdown Hydraulics
Cladding Material Property Cross-Reference

Topical Report:

19. CENPD-133P, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," August 1974
21. CENPD-133P, Supplement 2, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis (Modifications)," February 1975
23. CENPD-133, Supplement 4-P "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," April 1977
24. CENPD-133, Supplement 5-A "CEFLASH-4A, A FORTRAN77 Digital Computer Program for Reactor Blowdown Analysis," June 1985
18. CENPD-132, Supplement 4-P, Revision 1, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," August 2000

Safety Evaluation Report:

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975
81. S. A. Richards (NRC) to P. W. Richardson (Westinghouse CENP), "Safety Evaluation of Topical Report CENPD-132, Supplement 4, Revision 1, 'Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model' (TAC No. MA5660)," Dec. 15, 2000
61. D. M. Crutchfield (NRC) to A. E. Scherer (C-E), "Safety Evaluation of Combustion Engineering ECCS Large Break Evaluation Model and Acceptance for Referencing of Related Licensing Topical Reports," July 31, 1986

ID	Material Property	Model Utilized	CENPD-404-P	Zircaloy-4 Model Reference

[ ]

TABLE 14

ECCS Performance – CEFLASH-4AS
SBLOCA Blowdown Hydraulics
Cladding Material Property Cross-Reference

Topical Report:

20. CENPD-133P, Supplement 1, "CEFLASH-4AS, A Computer Program for the Reactor Blowdown Analysis of the Small Break Loss of Coolant Accident," August 1974
22. CENPD-133, Supplement 3-P "CEFLASH-4AS, A Computer Program for the Reactor Blowdown Analysis of the Small Break Loss of Coolant Accident," January 1977

Safety Evaluation Report:

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975
69. K. Kniel (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Reports CENPD-133, Supplement 3-P and CENPD-137, Supplement 1-P," September 27, 1977

ID	Material Property	Model Utilized		CENPD-404-P	Zircaloy-4 Model Reference
		ZIRLO	Zirc-4		

TABLE 15

ECCS PERFORMANCE – COMPERC-II
LBLOCA REFILL/REFLOOD HYDRAULICS
Cladding Material Property Cross-Reference

Topical Report:

25. CENPD-134P, COMPERC-II, A Program for Emergency Refill-Reflood of the Core", August 1974
26. CENPD-134P, Supplement 1, "COMPERC-II, A Program for Emergency Refill-Reflood of the Core (Modifications)," February 1975
27. CENPD-134, Supplement 2-A, "COMPERC-II, A Program for Emergency Refill-Reflood of the Core," June 1985

Safety Evaluation Report:

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975
61. D. M. Crutchfield (NRC) to A. E. Scherer (C-E), "Safety Evaluation of Combustion Engineering ECCS Large Break Evaluation Model and Acceptance for Referencing of Related Licensing Topical Reports," July 31, 1986

ID	Material Property	Model Utilized		CENPD-404-P	Zircaloy-4 Model Reference
		ZIRLO	Zirc-4		

TABLE 16

ECCS Performance – PARCH
LBLOCA Steam Cooling HTC and
SBLOCA Hot Rod Heatup (Pool Boiling)
Cladding Material Property Cross-Reference

Topical Report:

35. CENPD-138P, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," August 1974
36. CENPD-138P, Supplement 1, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," February, 1975
37. CENPD-138, Supplement 2-P, "PARCH A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," January, 1977

Safety Evaluation Report:

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975
65. K. Kniel (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Report CENPD-138, Supplement 2-P," April 10, 1978

ID	Material Property	Model Utilized		CENPD-404-P	Zircaloy-4 Model Reference
		ZIRLO	Zirc-4		

TABLE 17

ECCS Performance – STRIKIN-II
LBLOCA Hot Rod Heatup and
SBLOCA Hot Rod Heatup (Forced Convection)
Cladding Material Property Cross-Reference

Topical Report:

28. CENPD-135P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1974
29. CENPD-135P, Supplement 2, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program (Modifications)," February 1975
30. CENPD-135, Supplement 4-P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1976
31. CENPD-135-P, Supplement 5, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," April 1977
18. CENPD-132, Supplement 4-P, Revision 1, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," August 2000

Safety Evaluation Report:

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975
64. K. Kniel (NRC) to A. E. Scherer (C-E), "Combustion Engineering Emergency Core Cooling System Evaluation Model," November 12, 1976
79. R. L. Baer (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Report CENPD-135 Supplement No. 5," September 6, 1978
81. S. A. Richards (NRC) to P. W. Richardson (Westinghouse CENP), "Safety Evaluation of Topical Report CENPD-132, Supplement 4, Revision 1, 'Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model' (TAC No. MA5660)," December 15, 2000

ID	Material Property	Model Utilized		CENPD-404-P	Zircaloy-4 Model Reference
		ZIRLO	Zirc-4		

TABLE 17

ECCS Performance – STRIKIN-II
LBLOCA Hot Rod Heatup and
SBLOCA Hot Rod Heatup (Forced Convection)
Cladding Material Property Cross-Reference

Topical Report:

28. CENPD-135P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1974
29. CENPD-135P, Supplement 2, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program (Modifications)," February 1975
30. CENPD-135, Supplement 4-P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1976
31. CENPD-135-P, Supplement 5, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," April 1977
18. CENPD-132, Supplement 4-P, Revision 1, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," August 2000

Safety Evaluation Report:

71. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975
64. K. Kniel (NRC) to A. E. Scherer (C-E), "Combustion Engineering Emergency Core Cooling System Evaluation Model," November 12, 1976
79. R. L. Baer (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Report CENPD-135 Supplement No. 5," September 6, 1978
81. S. A. Richards (NRC) to P. W. Richardson (Westinghouse CENP), "Safety Evaluation of Topical Report CENPD-132, Supplement 4, Revision 1, 'Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model' (TAC No. MA5660)," December 15, 2000

ID	Material Property	Model Utilized	CENPD-404-P	Zircaloy-4 Model Reference

TABLE 18

NON-LOCA TRANSIENT ANALYSIS – CENTS COMPUTER CODE CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

52. CENPD-282-P-A, {Vols. 1 to 4 + Supplement 1}, "Technical Manual for the CENTS Code", Vols. 1,2 and 3 - February 1991 and Vol. 4 - December 1992, Supplement 1 - June 1993

Safety Evaluation Report:

70. Letter, M. J. Virgilio (NRC) to S. A. Toelle (CE), "Acceptance for Referencing of Licensing Topical Report CE-NPD 282-P, Technical Manual for the CENTS Code (TAC No. M82718)", March 17, 1994

R.C. Jones (NRC) to S.A. Toelle (CE), "Acceptance for Referencing of Licensing Topical Report CENPD-282-P Vol. 4, Technical Manual for the CENTS Code (TAC No. M85911)", February 24, 1995

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

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TABLE 19

NON-LOCA TRANSIENT ANALYSIS – CESEC COMPUTER CODE CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

56. Enclosure 1-P LD-82-001, "CESEC, Digital Simulation of a Combustion Engineering Nuclear Steam Supply System," January 6, 1982

Safety Evaluation Report:

59. C. O. Thomas (NRC) to A. E. Scherer (CE), "Combustion Engineering Thermal-Hydraulic Computer Program CESEC III", April 3, 1984

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

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TABLE 20

NON-LOCA TRANSIENT ANALYSIS – HERMITE COMPUTER CODE CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

44. CENPD-188-A, "HERMITE A Multi-Dimensional Space-Time Kinetics Code for PWR Transients", July 1976

Safety Evaluation Report:

74. O. D. Parr (NRC) to A. E. Scherer (CE), June 10, 1976

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 21

NON-LOCA TRANSIENT ANALYSIS – CEA EJECTION EVENT CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

45. CENPD-190-A, "CEA Ejection, C-E Method for Control Element Assembly Ejection", July 1976
28. CENPD-135-P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1974

Safety Evaluation Report:

74. O. D. Parr (NRC) to A. E. Scherer (CE), June 10, 1976

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 22

EXTENDED BURNUP – 16X16 FUEL BURNUP TO 60 MWD/KGU
CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

13. CEN-386-P-A, "Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 16x16 PWR Fuel", August 1992

Safety Evaluation Report:

58. A. C. Thadani (NRC) to A. E. Scherer (CE), "Generic Approval of C-E Topical Report CEN-386-P, Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 16x16 PWR Fuel", (TAC No. M82192), June 22, 1992

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 23

EXTENDED BURNUP OPERATION
CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

48. CENPD-269-P, Rev. 1-P, "Extended Burnup Operation of Combustion Engineering PWR Fuel," July 1984

Safety Evaluation Report:

62. E. J. Butcher (NRC) to A. E. Lundvall, Jr. (BGE) regarding Safety Evaluation Report for "Extended Burnup Operation of Combustion Engineering PWR Fuel" (CENPD-269-P Revision 1-P), October 10, 1985

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 24

EXTENDED BURNUP – 14x14 FUEL BURNUP TO 60 MWD/KGU CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

12. CEN-382(B)-P-A, "Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 14x14 PWR Fuel", August 1993

Safety Evaluation Report:

68. Letter, A. C. Thadani (NRC) to S. A. Toelle (ABB-CE), "Generic Approval of the Acceptability of 1-Pin Burnup Limit of 60 MwD/Kg for C-E 14x14 PWR Fuel (CEN-382(B)-P) (TAC No. M86305)", June 11, 1993

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

TABLE 25

EXTENDED BURNUP OPERATION
CLADDING MATERIAL PROPERTY CROSS-REFERENCE

Topical Report:

54. CENPD-388-P, "Extension of the 1-Pin Burnup Limit to 65 MWD/kgU for ABB PWR Fuel with OPTIN™ Cladding," February 1998

Safety Evaluation Report:

Currently under NRC Review

ID	Material Property	Model Utilized		CENPD-404-P	OPTIN Model Reference
		ZIRLO	OPTIN		

CENPD-404-NP-A

U.S. Nuclear Regulatory Commission

Safety Evaluation Report

Required Materials

5. Letter, LD-2001-0046, "Ductility of ZIRLO™ and Zircaloy-4 After High Temperature Oxidation in Steam"

Westinghouse Electric Company, LLC

2000 Day Hill Road
Windsor, CT 06095
USA

LD-2001-0046, Rev. 0
August 10, 2001

Mr. John S. Cushing, Project Manager
U. S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Subject: Ductility of ZIRLO™ and Zircaloy-4 after High Temperature Oxidation in Steam
(Contains Proprietary Information)

Dear Mr. Cushing:

Discussions with the NRC on CENPD-404-P, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," resulted in a request for additional information on the LOCA basis testing of ZIRLO™ cladding. This letter provides the requested information in Enclosure 1-P, "Ductility of ZIRLO™ and Zircaloy-4 after High Temperature Oxidation in Steam."

A non-proprietary version of Enclosure 1-P is provided in Enclosure 2. Three copies of each Enclosure are provided.

Westinghouse requests that the proprietary information in Enclosure 1-P be withheld from public disclosure in accordance with the provisions of 10 CFR 2.790 and that it be appropriately safeguarded. The reasons for classifying this information proprietary are delineated in the enclosed affidavit (Enclosure 3).

If you have any questions, please contact George Hess at (860) 731-6285 or Chuck Molnar at (860) 731-6286.

Sincerely yours,

G. Hess for

P. W. Richardson, Project Manager
Windsor Nuclear Licensing

cc: M. Chatterton (NRC, w/attachments)
R. Caruso (NRC, w/o attachments)

Enclosure 2 to LD-2001-0046, Rev. 0, August 10, 2001

Ductility of ZIRLO™ and Zircaloy-4 after High Temperature Oxidation in Steam

WESTINGHOUSE ELECTRIC COMPANY LLC

DUCTILITY OF ZIRLO™ AND ZIRCALOY-4 AFTER HIGH TEMPERATURE OXIDATION IN STEAM

INTRODUCTION

On January 26, 2001, the Nuclear Regulatory Commission (NRC) provided Westinghouse Electric Company LLC (WEC) with a copy of a technical paper by J. Bohmert entitled "Embrittlement of ZrNb1 at Room Temperature After High-Temperature Oxidation in Steam Atmosphere" (Reference 2). The paper questioned the validity of the 17% oxidation criteria for loss-of-coolant accident (LOCA) conditions for ZrNb1 fuel rod cladding. The NRC also requested either a meeting to discuss the subject or, alternatively, a written response providing information that WEC believed to be relevant to the subject. WEC met with the NRC twice to discuss the subject, February, 2001 and May, 2001 and has also prepared this report documenting the results of testing performed at Company facilities to further characterize the issue; specifically with respect to its ZIRLO™ cladding material.

SUMMARY

For a given oxide thickness, high temperature steam oxidation resulted in similar oxygen pickup in both ZIRLO™ and Zircaloy-4. The oxides remained black and adherent for all specimens. Additionally, oxygen was found to segregate to stabilize the alpha phase in both alloys. Hardness of the stabilized alpha phase is higher than the lower oxygen containing prior beta phase. Hydrogen pickup in both alloys was low (<100 ppm) following high temperature steam oxidation. ZIRLO™ and Zircaloy-4 show the same trends in ring compression tests at both room temperature and 275°F. Consequently, Westinghouse concludes that the validity of the 17% oxidation criteria for loss-of-coolant accident (LOCA) conditions for ZrNb1 fuel rod cladding raised by the Bohmert paper have no bearing on the performance of ZIRLO™ cladding material. Therefore, the existing 10 CFR 50.46 regulatory criteria regarding LOCAs remains applicable for ZIRLO™.

EXPERIMENTAL

Experiments were performed by the Westinghouse Electric Company (WEC), Science and Technology Department to assess the ductility of ZIRLO™ cladding following high temperature steam oxidation. Cladding samples of both ZIRLO™ and Zircaloy-4 were oxidized in high temperature steam from 1500°F to 2300°F for times ranging from 3 to 30 minutes. Cladding ductility was evaluated by a ring compression test as described by Hobson and Rittenhouse (Reference 1) and Böhmert (Reference 2).

High Temperature Steam Furnace

Figure 1 shows the high temperature steam oxidation facility used to prepare oxidized cladding specimens for subsequent testing. The high temperature steam environment was inside a 30-inch long Alloy 690 tube (0.875-inch OD). The tube was centered inside a vertical three-zone clamshell resistance furnace with the temperature of each zone controlled by a spring loaded Type K sheathed thermocouple in contact with the outer diameter of the Alloy 690 tube. The ends of the tube were capped with Swagelok fittings. Two inlet lines on the bottom fitting provided access for water/steam and for helium to purge the tube of air prior to heating. There was one outlet line on the top fitting that served as an exhaust port.

The source of the steam was deaerated water from an autoclave heated to 220°F. A high pressure metering pump was used to pump the autoclave water at a rate of 120 ml water/minute. The water was pumped into a preheat furnace maintained at about 315°F. from which the water/steam entered the bottom of the Alloy 690 tube. The bottom fitting on the tube rested on a ceramic brick and was heated to about 400°F by a small heating element to minimize condensation of the inlet steam.

Sample temperature was monitored by a Type K sheathed thermocouple (0.125-inch diameter) fed through the bottom end cap. A 0.74-inch diameter disk with a 0.125-inch hole in the center was slid over the sheathing and served as a support for the cladding specimens (see Figure 2). The specimens were placed on top of each other with the thermocouple in the ID of the tubing. Additional holes drilled in the disk allowed steam to flow up the Alloy 690 tube past the specimens.

High Temperature Steam Oxidation

Cladding specimens of both Zircaloy-4 and ZIRLO™ were prepared for high temperature steam oxidation. Cladding size was 0.374-inch OD with Zircaloy-4 having a nominal length of 1.25 inches and ZIRLO™ having a nominal length of 1.375 inches. Specimen preparation included engraving an identification number near the tube end, deburring the cut ends, measuring tube dimensions, cleaning the tubes according to the procedure used for autoclave testing, and weighing the specimens. After cleaning, specimens were handled only with gloves or tweezers.

Following insertion of the specimens inside the Alloy 690 tube, the tube was purged with helium to displace the air prior to heating. Typically, two specimens (one ZIRLO™ and one Zircaloy-4) were oxidized during the same furnace run. The water flow was started and the helium flow was terminated when the furnace temperature reached about 500°F. Delaying the start of the water flow minimized condensation of the steam during startup of the furnace. The furnace was then heated to the target oxidation temperature. Nominal heating rates between 500°F and the target temperatures were about 1°F/second. After holding the specimens at temperature for the specified time, the clam shell furnace was opened and the Alloy 690 tube and specimens cooled to room temperature. Cooling rates between the target temperature and 1000°F averaged about 9°F/second. In all cases, the ZIRLO™ and Zircaloy-4 specimens had a black, adherent oxide following the high temperature steam exposure. Following the oxidation run, the specimens were weighed to measure the total oxygen and hydrogen pickup..

Metallography

Three specimens (nominally 0.22 to 0.23 inch long) were sectioned from the oxidized tubes. The end piece was used for metallographic examination of the oxidized specimen and the two interior sections were used for ring compression tests. The remaining material was used for hydrogen analysis on selected specimens.

Transverse ring sections were mounted in epoxy, mechanically ground, and polished. Oxide thickness on the outer and inner diameters was measured on as-polished specimens at eight equally spaced locations around the tube. The mounts were then etched to reveal cladding microstructure consisting of stabilized alpha and prior beta phases. Vickers microhardness measurements using a 50 gram load were obtained across the cladding wall to assess oxygen penetration in the stabilized alpha and prior beta phases.

Ring Compression Tests

Ring compression tests were performed at room temperature and 275°F. The ring compression specimen was placed between two flat dies and then compressed by displacement of the upper die at a speed of 0.1 inch/minute. The load and displacement were recorded on a x-y recorder and digitally captured by a computer. Typical load displacement plots are shown in Figures 3 and 4 for ZIRLO™ and Zircaloy-4, respectively. Failure of the test specimen was characterized by through wall cracks at four locations around the circumference. The load dropped to zero upon tube failure.

A few initial tests were terminated following a displacement of 130 mils. Subsequent tests were terminated at tube failure or when the displacement was sufficient for the opposing ID surfaces to come in contact. This was noted by the sudden increase in load as shown in Figures 3a and 4a. Results of the ring compression test were maximum load and total displacement at tube failure or test termination.

RESULTS

High Temperature Steam Oxidation:

The high temperature steam oxidation results are documented in Tables 1 and 2. Included in the table are nominal oxidation temperature and time, specimen weight gain and measured oxide thickness. Figure 5 shows at plot of measured oxide thickness vs. weight gain. The relation between weight gain and oxide thickness is 20.4 mg/dm^2 for 1 micron and 20.7 mg/dm^2 for 1 micron for ZIRLO™ and Zircaloy-4, respectively. These relationships were derived from the slope of the best-fit line passing through the origin. These are significantly higher than the theoretical relationship of 14.7 mg/dm^2 for 1 micron of oxide if all of the oxygen is used to form oxide. The deviation from the theoretical value is consistent with significant oxygen pickup in the metal. In addition, the results indicate similar oxygen pickup in the metal for ZIRLO™ and Zircaloy-4 for comparable oxide thickness.

The equivalent cladding reacted (t_{eq}) was calculated by the following equation and tabulated in Tables 1 and 2.

$$t_{eq} = \frac{2\,W(Zr)\,\Delta m}{W(O_2)\,\rho(Zr)\,A\,t}$$

where:

W(Zr)	=	atomic weight of Zr (91.22 g)
$W(O_2)$	=	molecular weight of O_2 (32 g)
ρ(Zr)	=	density of Zr (6.51 g/cm^3)
A	=	surface area (cm^2)
t	=	initial cladding thickness (0.05715 cm)
Δm	=	measured weight gain (g)

The equivalent cladding reacted for each sample was calculated based upon specimen weight gain. Calculated values ranged from 0.03 to 0.39.

Metallography

The tubes oxidized at the lower temperatures (≤1700°F for ZIRLO™ and ≤1800°F for Zircaloy-4) exhibited alpha recrystallized or alpha + beta microstructures while at higher temperatures (≥1800°F for ZIRLO™ and ≥1950°F for Zircaloy-4), the microstructures consisted of oxygen stabilized alpha and prior beta. Vickers microhardness (50-gram load) was used to assess the relative hardness of these two phases across the cladding wall. Hardness profiles are shown in Figure 6 for ZIRLO™ and Zircaloy-4.

Micrographs of the hardness traces in ZIRLO™ are shown in Figure 7. The larger impressions in the prior beta phase indicate that phase is softer than the stabilized alpha. The hardness measurements on samples W9 and W8 reflect the presence of prior beta across most of the cladding wall. The increased hardness near the oxide is consistent with the presence of stabilized alpha due to oxygen diffusion into the cladding. The high hardness across the entire wall of sample W14 is consistent with the presence of stabilized alpha. Further increase in hardness near the oxide-to-metal interface suggests increased oxygen levels as the oxide is approached.

Figure 8 shows micrographs of the hardness impressions for Zircaloy-4 cladding. Again, larger impressions are observed in the softer prior beta material and smaller impressions in the stabilized alpha. The single low hardness value in the microhardness profile in Figure 6b for sample D14 occurred in a region of prior beta as show in Figure 8c.

For both Zircaloy-4 and ZIRLO™, there was no indication of precipitated hydrides in the microstructures suggesting the hydrogen pickup to be low. Selected samples were sent to Specialty Metals Plant in Blairsville for hydrogen analysis. The samples were analyzed with the oxide intact. Results are tabulated in Table 3 and show very low (<100 ppm) hydrogen pickup.

Ring Compression Tests

Tables 4 and 5 summarize the results of the ring compression tests and include maximum load, maximum displacement, and relative displacement. Relative displacement is maximum displacement divided by the initial cladding diameter of 0.374 inch. Plots of relative displacement vs. t_{eq} are shown in Figure 9 for both the room temperature and 275°F tests. The relative displacements decreased with increasing t_{eq} for both ZIRLO™ and Zircaloy-4.

DISCUSSION

High temperature steam oxidation of ZIRLO™ and Zircaloy-4 resulted in oxide formation on the outer surfaces of the cladding along with oxygen pickup in the metal. The measured weight gain of the samples resulted almost exclusively from the uptake of oxygen as the hydrogen measurements (see Table 3) revealed low levels of hydrogen. Deviation from the theoretical line relating oxide thickness and weight gain (Figure 5) is consistent with oxygen pickup in the metal for both ZIRLO™ and Zircaloy-4. The microhardness measurements further confirm the increased oxygen in the metal following high temperature steam oxidation. The oxygen stabilizes the alpha phase resulting in higher hardness in that phase compared to lower oxygen in the prior beta phase.

The results from the ring compression tests are shown in Figure 9. Also included on the figures is a line at 10% relative displacement indicating Böhmert's criteria (Reference 2) for brittle behavior in room temperature tests. Relative displacements below 10% were considered brittle and displacements above 10% were classified as ductile or partially ductile. The ring compression test results for both ZIRLO™ and Zircaloy-4 are similar with both alloys surpassing the 10% criteria at t_{eq} of 17% (0.17).

CONCLUSIONS

1. High temperature steam oxidation resulted in similar oxygen pickup in ZIRLO™ and Zircaloy-4 for a given oxide thickness. Oxides remained black and adherent for all specimens.
2. Oxygen segregates to stabilize the alpha phase in both alloys. Hardness of the stabilized alpha phase is higher than the lower oxygen containing prior beta phase.
3. Hydrogen pickup was low (<100 ppm) in both alloys following high temperature steam oxidation
4. ZIRLO™ and Zircaloy-4 show the same trends in ring compression tests at both room temperature and 275°F.

REFERENCES

1. Hobson, D. O., Rittenhouse, P. L., Embrittlement of Zircaloy Clad Fuel Rods by Steam during LOCA Transients, ORNL 4758, Oak Ridge National Laboratory, Oak Ridge 1972.
2. Böhmert, J., Embrittlement of ZrNb1 at room temperature after high-temperature oxidation in steam atmosphere, Kerntechnik, **57**, 1992, 55-58.

TABLE 1

HIGH TEMPERATURE STEAM OXIDATION OF ZIRLO™ CLADDING (LOT S93-6374Z)

ID #	STEAM RUN	NOM. TEMP. (°F)	NOM. TIME (min)	WT. GAIN (mg/dm^2)	MET. OXIDE (micron)	t(eq)

TABLE 2

HIGH TEMPERATURE STEAM OXIDATION OF ZIRCALOY-4 CLADDING (LOT S72-2170A)

ID #	STEAM RUN	NOM. TEMP. (°F)	NOM. TIME (min)	WT. GAIN (mg/dm^2)	MET. OXIDE (micron)	t(eq)

TABLE 3

HYDROGEN ANALYSIS OF ZIRLO™ AND ZIRCALOY-4 FOLLOWING HIGH TEMPERATURE STEAM OXIDATION

ALLOY	ID #	TEMP. (°F)	TIME (min.)	HYDROGEN (ppm)

TABLE 4

RING COMPRESSION TEST RESULTS FROM ZIRLO™ CLADDING (LOT S93-6374Z)

ID #	T(F)	T(MIN)	T(EQ)	ROOM TEMPERATURE			275 °F		
				MAX LOAD (lb)	MAX DISP (mils)	REL DISP	MAX LOAD (lb)	MAX DISP (mils)	REL DISP

TABLE 5

RING COMPRESSION TEST RESULTS FROM ZIRCALOY-4 CLADDING (LOT S72-2170A)

ID #	T(F)	T(MIN)	T(EQ)	ROOM TEMPERATURE			275 °F		
				MAX LOAD (lb)	MAX DISP (mils)	REL DISP	MAX LOAD (lb)	MAX DISP (mils)	REL DISP

FIGURE 1

SCHEMATIC DIAGRAM OF HIGH TEMPERATURE STEAM OXIDATION FACILITY

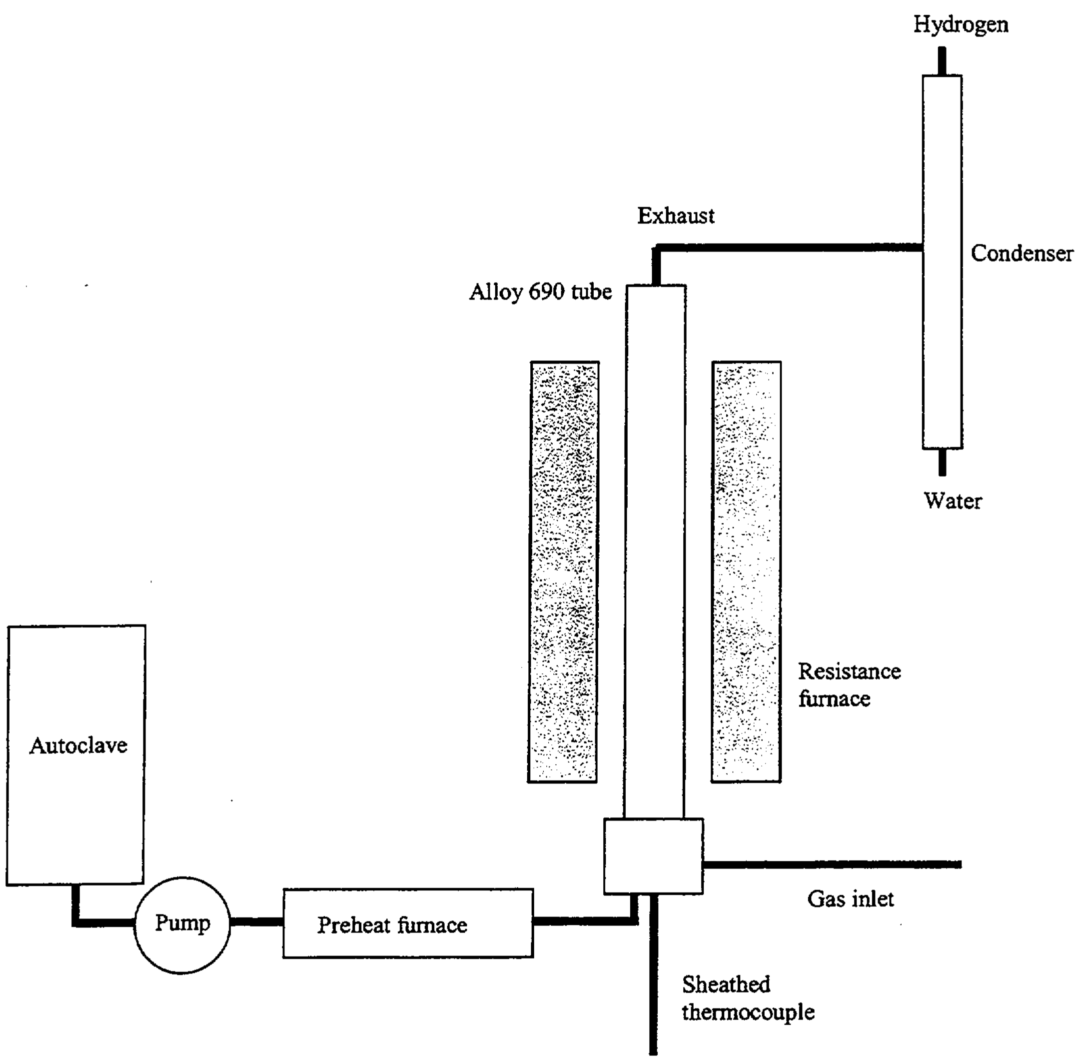


FIGURE 2

SPECIMEN HOLDER FOR HIGH TEMPERATURE STEAM OXIDATION. TWO TUBE SPECIMENS ARE STACKED VERTICALLY ON A PERFORATED DISK WITH THE THERMOCOUPLE LOCATED IN THE TUBE ID

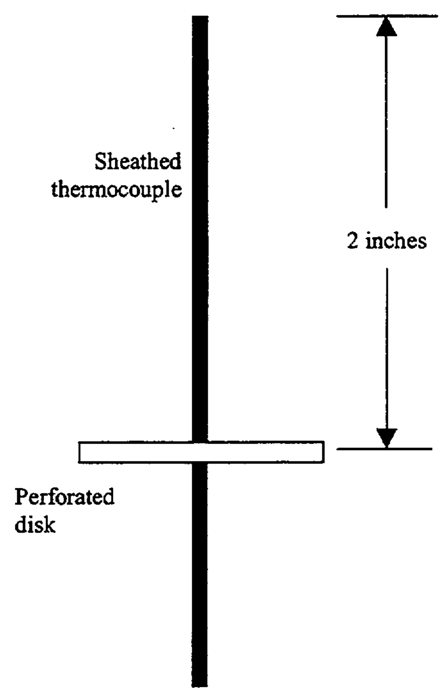


FIGURE 3

RING COMPRESSION TEST LOAD VS. DISPLACEMENT (275°F) FOR ZIRLO™ ™ CLADDING SAMPLES OXIDIZED IN HIGH TEMPERATURE STEAM AT THE FOLLOWING NOMINAL CONDITIONS

(A) 1800°F/5 MINUTES, (B) 2000°F/10 MINUTES, (C) 1950°F/30 MINUTES, AND (D) 2000°F/30 MINUTES

FIGURE 3: (CONT.)

FIGURE 4

RING COMPRESSION TEST LOAD VS. DISPLACEMENT (275°F) FOR ZIRCALOY-4 CLADDING SAMPLES OXIDIZED IN HIGH TEMPERATURE STEAM AT THE FOLLOWING NOMINAL CONDITIONS

(A) 1800°F/5 MINUTES, (B) 2000°F/10 MINUTES, (C) 1950°F/30 MINUTES, AND (D) 2000°F/30 MINUTES

FIGURE 4: (CONT.)

FIGURE 5

MEASURED WEIGHT GAIN VERSUS MEASURED OXIDE THICKNESS FOR ZIRLO™ AND ZIRCALOY-4 OXIDIZED IN HIGH TEMPERATURE STEAM

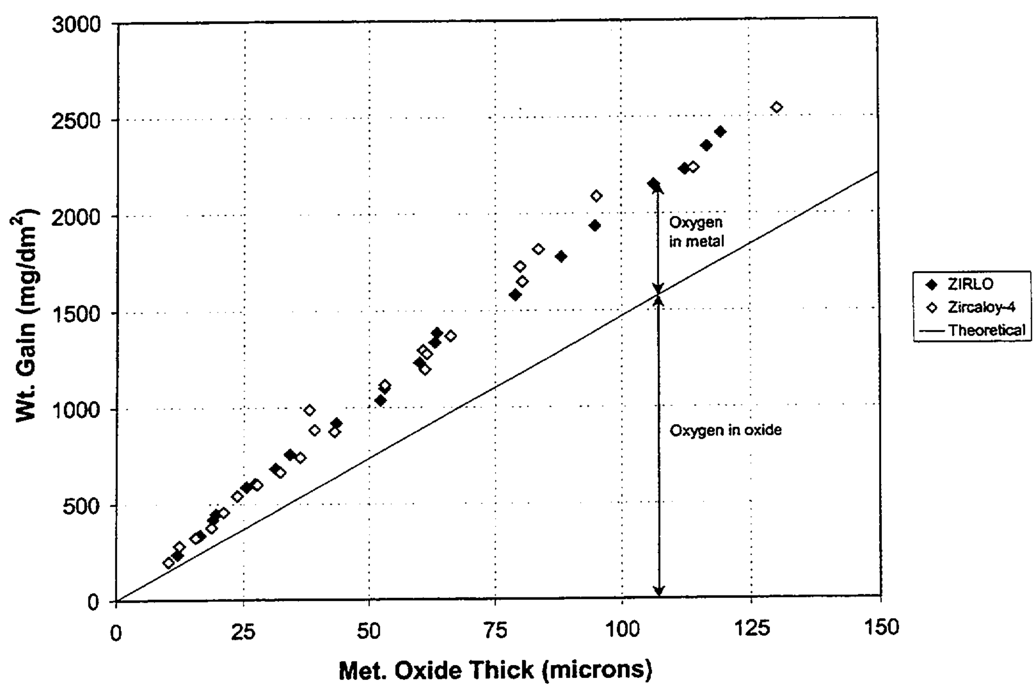


FIGURE 6

MICRO-HARDNESS TRACES ACROSS (A) ZIRLO™ AND (B) ZIRCALOY-4 CLADDING FOLLOWING HIGH TEMPERATURE STEAM OXIDATION

FIGURE 7

MICRO-HARDNESS TRACES ACROSS ZIRLO™ ™ CLADDING (LOT S93-6374Z) FOLLOWING HIGH TEMPERATURE STEAM OXIDATION

(A) 1800°F/5 MINUTES, (B) 2000°F/5 MINUTES, AND (C) 2100°F/30 MINUTES

FIGURE 7 (CONT.)

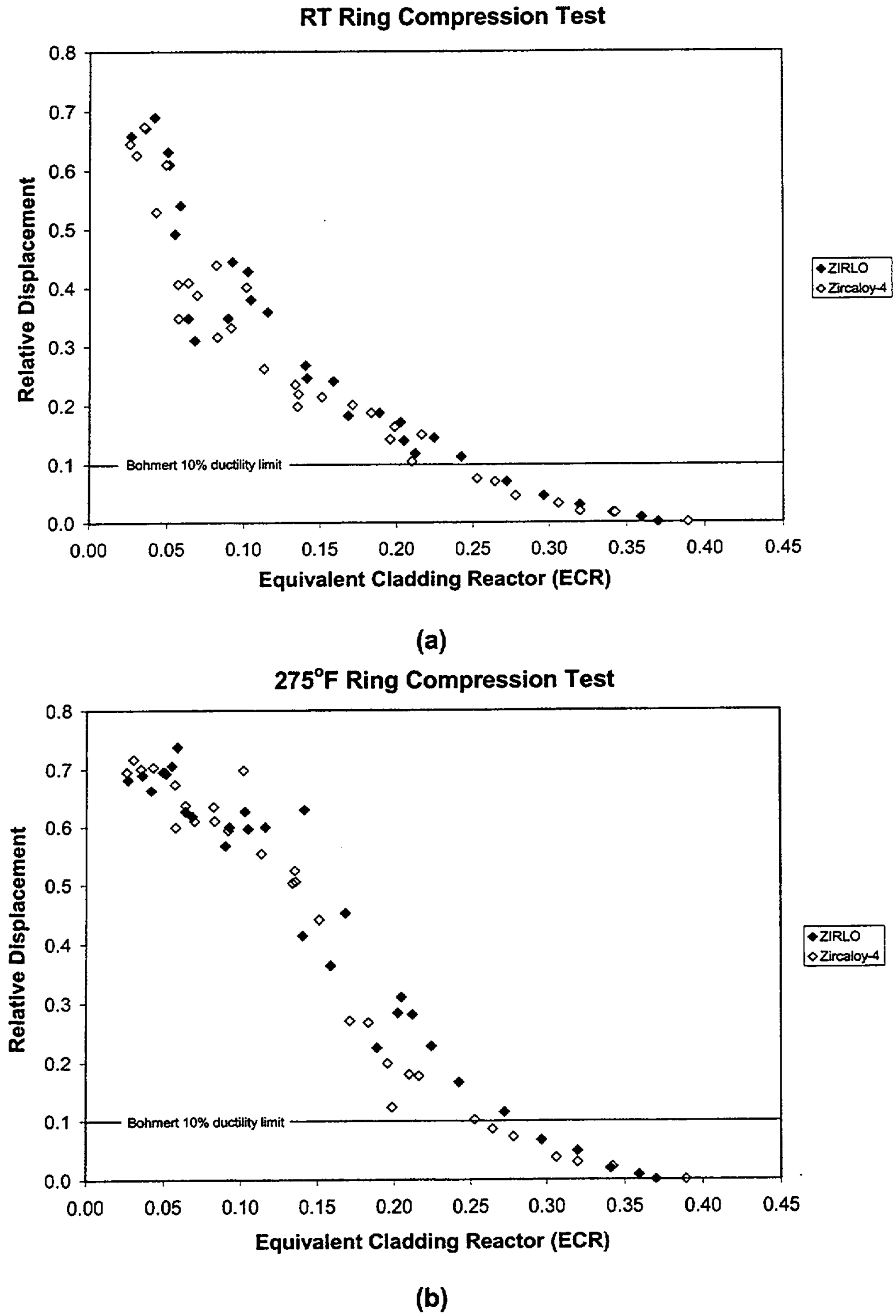
FIGURE 8

MICRO-HARDNESS TRACES ACROSS ZIRCALOY-4 CLADDING (LOT S722170A)
FOLLOWING HIGH TEMPERATURE STEAM OXIDATION
(A) 1950°F/5 MINUTES, (B) 2000°F/5 MINUTES, AND (C) 2100°F/30 MINUTES

FIGURE 8 (CONT.)

FIGURE 9

RING COMPRESSION TEST RESULTS FOR ZIRLO™ AND ZIRCALOY-4 CLADDING TESTED AT (A) ROOM TEMPERATURE AND (B) 275°F



CENPD-404-NP-A

U.S. Nuclear Regulatory Commission

Safety Evaluation Report

Required Materials

6. Letter, LTR-NRC-01-32, "Selected Page Revisions for Topical Report CENPD-404-P, Rev. 0"

Westinghouse Electric Company LLC

2000 Day Hill Road
Windsor, CT 06095
USA

27 August, 2001
LTR-NRC-01-32

U.S. Nuclear Regulatory Commission
Attn: Document Control Desk
One White Flint North
11555 Rockville Pike
Rockville, Maryland 20852-2738

Subject: Selected Page Revisions for Topical Report CENPD-404-P, Rev. 0 [Enclosure 1-P and 3-P Contain Westinghouse Proprietary Class 2 Material]

References:
1. Letter, P. W. Richardson (CENP) to USNRC Document Control Desk, "Submittal of CENPD-404-P, Rev. 0 Regarding Implementation of ZIRLO™ Cladding Material in CENP Fuel Designs". LD-2001-005, January 22, 2001, LD-2001-0005
2. Letter, P. W. Richardson (WEC) to USNRC Document Control Desk, "Assessment of Ft. Calhoun Fuel Rod Fretting History and Root Cause As It Relates to Implementation of ZIRLO™ Cladding Material in Fuel Designed By CE Nuclear Power", LD-2001-0028, May 3, 2001
3. Letter, P. W. Richardson (WEC) to J. S. Cushing (NRC), "Response to Requests for Additional Information on Topical Report CENPD-404-P, Rev. 0", LD-2001-0045, Rev. 0, August 10, 2001
4. Letter, P. W. Richardson (WEC) to J. S. Cushing (NRC), "Ductility of ZIRLO™ and Zircaloy-4 After High Temperature Oxidation in Steam", LD-2001-0046, Rev. 0, August 10, 2001

On January 22, 2001, topical report CENPD-404-P, Rev. 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Designs", was submitted (Reference 1) for Nuclear Regulatory Commission (NRC) review and approval. Several additional submittals followed which provided additional information (References 2 to 4) in response to various NRC requests. During the course of the review, NRC staff requested that WEC reconsider the proprietary classification of selected material so that it would be possible for the NRC staff reviewers to prepare a complete and meaningful Safety Evaluation (SE) that could be placed in the public domain. WEC has reconsidered its original proprietary classification as requested and is providing herewith revised pages for the NRC's information and use. In addition, during the proprietary classification review WEC identified several editorial omission/typographical errors which are also being corrected at this time.

Enclosure 1-P provides selected topical report (i.e., CENPD-404-P, Rev. 0) page revisions. Enclosure 2 provides a page revision regarding Ft. Calhoun Fuel Rod Fretting History (Reference 2) for proprietary material content. Enclosure 3-P provides a page for RAI Response No. 11 (Reference 3) which has been revised to correct a typographical omission regarding the magnitude specification of an equation term. Since some of these pages continue to contain material that is proprietary, Enclosure 4 provides the non-proprietary versions of the affected pages.

In addition to the revised pages discussed above, this letter also provides requested feedback regarding the SE Conditions the NRC plans to impose on CENPD-404-P, Rev. 0. In particular, the NRC asked WEC to review the SE for proprietary material content and for concurrence with the Conditions that would be imposed on the subsequent use of the topical report. Regarding proprietary material content, WEC identified no occurrences of the use of proprietary information not being corrected by the submission of the revised pages contained herewith. As for the proposed SE Conditions, WEC understands the NRC intent for the five (5) conditions to be imposed and accepts these conditions as a stipulation for use of CENPD-404-P, Rev. 0. The Conditions, as we understand them, are:

1) The predicted corrosion limit, as predicted by the best-estimate model will remain below 100 microns for all locations of the fuel.
2) All the conditions listed in the SERs for all the CENPD methodologies used for ZIRLO fuel analysis will continue to be met, except that the use of ZIRLO cladding in addition to Zircaloy-4 cladding is now approved.
3) All CENP methodologies will be used only within the range for which ZIRLO data was acceptable and for which the verifications discussed in CENPD-404-P and responses to RAIs were performed.
4) Until data is available demonstrating the performance of ZIRLO cladding in CENP plants, the fuel duty will be limited to the current maximum fuel duty for each CENP plant with some provision for adequate margin to account for variation in core design (e.g., cycle length, plant operations, etc.). Details of this condition will be addressed on a plant specific basis during the approval to use ZIRLO in a specific plant.
5) The burnup limit for this approval is 60 MWD/MTU.

WEC has determined that the information contained in Enclosures 1-P and 3-P is proprietary in nature. Consequently, it is requested that this information be withheld from public disclosure in accordance with the provisions of 10 CFR 2.790 and that copies be appropriately safeguarded. The reasons for the classification of this information as proprietary remain the same as those delineated in the original affidavits provided with References 1 and 3. Enclosure 4 provides the non-proprietary versions of the affected pages.

If you have any questions regarding this matter, please do not hesitate to call Chuck Molnar of my staff at (860) 731-6286.

Very truly yours,
Westinghouse Electric Company LLC

Philip W. Richardson
Licensing Project Manager
Windsor Nuclear Licensing

Enclosure(s): As stated

xc: w/o Enclosures

J. S. Cushing (NRC)
M. S. Chatterton (NRC)
R. Caruso (NRC)

Enclosure 4 to LTR-NRC-01-32

WESTINGHOUSE ELECTRIC COMPANY LLC

NON-PROPRIETARY VERSION PAGE REVISIONS FOR

1) CENPD-404-NP, REV. 0
2) FT. CALHOUN FUEL ROD FRETTING HISTORY AND ROOT CAUSE
3) RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

AUGUST 2001

NON-PROPRIETARY VERSION CENPD-404-NP, REV. 0 PAGES

Figure 3.3-1 provides a forecast of the number of plants expected to use ZIRLO™ in regions and full core applications in the future. Table 3.3-2 provides a summary of the high burnup experience of ZIRLO™ as of July 1999 and Table 3.3-3 summarizes the current LTA programs.

ZIRLO™ has improved corrosion resistance compared to Zircaloy-4 [.] Also, no oxide spalling has been observed in current ZIRLO™ fuel for either low or high duty operation. Westinghouse has also implemented over 1 million ZIRLO™ fuel rods in assemblies with ZIRLO™ and Zircaloy-4 Optimized Fuel Assembly (OFA) type spacer grids without incidence of leakers due to grid-to-rod fretting. The OFA type spacer grids utilizes a vertical type grid spring. Fuel rod fretting failures have been observed in Westinghouse fuel with a slanted grid spring [ ] design; however this design is being modified to improve its grid-to-rod fretting resistance. Further discussion on grid-to-rod fretting is provided in Section 5.4.7.

3.4 ZIRLO™ Cladding and Fuel Duty Considerations

There has been an industry trend toward greater Pressurized Water Reactor (PWR) plant operating efficiencies over the last decade. The economic benefits derived from higher power ratings, extended burnups, and higher operating temperatures have led to aggressive fuel duty conditions, characterized by high fuel rod surface temperatures, with subcooled boiling, and high power densities at ever-greater residence times. Such harsher core environments have placed greater demands on fuel than ever before.

More demanding PWR fuel duties have necessitated closer evaluation of the corrosion resistance of fuel cladding materials. It has been common practice within the nuclear industry to present experimental fuel rod corrosion data as plots of the maximum oxide measured on a fuel rod versus the fuel rod average burnup. This type of plot is a convenient way to represent the data, since the measured oxide and burnup data are readily available. However, this representation of the data can be misleading. The plots show the range of burnups and thickness for which corrosion data are available. However, only limited conclusions about corrosion performance can, or should, be drawn from these plots.

when ZIRLO™ was implemented in the Westinghouse OFA grid design. Further discussion on grid-to-rod fretting is provided in Section 5.4.7.

CENP has implemented different advanced cladding materials in LTAs utilizing the STD and Turbo grid designs. Table 3.5-1 summarizes these LTA test programs. In these test programs fuel rod wear measurements have been made which demonstrate negligible wear differences due to the use of the advanced cladding materials. Some of these materials are similar to ZIRLO™ in that tin content was reduced and niobium added. Table 3.5-2 summarizes the differences in chemical compositions of the different advanced cladding materials evaluated. Even though the composition of the advanced cladding materials used in these LTAs are not exactly the same as ZIRLO™ cladding, the wear performance for ZIRLO™ is expected to be similar particularly with a robust CENP spacer grid design similar to the Westinghouse OFA spacer grid design.

CENP uses two different type of fuel pellet designs, standard and value added. The value added fuel pellet contains smaller end dishes, an increased diameter, and a slight increase in density to increase uranium loading compared to the standard fuel pellet design. The FATES3B fuel performance code will be used to evaluate both pellet designs in the reload analysis with the ZIRLO™ cladding.

ZIRLO™ cladding is more robust than OPTIN cladding due to its improved corrosion resistance and lack of oxide spallation. Small amounts of oxide spallation have been recently observed in OPTIN cladding in two cycle high duty fuel assemblies. Typical maximum FDI values for CENP plant designs were evaluated using the methodology described in Section 3.4. A maximum value of [ ] was calculated for 14x14 fuel and [ ] for 16x16 fuel. Therefore, the application of ZIRLO™ in CENP plants is well within the ZIRLO™ database shown in Figure 3.4-2.

3.6 ZIRLO™ Application to High Burnup

ZIRLO™ has been approved by the NRC as an acceptable cladding material and is licensable to a peak rod average burnup of 62 MWd/kgU (References 3-1, 3-2, and 3-8). Furthermore, ZIRLO™ cladding has been shown to be capable of significantly higher burnups than 62 MWd/kgU because of its resistance to waterside corrosion and improved dimensional stability under irradiation. CENP burnup application will remain consistent with approved burnups for the CENP fleet of plants as described below.

3.6.1 Application to NRC Approved 60 MWd/kgU Peak Pin Burnup

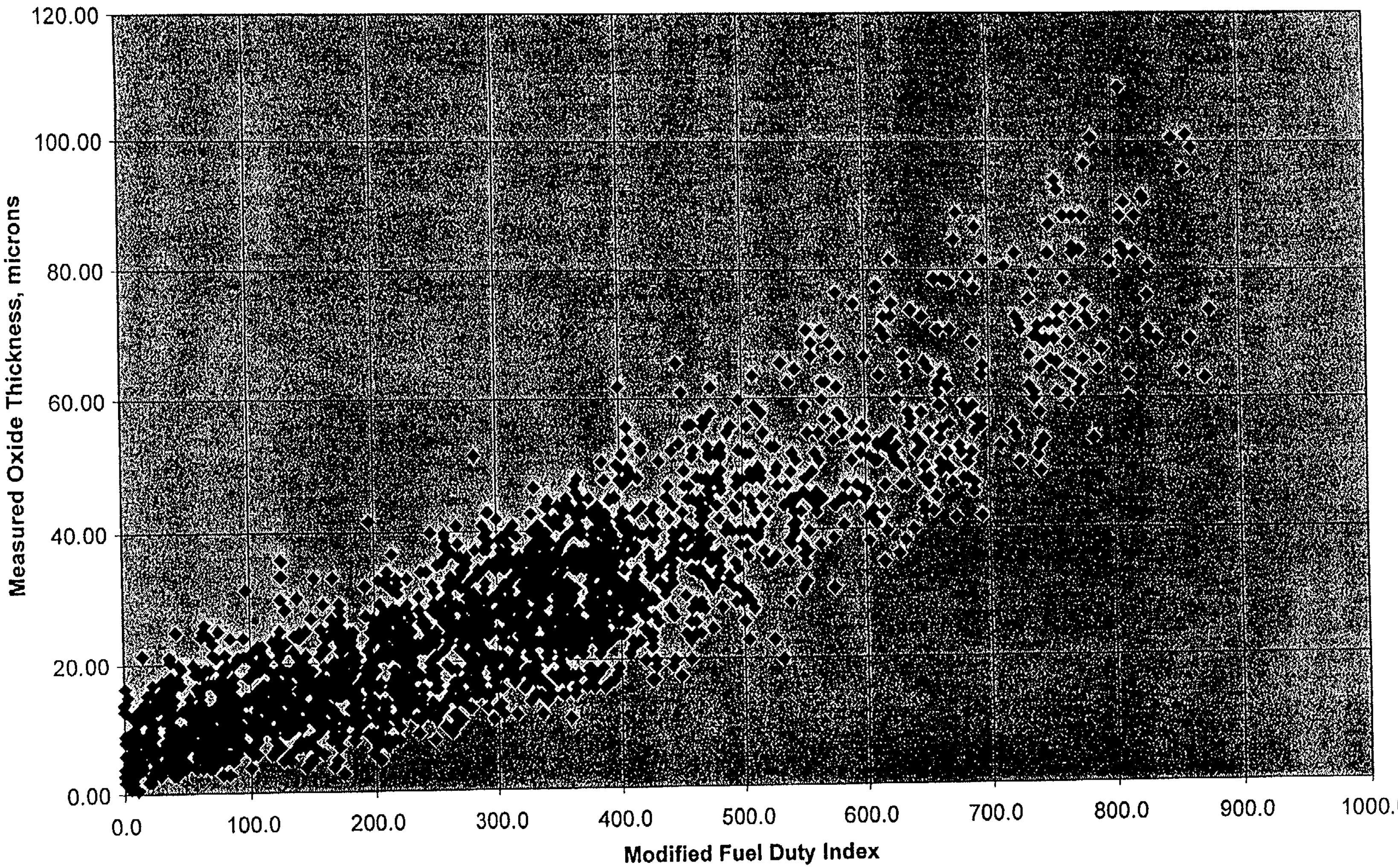
The current NRC approved 1-pin peak burnup limit for the CENP 14x14 fuel design is 60 MWd/kgU, Reference 3-6. Similarly, the approved 1-pin peak burnup limit for the CENP 16x16 fuel design is also 60 MWd/kgU, Reference 3-7. Consequently, CENP will limit ZIRLO™ cladding to a 1-pin peak burnup of 60 MWd/kgU, even though it has demonstrated acceptable performance in excess of this value.

3.6.2 Application to 62 MWd/kgU in Conjunction with CENP High Burnup OPTIN Topical

Reference 3-3 provided the justification for extending the operation of CENP PWR fuel designs to peak pin burnups in excess of 60 MWd/kgU. Although Reference 3-3 requested a peak burnup of 65 MWd/kgU, it is now understood by CENP that burnup will be limited for the foreseeable future by the NRC to 62 MWd/kgU. As documented in Reference 3-3, it was intended that OPTIN cladding only be irradiated to burnups in excess of 60 MWd/kgU under operating conditions characterized as low duty. It is recognized that if the duty cycle is too severe, one or more of the design and safety analysis criteria could be threatened. Consequently, it became necessary to define the low duty application of Reference 3-3 in order to continue forward. Efforts to successfully define low duty and obtain approval of Reference 3-3 are in progress.

Design and licensing issues for extending peak burnups above 60 MWd/kgU have been addressed in Reference 3-3 for the other fuel assembly components. The models related to the fuel stack, for example, were shown to be valid and acceptable to 65 MWd/kgU. The response of the fuel assembly and structural components to extended burnup were also shown to be acceptable. Therefore, the substitution of a more robust cladding material such as ZIRLO™ supports the successful operation to 62 MWd/kgU without duty limitations. Existing duty cycles are within the successful experience database for ZIRLO™ cladding.

Figure 3.4-2 ZIRLO Measured Oxide Thickness vs. Modified Fuel Duty Index



$\dot{\varepsilon}_{irr}$ = [ ] irradiation creep rate, %/hour

$\dot{\varepsilon}_{th}$ = [ ] thermal creep rate, %/hour

t = time, hours

σ_{θ} = [ ] circumferential stress, MPa

T = temperature, °K

$\dot{\phi}$ = fast neutron flux, n/cm^2/sec, E > 1 Mev

Φ = fast neutron fluence, n/cm^2, E > 1 Mev

ε_p = [ ] primary strain, in/in

K = time coefficient

$\dot{\varepsilon}_{ths}$ = steady-state [ ] circumferential [ ] thermal creep rate, in/in

[ ] (4-5)

[ ] (4-6)

where

E = elastic modulus, MPa

T_F = temperature, °F

[ ] (4-7)

[ ] (4-8)

The combined irradiation and thermal creep rate is

[ ] (4-9)

$\dot{\varepsilon}_{eff}$ = total [ ] creep rate, %/hour

F_1 = ZIRLO™ thermal creep [ ]

F_2 = ZIRLO™ irradiation creep [ ]

C_c = ZIRLO™ irradiation creep [ ] used in benchmarking, (k) of the North Anna 1 ZIRLO™ fuel rod design

[

]

[

(4-10)

where

] (4-10a)

[ ] (4-20)

Use of Equation 4-20 in FATES3B is consistent with the creepdown data where creep correlation fitting coefficients are determined using measured hoop strains.

4.3.1.4 NCLO Application and Creep Rate Uncertainty

A creep rate [ ] somewhat similar to a 95% probability) is applied for Zircaloy-4 cladding in the CENP fuel performance analysis for NCLO critical pressure in FATES3B as described in Reference 4-4. The ZIRLO™ cladding creep rate [ ] have been established in Reference 4-10 as lower and upper bounds, respectively, for creep rates at a 95% probability. The upper bound [,] is used in the ZIRLO™ NCLO application in FATES3B.

Tensile creep behavior is treated the same as compressive creep for ZIRLO™ (Reference 4-10). As discussed in Reference 4-4, Section 4.1.1.1, some evidence exists that indicates tensile creep [ ] may not differ significantly from compressive creep. Since NCLO conditions of interest are in the neighborhood of [.]

It has been concluded that the CENP internal pressure and the NCLO analysis is quite conservative (discussed in considerable detail in Reference 4-4). Thus, any small potential differences between tensile creep and compressive creep in the stress range of interest are insignificant.

4.3.2 Fuel Rod Axial Growth

Fuel rod axial growth occurs in-reactor as a result of fast neutron irradiation. Fuel rod axial growth is applied in FATES3B to obtain clad length relative to the length of the fuel column to

4.3.6 Verification of FATES3B (Creepdown)

The review of ZIRLO™ cladding material properties and correlations described above has resulted in the conclusion that only the ZIRLO™ creep (creepdown and NCLO applications) and ZIRLO™ axial growth correlations need to be modeled in the FATES3B fuel performance computer code to adequately simulate ZIRLO™ clad fuel rod performance in CENP nuclear fuel designs. Other thermal and mechanical properties used in FATES3B are sufficiently similar to, or identical to, Zircaloy-4 (OPTIN), and do not need to be modified.

The purpose of this section is to provide verification results of comparisons between the FATES3B predictions for creepdown of the North Anna Unit 1 fuel rods clad with ZIRLO™ with the measured creepdown data. For this benchmarking exercise, the North Anna Unit 1 fuel rods which were simulated with the PAD 4.0 code, Reference 4-10, were simulated with FATES3B modified for ZIRLO™ applications. The fuel stack was also modeled in FATES3B to simulate the expected behavior of the fuel based on the PAD 4.0 simulation. The data used for benchmarking FATES3B consists of [

] was irradiated for one cycle to minimize or eliminate pellet-clad interaction effects. These fuel rods attained an average burnup of

.] These [ ] fuel rods each experienced similar axial power shapes and peak power histories. Minor corrections were made to the diameter predictions to account for expected oxide thicknesses which were included in the Westinghouse measured diameters. Diameter measurements were made at up to [ ] of each fuel rod. However, the measurements were made at the [ ] for each rod.

A scatter plot of predicted versus measured diameter is shown in Figure 4.3.6-1 for individual measurements. These predictions are concluded to be very good. The diametral creepdown was also averaged for all [ ] fuel rods and plotted in Figure 4.3.6-2. Again, the predictions are concluded to be good. In general, the FATES3B predicted cladding creepdown for all [

] because the design characteristics and the power histories were nearly identical. The measured creepdown differed between individual fuel rods to a greater

4.4.2 Impact on DNB Propagation (NCLO)

The impact of ZIRLO™ on DNB propagation is a consideration for DNB transients. High temperature creep and rupture of ZIRLO™ cladding during DNB is modeled and accounted for in the evaluations of fuel failure and the calculations of dose consequences.

4.4.2.1 High Temperature Creep and Rupture

High temperature creep behavior of ZIRLO™, required for mechanistic DNB propagation evaluations (Reference 4-4), is obtained from Reference 4-11. High temperature creep strains were measured as a function of time on ZIRLO™ tubing under conditions of [.] Different deformation mechanisms were observed which depend on the stress level and phase of the material.

Strain rate is given by

[ ] (4-33)

where

S = hoop stress, MPa
e = [ ] strain, in/in
t = time, seconds
T = temperature, °K

and

[ ]

[

]

[ ] (4-38)

where

ΔP = pressure difference across wall, MPa

D_o = initial tube diameter, inches

w_o = initial wall thickness, inches

D = deformed diameter, inches

w = deformed wall thickness, inches

An additional empirical correction to the calculated strain increment during a given time increment is required if the temperature is [ ] and the hoop stress is [ ] as recommended in Reference 4-11. This empirical correction, which accounts for the effect of [,] reduces the calculated strain increment. The correction is provided in terms of the engineering strain.

[.]

[ ] (4-39)

where

$\Delta\varepsilon_{eff}$ = [ ] strain increment, in/in

$\Delta\varepsilon$ = [ ] strain increment, in/in

Y = the summed $\Delta\varepsilon_{eff}$ in the [ ] regimes, in/in

M = coefficient, dependent on temperature, [ ]

4.4.2.4 Discussion of Conservatism for DNB Propagation

The CENP analysis of DNB propagation is extremely conservative. Reference 4-4 provides a detailed discussion of the propagation model conservatisms. The fuel rod maximum internal gas pressure is also conservatively bounded and the methodology for determining the allowable maximum pressure limit (i.e., the NCLO limit) is conservative.

In addition to these documented conservatisms, it has been concluded that DNB propagation is not a likely event because of the local thermal effects and deformation mechanisms associated with DNB and clad ballooning. Rod-to-rod gap closure from a ballooning fuel rod experiencing DNB clearly degrades the surface heat transfer of an adjacent rod only at a local area on the circumference. Thus, occurrence of DNB on an adjacent rod will be highly circumferentially oriented and high temperature deformation would likely occur only on the surface of the adjacent fuel rod facing the original fuel rod experiencing DNB. Consequently, DNB propagation and fuel rod failure are construed to involve at most only one additional row of adjacent fuel rods. However, if a worst case scenario is envisioned (i.e., where the ballooning occurs symmetrically), the resulting fuel-clad internal void volume within the ballooning region of the fuel rod acts to rapidly reduce the internal pressure and, thereby, halt DNB propagation. This is the case even if the bulk of the fission gases present in the fuel matrix is released due to local temperature increases. A clad strain less than the strain level required for DNB propagation equalizes internal pressure with external pressure, and terminates the clad ballooning. Therefore, while DNB propagation is conservatively assumed, the physical mechanisms involved do not actually support the occurrence of DNB propagation.

4.4.2.5 Hydrides and Hydride Reorientation in ZIRLO™

The presence of hydrides and the potential for hydride reorientation due to operation with internal pressure in excess of external pressure (i.e., NCLO) was evaluated in Reference 4-4. Tensile stresses and temperatures are the controlling parameters for adverse hydride orientation. The tensile stresses and peak temperatures for operation at NCLO conditions were concluded to be [ ] that might result in adverse hydride reorientation. Similar observations were made by Westinghouse in Reference 4-24 for operation at higher than RCS pressure. Therefore, operation with ZIRLO™ will be similar to operation with Zircaloy-

A description of the CENP typical reload analysis methodology is given in Reference 4-8 and is summarized here. An erbia bearing fuel rod is used as the reference design basis for the analysis of each fuel type (14x14 and 16x16). [

]

[

.] The burnup dependent radial peaking factor used herein, normalized to 1.0, for the 14x14 design and the 16x16 design are shown in Figures 4.6.1-1 and 4.6.1-2, respectively. Axial power distributions in terms ofLHR's are shown in Figures 4.6.1-3 and 4.6.1-4. The LHR history of the fuel rod is, therefore, the axial LHR distribution multiplied by the radial peaking factor as a function ofburnup. In this case, the radial peaking factor has been determined to be that which results in a maximum internal hot gas pressure that is just under the NCLO pressure limit. Consequently, this type of radial fall-off curve may typically be used to guide fuel management.

4.6.1.1 Fuel Temperatures

The only cladding properties or correlations which required modification to enable FATES3B to model ZIRLO™ cladding were circumferential creep and irradiation induced axial growth. Creep and growth are time dependent deformation. Consequently, conditions in the OPTIN clad fuel rod and the ZIRLO™ clad fuel rod will be identical near beginning of life. Fuel temperatures remain quite similar and differ a small amount during gap closure due to feedback effects of the deformations of the cladding. The fuel centerline temperatures differ between the OPTIN design and the ZIRLO™ design by [ ] at a fuel rod average burnup of 30 MWd/kgU when gap closure has occurred. The differences in temperatures are considered to be insignificant.

4.6.1.2 Power-to-Centerline Melt (PTM)

The power-to-centerline melt for the 14x14 fuel rod design and the 16x16 fuel rod design are shown in Figures 4.6.1.2-1 and 4.6.1.2-2, respectively. It can be seen that centerline melt is predicted to occur at [ ] LHRs for OPTIN clad fuel rods and ZIRLO™ clad fuel rods. [.] Reactivity decreases precludes higher burnup fuel rods from attaining LHR's that would cause melting.

4.6.1.3 Internal Hot Gas Pressure

Internal hot gas pressure for the 14x14 fuel rod design and the 16x16 fuel rod design are shown in Figures 4.6.1.3-1 and 4.6.1.3-2, respectively. Internal pressure initially decreases from beginning of life due to fuel densification and then gradually increases as fission gas builds up in the fuel matrix and is released. The decrease in radial peaking factor (and, therefore, LHR) at burnups above about 40 MWd/kgU is sufficient to keep the internal pressure below the NCLO critical pressure. Identical power histories have been applied to the OPTIN clad fuel rod and the ZIRLO™ clad fuel rod as described in Section 4.6.1. It can be seen that the pressure in the ZIRLO™ clad fuel rod gradually increases to end of life (EOL) values that are slightly higher than the OPTIN clad fuel rod. This increased pressure is primarily due to the reduced axial growth experienced by the ZIRLO™ clad fuel rod. [ ] in the ZIRLO™ clad fuel rod relative to the OPTIN clad fuel rod. The difference, however, is considered to be insignificant. Note that although the ZIRLO™ clad fuel rod internal pressure would [ ] of the OPTIN clad fuel rod, it is [ ] of the ZIRLO™ clad fuel rod. Critical pressure limits are discussed in the next section.

4.6.1.4 Critical Pressure Limit for NCLO

Critical pressure limits are determined by the FATES3B fuel performance code based on the NCLO pressure criterion. That is, the critical pressure limit is the internal hot gas pressure where outward tensile creep of the cladding due to the differential pressure loads would just

These interrelated effects, when combined with the range of operating conditions in a typical core, can produce [

]. In addition, the difference in oxide thickness between the two materials will increase as burnup increases, and the rate of axial growth of the rods will differ.

Because of these [ ], the best basis for comparisons of fretting behavior is the actual performance in reactors where the transition has already been made between cladding materials. The cases that are considered most relevant [

].

Table 5.4.7-4 lists the applicable experience [

].

The experience with [ ] is also relevant, since the fuel assembly designs were deployed in a [

]. Inspection results are shown in Table 5.4.7-5. Note that [ ] was made at the same time as the transition from low-tin Zircaloy-4 to ZIRLO™ cladding.

5.4.7.3 Conclusions Related to Grid-to-Rod Fretting Wear

The effect of the change from OPTIN to ZIRLO™ cladding on grid-to-rod fretting will involve complex interactions among the various factors contributing to the fretting mechanism. Based on a review of the individual contributing factors, and on the available data from relevant reactor experience, the incidence of fretting failures in the CENP fuel designs is expected to remain small.

Reference 22 it was concluded that the robust interface between the CENP 14x14 and 16x16 guide tubes and control element assemblies (CEAs) is sufficient to preclude any similar issue for CENP reactors. Specifically, there is a factor of 30 on the critical buckling force that exists with CENP type guide tubes due to the larger geometric shape, as compared to Westinghouse 17x17 thimble tubes, to resist tube buckling induced distortions that may result from differential behavior of the guide tubes during irradiation or from variations in material properties.

The above discussion does not indicate a strong dependence on fuel rod behavior for the fuel assembly bow phenomena. However, the introduction of ZIRLO™ will alter the dynamics of the Zircaloy-4 creep rate early in life and these differences may produce small differences in the rod bow which may have a feed back effect on overall lateral fuel assembly stiffness and possible bow effects. These effects are judged to be relatively insignificant based on the Westinghouse observations that assembly bow has not increased with the introduction of ZIRLO™.

5.4.8.2 Spacer Grid Irradiation Growth and Spring Tab Relaxation

The spacer grids will continue to be fabricated from Zircaloy-4 for CENP fuel assemblies with ZIRLO™ clad fuel rods. Therefore, growth and relaxation properties of the grids will not be affected.

5.4.8.3 Fuel Assembly Hold Down Margin

The only parameter in the hold down evaluation that would be influenced by the use of ZIRLO™ cladding in a CENP fuel assembly would be that related to the weight of the fuel bundle. Section 5.3.11 shows the density of ZIRLO™ to be conservatively predicted to be [ ] than that of OPTIN. When this [ ] fuel rod density is considered with all other key parameters in the analyses of record for 14x14 and 16x16 CENP current fuel bundle designs, the hold down margins calculated by the SIGREEP code continue to meet the required criterion. Thus, the use of ZIRLO™ cladding in current CENP fuel bundle designs is acceptable from a hold down margin standpoint.

6.0 ECCS Performance Analysis

6.1 Introduction

This section describes the implementation of ZIRLO™ cladding in the CE Nuclear Power (CENP) Large Break Loss-of-Coolant Accident (LBLOCA) and Small Break Loss-of-Coolant Accident (SBLOCA) Emergency Core Cooling System (ECCS) performance evaluation models. Section 6.2 describes the cladding related models for Zircaloy-4 used in the CENP LBLOCA and SBLOCA evaluation models. Section 6.3 describes the modifications that have been made to those models to represent ZIRLO™ cladding. It includes a description of the cladding model for ZIRLO™ for each parameter that requires a model different than that used for Zircaloy-4. It also identifies those parameters for which the Zircaloy-4 model is applicable to ZIRLO™ and provides a basis for the applicability of the Zircaloy-4 model to ZIRLO™. Section 6.4 discusses the maintenance of the interface between the fuel performance model, FATES3B, and the ECCS performance evaluation model for ZIRLO™ cladding. Section 6.5 presents the results of both a LBLOCA and SBLOCA ECCS performance analysis of ZIRLO™ cladding. The results are compared to the results of equivalent analyses of Zircaloy-4 cladding. The conclusions of the implementation of ZIRLO™ cladding in the CENP LBLOCA and SBLOCA ECCS performance evaluation models are presented in Section 6.6.

The implementation of ZIRLO™ cladding in the CENP evaluation models is based on the NRC-accepted implementation of ZIRLO™ cladding in the Westinghouse Appendix K evaluation models (Reference 6-45). As described in Reference 6-45, Westinghouse determined that many of the physical and mechanical properties of ZIRLO™ are similar to those of Zircaloy-4 when the two alloys are in the same metallurgical phase. Consequently, many of the material property models for Zircaloy-4 are applicable to ZIRLO™. However, the change from the alpha phase to the beta phase for ZIRLO™ occurs over a different temperature range than it does for Zircaloy-4. This requires that several material property models applicable to Zircaloy-4 be modified to represent ZIRLO™. In particular, the models for specific heat, cladding creep, cladding rupture temperature and strain, and assembly blockage following rupture were modified to represent ZIRLO™ in the Westinghouse Appendix K evaluation models. The

In comparison, for cladding temperatures $\leq$2200°F, the Westinghouse equation that is used for both Zircaloy-4 and ZIRLO™ gives a density that is less than 2% different than the constant value that is used for Zircaloy-4 in the CENP evaluation models. On the basis that this is an insignificant difference, the CENP evaluation models use the same constant value of density (i.e., 409 lbm/ft^3) for ZIRLO™ as used for Zircaloy-4.

6.3.3 Thermal Conductivity

The thermal conductivity of Zircaloy-4 is used for ZIRLO™ in the Westinghouse Appendix K evaluation models. In the Westinghouse Appendix K evaluation models, the thermal conductivity (k, BTU/hr-ft-°F) is the maximum of the two values obtained from the following equations:

$$k = 7.404 + 2.9 \times 10^{-3} T$$
$$k = 5.621 + 5.3 \times 10^{-3} T$$

where T is cladding temperature (°F).

The equation for thermal conductivity for Zircaloy-4 used in the CENP evaluation models, with the exception of CEFLASH-4AS, is the following equation, which is taken from Reference 6-38:

[ ]

CEFLASH-4AS uses the following equation given on page 3 of Reference 6-13:

[ ]

The three models are compared in Figure 6.3.3-1. The thermal conductivity calculated using the Westinghouse model ranges from –5% to +7% different from that calculated using the CENP model over the temperature range of interest. The CENP model also compares favorably with the data for ZIRLO™ and Zircaloy-4 presented in Reference 6-45 (page 62 of Section G). Therefore, consistent with the approach used in the Westinghouse Appendix K evaluation

6.3.5 Thermal Expansion

The thermal expansion for Zircaloy-4 is used for ZIRLO™ in the Westinghouse Appendix K evaluation models for both radial and axial expansion. The model for thermal expansion in the radial direction (Δr/r) is given by the following equation:

[ ]

where T is cladding temperature (°F).

The CENP evaluation models use the thermal expansion model described in Reference 6-38. Note that in the CENP evaluation models, only the radial thermal expansion model is used. In Reference 6-38, the model is presented as a graph of thermal expansion versus temperature. As coded in STRIKIN-II, the model consists of a table of values for thermal expansion versus temperature (Reference 6-18, Appendix I). In PARCH, the model consists of a functional fit of the graphical information (Reference 6-24, Section II.b and Appendix B). As stated in Section 6.2.1, CEFLASH-4A uses the same model as used in PARCH.

The Westinghouse and CENP models are compared in Figure 6.3.5-1. As seen in the comparison, the change in thermal expansion that occurs as a result of the transformation from the alpha to the beta phase is reflected in the CENP model for Zircaloy-4. However, the Westinghouse model, which is applied to both Zircaloy-4 and ZIRLO™ , [.] Therefore, in the case of the CENP evaluation models, consistency with the Westinghouse Appendix K evaluation model approach (i.e., using the Zircaloy-4 model for ZIRLO™) would mean [.] A sensitivity study has shown that cladding temperature is not sensitive to changes in the cladding thermal expansion model that would result from modifying the Zircaloy-4 model to reflect the alpha-to-beta phase transformation temperatures for ZIRLO™. For example, use of the Westinghouse model for thermal expansion in the CENP LBLOCA evaluation model resulted in less than a [ ] change in the PCT for a typical case. Based on this lack of sensitivity of the PCT to changes in the cladding thermal expansion model, the CENP evaluation models use the CENP Zircaloy-4 thermal expansion model for ZIRLO™.

6.3.6 Modulus of Elasticity

The modulus of elasticity for Zircaloy-4 is used for ZIRLO™ in the Westinghouse Appendix K evaluation models. Consistent with the Westinghouse approach, the CENP evaluation models also use the modulus of elasticity of Zircaloy-4 for ZIRLO™.

The model for the modulus of elasticity (E, kpsi) for Zircaloy-4 used in the CENP evaluation models is described in Reference 6-38. As coded in STRIKIN-II and PARCH, the model uses an equation for temperatures less than or equal to [ ] and linear interpolation from a table of values for temperatures above [.] The equation used in PARCH is as follows:

[ ]

where T is cladding temperature (°F). The same equation, but with more significant figures for the constants, is used in STRIKIN-II. The following table of values is used for temperatures above [.]

Temperature, °F	Modulus of Elasticity, kpsi
[	]

The model is depicted in Figure 6.3.6-1.

Any actual difference between the modulus of elasticity of Zircaloy-4 and ZIRLO™ will have an insignificant impact on PCT for the following reasons. The modulus of elasticity, in conjunction with Poisson's ratio, is used in the calculation of the change in the cladding inside diameter due to mechanical expansion/contraction of the cladding. This change, together with the change due to thermal expansion and plastic strain, is used to calculate the cladding inside diameter that is used in the calculation of the gap conductance in STRIKIN-II and PARCH. The mechanical component of the change in cladding diameter is small in comparison to the change due to thermal expansion and, when it occurs, plastic strain. Also, after the cladding ruptures, there is no differential pressure across the cladding and, consequently, there is no longer a mechanical component to the change in cladding diameter.

The cladding inside diameter is also used in the calculation of the gap pressure. In particular, it is used to calculate the volume of the gap between the fuel and the cladding. This volume is combined with the plenum volume at the top of the fuel rod and the fuel dish and porosity volumes to give the total gas volume used in the calculation of the gap pressure. For the same reason as described above, variations in the modulus of elasticity will have an insignificant impact on the gas volume and gap pressure.

Lastly, the modulus of elasticity is used in the calculation of the mechanical interface pressure between the fuel and the cladding, which is used in the calculation of the gap conductance when the fuel and cladding are in contact with each other. As described in Section 6.3.8, for a given transient, the fuel and cladding are either never in contact or are in contact for a short length of time. Consequently, variations in the modulus of elasticity will not have a significant impact on the transient gap conductance.

6.3.7 Poisson's Ratio

Poisson's ratio for Zircaloy-4 is used for ZIRLO™ in the Westinghouse Appendix K evaluation models. Consistent with the Westinghouse approach, the CENP evaluation models also use Poisson's ratio for Zircaloy-4 for ZIRLO™.

The equation for Poisson's ratio (μ) for Zircaloy-4 used in the CENP evaluation models is the following equation from Reference 6-38:

$$\mu = 0.301 - 7.03\text{x}10^{-5}T \quad [\qquad\qquad]$$

where T is cladding temperature (°F). [ ] is used for Poisson's ratio. The model is depicted in Figure 6.3.7-1.

As described in Section 6.3.6, Poisson's ratio, in conjunction with the modulus of elasticity, is used in the calculation of the inside diameter of the cladding, which is used in the calculation of the gap conductance and the gap pressure. For the same reasons described in Section 6.3.6, variations in Poisson's ratio will have an insignificant impact on the transient gap conductance and gap pressure and, hence, on the cladding temperature.

6.3.8 Diamond Pyramid Hardness

Cladding hardness is not used in the Westinghouse Appendix K evaluation models. However, it is used in the CENP evaluation models. In particular, the diamond pyramid hardness is used in the calculation of the fuel-to-cladding gap conductance in the STRIKIN-II and PARCH computer codes when the fuel and cladding are in contact with each other.

Figure 6.3.8-1 depicts the model for the diamond pyramid hardness used in the CENP evaluation models for Zircaloy-4. The model is described in Reference 6-38. It is based on data obtained for temperatures ranging from room temperature to 1600°F. Above 1600°F Zircaloy-4 becomes soft and hardness measurements are difficult. Consequently, above 1600°F the model consists of [

.]

Since the Westinghouse Appendix K evaluation models do not use a cladding hardness model, Reference 6-45 does not provide any specific information regarding the hardness of ZIRLO™. However, as described in Reference 6-45, the material properties of ZIRLO™ are similar to those of Zircaloy-4, except as they may be impacted by the difference in the temperature range over which the alpha-to-beta phase change occurs. As shown in Figure 6.3.8-1, there is no significant change in the behavior of the hardness of Zircaloy-4 as a result of the alpha-to-beta phase change. Therefore, it is expected that the hardness of ZIRLO™ is not significantly different from that of Zircaloy-4 even given the different temperature range over which the alpha-to-beta phase change occurs for the two alloys.

In addition, the cladding hardness is used in the calculation of the gap conductance only when the fuel and cladding are in contact. They are not initially in contact at lowburnup, including the burnup (typically ~1000 MWD/MTU) that produces the minimum initial gap conductance and maximum initial fuel average temperature. Also, at higher burnup, when the fuel and cladding may initially be in contact, they will remain in contact for only a short period of time during the LOCA transient as a result of the thermal and mechanical expansion of the cladding. Therefore, any differences in the diamond pyramid hardness between Zircaloy-4 and ZIRLO™ will have an insignificant impact on the transient gap conductance and, hence, on the cladding temperature.

For these reasons, the CENP evaluation models use the Zircaloy-4 model for diamond pyramid hardness for ZIRLO™.

6.3.9 Cladding Rupture Temperature

6.3.9.1 CENP Large Break LOCA Evaluation Model

NUREG-0630 (Reference 6-39) describes the cladding rupture temperature, rupture strain, and assembly blockage models that were developed by the NRC for use in Appendix K evaluation models. The NUREG-0630 models for cladding rupture temperature, rupture strain, and assembly blockage are used in the Westinghouse Appendix K LBLOCA evaluation model and in the CENP LBLOCA evaluation model. However, because of the change in the temperature range over which the alpha-to-beta phase change occurs for ZIRLO™ versus Zircaloy-4, the models are not applicable to ZIRLO™ cladding. Consequently, Westinghouse conducted a rod burst test program for ZIRLO™ cladding and, following the methodology of NUREG-0630, developed rupture and blockage models for ZIRLO™ cladding that are used in the Westinghouse Appendix K evaluation models.

The ZIRLO™ cladding rupture temperature model is described in Reference 6-45 (pages 31-32 and Appendix D). The model is compared to the NUREG-0630 model in Figure 6.3.9.1-1. As described in Reference 6-45, unlike the NUREG-0630 model for Zircaloy-4, the ZIRLO™

model is not [.]

In implementing the rupture temperature versus engineering hoop stress model depicted in Figure 6.3.9.1-1, the Westinghouse LBLOCA Appendix K evaluation model includes a second criterion for predicting the occurrence of cladding rupture, namely, that [.]

The CENP LBLOCA evaluation model uses the Westinghouse model for the rupture temperature of ZIRLO™ cladding depicted in Figure 6.3.9.1-1. The model is presented in tabular form in Table 6.3.9.1-1 for the cladding dimensions of the CENP 14x14 and 16x16 fuel assemblies. The CENP LBLOCA evaluation model does not employ the second criterion .] This results in earlier cladding rupture for any case in which the rupture temperature is reached before [.] Calculating early cladding rupture is consistent with Appendix K, which requires that the incidence of cladding rupture shall not be underestimated.

6.3.9.2 CENP Small Break LOCA Evaluation Model

The CENP SBLOCA evaluation model uses the Westinghouse model for the rupture temperature of ZIRLO™ cladding [.] The model is presented in tabular form in Table 6.3.9.1-1 for the cladding dimensions of the CENP 14x14 and 16x16 fuel assemblies.

As described in Section 6.2.5, the CENP SBLOCA evaluation model does not use the NUREG-0630 cladding rupture temperature model for Zircaloy-4 cladding. Rather, it uses the [ ] curve for rupture temperature versus differential pressure described in Reference 6-38. The curve is compared to the Westinghouse ZIRLO™ model in Figure 6.3.9.2-1 for the cladding dimensions of the CENP 14x14 and 16x16 fuel assemblies that are identified in Table 6.3.9.1-1.

6.3.10 Cladding Rupture Strain

6.3.10.1 CENP Large Break LOCA Evaluation Model

The ZIRLO™ model for circumferential strain at the burst elevation developed by Westinghouse is described in Reference 6-45 (page 32 and Appendix D). The model is a correlation of rupture strain as a function of rupture temperature that conservatively bounds the ZIRLO™ test data. The model is compared to the NUREG-0630 model in Figure 6.3.10.1-1. Similar to the ZIRLO™ cladding rupture temperature model, [.]

The CENP LBLOCA evaluation model uses the Westinghouse ZIRLO™ model for circumferential rupture strain described above. The model is presented in tabular form in Table 6.3.10.1-1.

Note that the Westinghouse rupture strain model, for both Zircaloy-4 and ZIRLO™ ,[ ]

This revision to the rupture strain model, which is applicable to both the LBLOCA and SBLOCA evaluation models, is described in Reference 6-46. It was reviewed and accepted by the NRC in Reference 6-47.

The CENP evaluation model for Zircaloy-4 does not include [.] Consequently, the ZIRLO™ rupture strain model described above is applied [ ] in the CENP LBLOCA evaluation model.

6.3.10.2 CENP Small Break LOCA Evaluation Model

The CENP SBLOCA evaluation model uses the Westinghouse ZIRLO™ model for circumferential rupture strain as a function of rupture temperature. The model is presented in tabular form in Table 6.3.10.1-1. The model does not include the [ ] described in Section 6.3.10.1.

As described in Section 6.2.5, the CENP SBLOCA evaluation model does not use the NUREG-0630 cladding rupture strain model for Zircaloy-4 cladding. Rather, it uses the [ ] curve for rupture strain versus differential pressure described in Reference 6-38. The [ ] curves for both the CENP 14x14 and 16x16 fuel assembly dimensions are compared to the Westinghouse ZIRLO™ model in Figure 6.3.10.2-1.

6.3.11 Assembly Blockage versus Rupture Temperature

The ZIRLO™ model for assembly blockage is described in Reference 6-45 (pages 32-33). It was developed from [.] The model is compared to the NUREG-0630 model in Figure 6.3.11-1.

The CENP LBLOCA evaluation model uses the Westinghouse ZIRLO™ model for assembly blockage. The model is presented in tabular form in Table 6.3.11-1. The CENP SBLOCA evaluation model does not use an assembly blockage model.

6.3.12 Pre-Rupture Plastic Strain

The pre-rupture plastic strain model used in the CENP LBLOCA evaluation model calculates plastic strain as a function of the cladding temperature and the cladding rupture temperature and rupture strain. The model 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 determined for each sample. An equation for K was then obtained by linear regression analysis of the logarithmic transform of the Arrhenius equation:

$$K = A * EXP(-Q/RT)$$

where:

K = parabolic rate constant, $(gm/cm^2)^2/sec$

A = constant, $(gm/cm^2)^2/sec$

Q = activation energy, cal/mole

R = gas constant, 1.987 cal/mole-°K

T = cladding temperature, °K

This yielded the following equation for the parabolic rate constant for ZIRLO™ , at the upper 90% confidence level:

[ ]

where:

K = parabolic rate constant, $(gm\ O/cm^2)^2/sec$

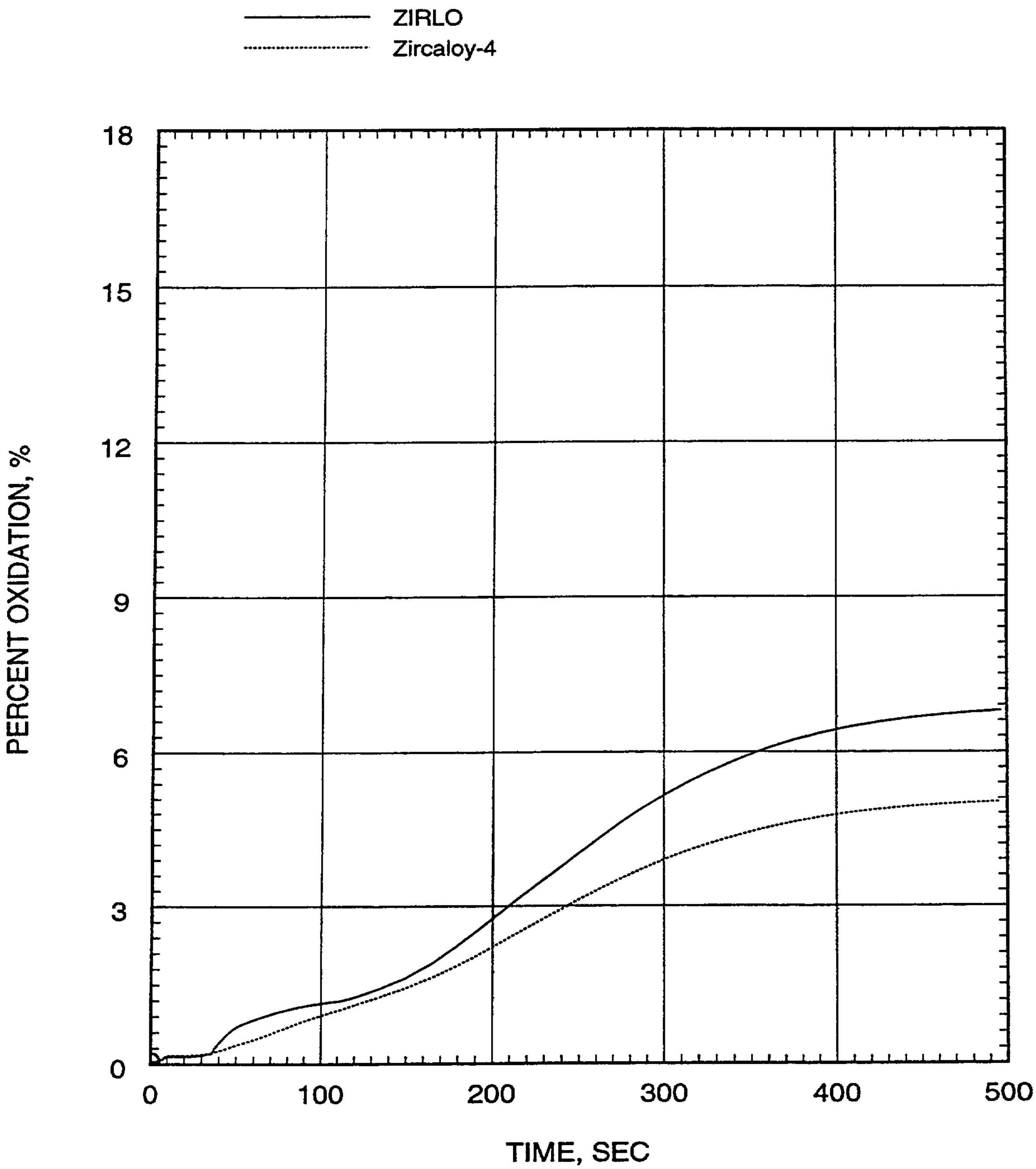
T = cladding temperature, °K

Figure 6.3.13-1 compares the equation for the ZIRLO™ parabolic rate constant with the Baker-Just model equation (Reference 6-41). The comparison shows that the Baker-Just model predicts higher reaction rate constants than the ZIRLO™ model for temperatures above approximately 1800°F .

In compliance with Appendix K to 10 CFR 50, the CENP evaluation models use the Baker-Just metal-water reaction rate model for ZIRLO™ cladding. Since the Baker-Just model predicts higher reaction rates than the upper 90% confidence level fit to the ZIRLO™ oxidation test data, it provides a conservative prediction of the metal-water reaction rate for ZIRLO™ cladding.

Figure 6.5.1.3-4

Maximum Cladding Oxidation Percentage for the LBLOCA ECCS Performance Analysis of ZIRLO™ Cladding (0.6 DEG/PD Break, Maximum Stored Energy Case)



licensing basis analyses resulted in clad temperatures which were predicted to reach 1380°F or greater. These analyses are 1) Control Element Assembly (CEA) ejection, and 2) Locked Rotor/Shaft Break analysis. For other non-LOCA analyses, clad temperatures remain below approximately 1000°F. Therefore, the use of ZIRLO™ cladding has no effect on the results of these licensing basis analyses.

Each of the two potentially affected non-LOCA licensing basis analyses were evaluated to determine what effect the use of ZIRLO™ may have on analysis results and the margin to acceptance criteria.

7.3.1 CEA Ejection

The CEA ejection accident is defined as the mechanical failure of a control element drive mechanism (CEDM) pressure housing or CEDM nozzle, resulting in the ejection of a CEA and drive shaft. The consequences of such a mechanical failure are a rapid positive reactivity insertion and system depressurization together with an adverse core power distribution, possibly leading to localized fuel rod damage.

Licensing Criteria

The CEA ejection event is analyzed at hot full power (HFP) and hot zero power (HZP) conditions. The analyses demonstrate that any consequential damage to the core or the reactor coolant system does not prevent long-term core cooling and that off-site doses remain within the guidelines of 10CFR100. More specific and restrictive criteria are applied to ensure that fuel dispersal into the coolant, gross lattice distortion, or severe shock waves do not occur. These criteria are:

1. The average fuel pellet energy at the hot spot remains below 200 cal/gm (alternately, DNB is used as a criteria for fuel failure at some CENP plants. Section 4.4 discusses the application of ZIRLO and DNB and Section 4.7 concludes that the effect is insignificant.
2. Fuel centerline temperature is limited to less than the incipient melting temperature of the fuel.

3. Peak RCS pressure is less than that which would cause clad stresses to exceed the faulted condition stress limits.

The FATES3B computer code (discussed in Section 4.0) is used to analyze the fuel performance properties. The fuel performance properties are used as input to the STRIKIN-II code, which in turn calculates fuel and clad temperatures versus time, as well as the fuel stored energy. A detailed discussion of the analysis methodology may be found in Reference 7-5.

Evaluation

Sensitivity analyses of the HFP and HZP CEA ejection events were performed, accounting for the specific heat versus temperature relationship of ZIRLO™. These analyses demonstrate that the use of ZIRLO™ cladding results in a [ ] in both the fraction of fuel melted at the hot spot as well as the peak fuel stored energy when compared to the results for Zircaloy-4.

7.3.2 Locked Rotor/Shaft Break

The Locked Rotor/Shaft Break accident is an instantaneous seizure of the reactor coolant pump (RCP) rotor or a break of the RCP shaft. Flow through the affected reactor coolant loop is rapidly reduced, leading to the initiation of a reactor trip on low loop flow. Following reactor trip, heat stored in the fuel rods continues to be transferred to the coolant causing the coolant to expand, resulting in an insurge into the pressurizer and an increase in the RCS pressure. The rapid flow reduction also results in a reduction in the minimum DNBR and potentially results in some fuel rods experiencing DNB.

Licensing Criteria

The Locked Rotor/Shaft Break event is analyzed using the following computer codes. The CENTS or CESEC computer code is used to calculate nuclear power, RCS flow and pressure during the transient. The TORC computer code (Reference 7-6) is then used to calculate the DNB vs. Integrated Radial Peaking Factor (Fr) for the limiting conditions. The ABBFFEC utility code is then used to calculate the number of fuel pins experiencing DNB and the number that subsequently fail based on both statistical convolution and deterministic methods. Two separate analyses are performed. The first analysis is performed to determine the limiting coolant conditions (i.e., pressure, flow, temperature), and the associated DNB vs. Fr pairs. A second analysis is performed to predict the number of fuel rods experiencing DNB. The second analysis is not affected by the use of ZIRLO™ because the ABBFFEC code results are not dependent on the type of cladding.

Evaluation

Sensitivity analyses have been performed to determine the effect of ZIRLO™ on the limiting coolant conditions (i.e., pressure, flow, and temperature), and the associated DNB vs. Fr pairs. Conservative analyses have determined that use of ZIRLO™ results in a [ ] when compared to Zircaloy-4.

7.4 Conclusions

Based on a review of typical non-LOCA licensing basis analyses performed for CENP designed nuclear power plants, it has been determined that only two non-LOCA events resulted in clad temperatures which were predicted to reach a clad temperature of 1380°F or greater. These analyses are 1) CEA ejection, and 2) Locked Rotor/Shaft Break accident. For other non-LOCA analyses, the clad temperatures remain below approximately 1000°F. Therefore, the introduction of ZIRLO™ cladding has no effect on these analyses.

Each of the two potentially affected non-LOCA licensing basis analyses were evaluated to determine what effect the use of ZIRLO™ may have on analysis results. This evaluation showed that use of ZIRLO™ clad material in CENP designed fuel produces acceptable results.

Non-Proprietary Version Ft. Calhoun Fuel Rod Fretting History and Root Cause Page

In summary, the Ft. Calhoun fuel failures are due to an inadequate grid design, not the ZIRLO™ cladding material. As pointed out in the ZIRLO™ Topical Report (CENPD-404-P, Rev. 0), cladding material as it affects mechanical properties does play a role in grid to rod fretting. For example, a different rod growth characteristic will affect how the cladding is exposed to the wearing surface of the grid support. However, the design of the grid is the dominant factor in determining whether fretting failures will occur.

NON-PROPRIETARY VERSION RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION PAGE

Question #11:

Equation 3-1, provide detail information to show how the T_{avg} is obtained.

Response:

The methodology for calculating the mFDI is summarized below in further detail.

The Fuel Duty Index, FDI, (Reference 11-1) was developed as an alternative to representing fuel rod corrosion as a function of burnup. The corrosion was expressed as a function of the time average fuel rod surface temperature and the total irradiation time. Subsequent studies indicated that the correlation between corrosion and the FDI could be improved (Reference 11-2) if a coolant boiling term was included. The definition of the FDIB with the boiling is:

$$FDIB = [(T_{avg} - 580)/100) * (hrs/1000)]^2 + b\, m_{e,total} \quad (1)$$

where:

T_{avg} = Time averaged rod surface temperature, °F
hrs = Total irradiation time, hrs
$m_{e,total}$ = Total mass evaporated per unit area, 10^6 lb/ft²
b = Empirical constant = [ ]

A description of a single channel thermal model used for computing the FDI inputs is provided below. The channel considered is the flow area surrounded by four fuel rods.

Inputs required for the calculation are;

- Channel hydraulic diameter, ft
- System pressure, psi
- Inlet temperature, °F
- Core coolant mass flux, lb/hr/ft²
- Rod power kw/ft
- Rod axial power shape

System inputs may be time dependent.

The enthalpy rise at any axial location, z, and time, t, is given by:

$$H(z,t) = H(0,t) + F_{mix} \int_0^z \frac{4q_{avg}(z,t)dz}{G(t)De} \quad (2)$$

The F_{mix} factor is determined by the ratio of the single channel hydraulic diameter to an effective core hydraulic diameter which accounts for guide thimbles and inter assembly spacing.

where;

q_{avg} = Channel average heat flux, BTU/hr/ft²
G = Coolant mass flux, lb/hr/ft²
D_e = Channel hydraulic diameter, ft, = 4 Area/Wetted perimeter
z = Axial location, ft

The channel average heat flux is calculated by converting Kw/ft to heat flux and taking the average heat flux of the four rods comprising the flow channel.