

**SER Compliance with
WCAP-12610-P-A & CENPD-404-P-A Addendum 1-A
“Optimized ZIRLO™” (Non-Proprietary)**

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1.0 Introduction

This report is being provided to address Conditions 6 and 7 of Section 5.0 of the SER to topical report WCAP-12610-P-A & CENPD-404-P-A Addendum 1-A (Reference 1) to provide Optimized ZIRLO™* LTA and creep/growth data. The data demonstrate that the current fuel performance models are applicable for Optimized ZIRLO™ fuel rods.

Condition 6 of the SER to Reference 1 states the following:

6. “The licensee is required to ensure that Westinghouse has fulfilled the following commitment: Westinghouse shall provide the NRC staff with a letter(s) containing the following information (Based on the schedule described in response to RAI #3):
 - a. Optimized ZIRLO™ LTA data from Byron, Calvert Cliffs, Catawba, and Millstone.
 - i. Visual
 - ii. Oxidation of fuel rods
 - iii. Profilometry
 - iv. Fuel rod length
 - v. Fuel assembly length
 - b. Using the standard and Optimized ZIRLO™ database including the most recent LTA data, confirm applicability with currently approved fuel performance models(e.g., measured vs. predicted).

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

Condition 7 of the SER to Reference 1 states the following:

7. “The licensee is required to ensure that Westinghouse has fulfilled the following commitment: Westinghouse shall provide the NRC staff with a letter containing the following information (Based on the schedule described in response to RAI #11):
 - a. Vogtle growth and creep data summary reports.
 - b. Using the standard ZIRLO™ and Optimized ZIRLO™ database including the most recent Vogtle data, confirm applicability with currently approved fuel performance models (e.g., level of conservatism in W rod pressure analysis, measured vs. predicted, predicted minus measured vs. tensile and compressive stress).

* ZIRLO™ trademark property of Westinghouse Electric Company LLC

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

2.0 Condition 6 Compliance – LTA Data

2.1 LTA Program Schedule

The four listed LTA programs are at different stages of their execution. While the Byron LTA program has concluded, the Calvert-Cliffs, Catawba and Millstone LTA programs are still on-going. The Byron LTA program included both stress relief annealed (SRA) and partially recrystallized annealed (PRXA) Optimized ZIRLO™ while the other three LTA programs only included PRXA Optimized ZIRLO™. Table 1 provides a summary of the status of the various LTA programs. It should be noted that the availability of data and plans associated with future dates are projections and depend on the operation of the plants and thus may change in the future.

Table 1 – Optimized ZIRLO™ LTA Irradiation and Planned Examination Status

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a,c

2.2 Data Presentation and Analysis

2.2.1 Visual Examination

Visual inspections were performed subsequent to each irradiation cycle in all of the LTA programs. A summary of the visual inspections from each of the on-going LTA programs is described in the following subsections. In summary, no anomalous performance was observed.

Byron LTA

Visual inspections were performed on the Byron LTAs after each of the three irradiation cycles. Minor crud was reported on both SRA Optimized ZIRLO™ and Standard ZIRLO™ fuel rods at each inspection. No anomalies were reported for any of the three alloy variations.

Calvert Cliffs LTA

Visual inspections were performed on assemblies []^{a,c} after one 24-month cycle. Minor crud was observed on fuel rods in both assemblies but no anomalies were found. There were no areas of localized crud or corrosion accumulation.

Catawba 1 LTA

The Catawba LTA program is composed of []^{a,c} assemblies of the Westinghouse 17x17 Next Generation Fuel (NGF) design. []^{a,c} LTAs were inspected after 1 cycle of operation in the Catawba Unit 1 plant. Dark crud was observed on the fuel rods and on many assembly components. The dark crud is thought to be due to the replacement of steam generators, consistent with the crud observed in the McGuire plants following steam generator replacement there. []^{a,c} LTAs were inspected after 2 cycles of operation in the Catawba Unit 1 plant. Minor quantity of crud was observed on the fuel rods in the assemblies but no anomalies were observed.

Millstone 3 LTA

The Millstone LTA program is composed of []^{a,c} assemblies of the Westinghouse 17x17 NGF design. []^{a,c} LTAs were inspected after 1 cycle of operation. Minor crud was observed on fuel rods in both the NGF LTAs and Standard ZIRLO™ Robust Fuel Assembly (RFA) assemblies. No anomalies were observed. []^{a,c} NGF LTAs were inspected after 2 cycles of operation in the Millstone Unit 3 plant. Expected normal quantity of non-adherent crud was observed on the fuel rods in the assemblies but no anomalies were observed.

2.2.2 Oxidation of Fuel Rods

Fuel rod oxide measurements are currently available from the Byron, Catawba, and Millstone LTAs. In the future, per the schedule shown in Table 1, additional data are expected to become available from the continuation of the Catawba, Millstone, and Calvert Cliffs LTA programs. The oxide thickness from the Byron LTA program was measured after each cycle of operation. The oxide thickness from the Catawba and Millstone LTA programs was measured after 2 cycles of operation. The data (Figures 1 and 2) show the corrosion rate of the Optimized ZIRLO™ to be significantly lower relative to that of the Standard ZIRLO™.



Figure 1 – Measured Oxide Thickness Plotted as a Function of the Modified Fuel Duty Index



Figure 2 – Measured Oxide Thickness Plotted as a Function of Rod Peak Burn-up

2.2.3 Profilometry

The fuel rod profile was measured after one cycle of operation on []^{a,c} PRXA Optimized ZIRLO™ rods []^{a,c}. These rods were inserted into the Byron []^{a,c} host assembly prior to the third cycle of irradiation of the host assembly. []

[]^{a,c}. Diameter profile measurements of these fuel rods after one irradiation cycle and prior to clad-pellet contact show the fuel rod creep down is well within the PAD fuel rod performance code predictions. Representative measured vs. PAD predictions for the PRXA Optimized ZIRLO™ fuel rods are shown in Figures 3 to 5.



Figure 3 – Comparison of Fuel Rod Diameter between Measured and PAD 4 Predicted for PRXA Optimized ZIRLO™ Rod A06



Figure 4 - Comparison of Fuel Rod Diameter between Measured and PAD 4 Predicted for PRXA Optimized ZIRLO™ Rod B07



Figure 5 - Comparison of Fuel Rod Diameter between Measured and PAD 4 Predicted for PRXA Optimized ZIRLO™ Rod C16

Figures 3 to 5 show good agreement in the outer diameter profiles between the PAD code predictions and the measured values. In particular, the region of highest creep rate (i.e., elevations of 80 to 120 inches) shows excellent agreement. The predictions follow the measured axial shape which indicates that the code is well behaved with respect to the in-reactor irradiation creep model temperature dependence. The agreement between measurements and predictions is well within expected measurement uncertainties and code design uncertainties in the creep rate. These comparisons demonstrate that the creep rate of the PRXA Optimized ZIRLO™ is equivalent to that of the Standard ZIRLO™ and confirms that the licensed PAD 4 creep model is applicable for Optimized ZIRLO™. Similarly, the FATES code would also be applicable in predicting creep behavior of the PRXA Optimized ZIRLO™ in the CE fuel design, since it uses the same creep model as PAD.

2.2.4 Fuel Rod Length

Fuel rod length was measured on the Byron SRA Optimized ZIRLO™ fuel rods and the Byron, Catawba, and Millstone PRXA Optimized ZIRLO™ fuel rods. The measured fuel rod length is plotted with the Standard ZIRLO™ assembly average fuel rod growth database in Figure 6. The measurements show the growth of SRA and PRXA Optimized ZIRLO™ to be within the scatter band of the ZIRLO™ fuel rod growth database.



Figure 6 – Fuel Rod Growth Measurements from SRA and PRXA Optimized ZIRLO™

2.2.5 Fuel Assembly Length

Fuel assembly growth data are currently available from the Byron, Catawba, and Millstone programs. The assembly growths of the Optimized ZIRLO™ LTAs are plotted in Figure 7 along with the Standard ZIRLO™ database. The comparison shows Optimized ZIRLO™ to behave comparable to Standard ZIRLO™.



Figure 7 – Assembly Growth Plotted as a Function of Fast Neutron Fluence

2.3 Summary

The LTA measurements showed the corrosion rate of the SRA Optimized ZIRLO™ and PRXA Optimized ZIRLO™ to be significantly lower than that of the Standard ZIRLO™ and thus this property is bounded by the predictive capability of the approved ZIRLO™ corrosion model. The measured Byron fuel rod creep data confirm that the creep rate of the PRXA Optimized ZIRLO™ is within the expected accuracy of the licensed creep model. Similarly, the measured SRA/PRXA Optimized ZIRLO™ fuel rod growth is also within the predictive capability of the Standard ZIRLO™ fuel rod growth model as the measured values are well within the scatter band of the Standard ZIRLO™ fuel rod growth database. The measured Optimized ZIRLO™ fuel assembly growth is also within the scatter band of the Standard ZIRLO™ fuel assembly growth database.

3.0 Condition 7 Compliance – Creep/Growth Data

3.1 Creep/Growth Test Program Schedule and Status

The irradiation schedule of the Creep/Growth test is shown in Figure 8. The current status is as follows. Test assemblies A1, A3 and A5 have been discharged. Table 2 lists the status of the data evaluation. The data evaluation consists of sample laser outside diameter (OD) and length measurements, sample oxide thickness measurements, coolant temperature calculations based on the post-run fuel assembly powers, determination of the gamma-heating rate, sample temperature and hoop stress, and measurement of the fast fluence by retrospective dosimetry. In the case of test assemblies A1, A5, and A3, the OD, length and oxide thickness measurements have been performed and the OD and length strains calculated. The coolant temperature, sample temperature and hoop stress analysis are completed. The fluence/dosimetry measurements for test assembly A1 are in-progress. In the interim, calculated fluence values are being used.

The irradiation of test assembly A2 has been completed and it is currently in temporary storage in the Vogtle fuel pool. Test assembly A2 is scheduled for shipment to a hot cell in January 2009.

Test assembly A4 is still under irradiation. The test assemblies A1, A5, and A3 data are available for evaluation. Data from the remaining test assemblies will be provided in the future.

Table 2 – Status of the Creep/Growth Data Evaluation

Assembly	Parameter	Status
A1, A3, A5	OD	Complete
A1, A3, A5	Length	Complete
A1, A3, A5	Oxide thickness	Complete
A1, A3, A5	Coolant T	Complete
A1, A3, A5	Hoop Stress & T	Complete
A1, A3, A5	Fluence	Calculations are available. Measurements are in-progress
Notes:		
1. A2 is in temporary storage in the Vogtle fuel pool		
2. A4 is in-reactor		

Cycle#:	10	11	12	13	14	15
Date:	<u>Fall 2002</u>	<u>Spring 2004</u>	<u>Fall 2005</u>	<u>Spring 2007</u>	<u>Fall 2008</u>	<u>Spring 2010</u>
<u>Assembly</u>	A1, A2, and A3 contain [] ^{a,c}	
A1	x-----x					
A2	x-----x					
A3	x-----x					
	A4 and A5 contain [] ^{a,c}	
A4	x-----x					
A5	x-----x					

Figure 8 – Irradiation Schedule of the Creep/Growth Test

3.2 Creep/Growth Irradiation Conditions

The samples are located in segmented rods suspended inside the fuel assembly thimble tubes. All of the test samples are placed in positions approximately 90 cm above and below the core midplane. The samples are free-standing in the core. That is, the samples are not located at the axial positions of the mid-grids or intermediate flow mixer (IFM) grids. The samples are radially located relatively close to core center. The samples are always hosted by a one-cycle burned fuel assembly. Fast flux calculations showed that the fast flux for these conditions is approximately the same for all of the samples (the fast flux is approximately constant) and remains the same from cycle-to-cycle. The dosimetry measurements are being performed to confirm these calculations.

The amount of gamma-heating was determined by testing samples having the same tubing with two different internal heating rates. The samples did not contain any fuel. Each sample had either a solid cylinder or an internal tube to support the sample if collapse were to occur (the samples were tested at compressive stress levels that calculations showed would not result in collapse). Since the mass of the solid cylinders was much greater than the internal tubes, these two different types of samples generated different amounts of internal heat due to gamma-heating. As a result, the gamma-heating was evaluated by parametric calculations using the diameter strain data. The gamma-heat was used to calculate the sample temperature distributions. The calculated temperatures for test assemblies A1, A5, and A3 were in the range of []^{a,c}. The samples in the lowest axial positions are associated with temperatures of []^{a,c}, and the samples in the highest axial position are associated with temperatures of []^{a,c}.

3.3 Creep/Growth Test Data

The results to be presented are 1) the irradiation growth and creep of Standard ZIRLO™ and PRXA Optimized ZIRLO™ and 2) the irradiation creep of Standard ZIRLO™ under tension and compression hoop stresses. The presentation of the irradiation growth and irradiation creep data summarizes currently available Creep/Growth data in partial compliance with Condition 7a of the SER to Reference 1.

The measurement accuracy associated with the OD and length laser measurements is excellent. Consider the OD data. The 95% confidence interval of the mean OD value is about []^{a,c}. The 95% confidence interval measurement error is very small because the data for each sample consist of []^{a,b,c}.

The fast fluence for test assemblies A1, A5, and A3 are []^{a,c} respectively. The Creep/Growth test does not contain fuel so the irradiation is properly characterized by fast fluence and not burnup.

3.3.1 Irradiation Growth

Figures 9 and 10 present the diameter irradiation growth data for Standard ZIRLO™, PRXA Optimized ZIRLO™ and SRA Optimized ZIRLO™ fabricated by a []^{a,c} 4-pass tube reduction sequence from TREX to final size tubing. The irradiation growth samples had holes to allow the coolant water to be both at the OD and ID. This insured that the samples were unstressed. Each marker in Figures 9 and 10 represents one sample. Irradiation growth data are available for two PRXA Optimized ZIRLO™ lots. Figures 9 and 10 show that the irradiation growth of the two PRXA Optimized ZIRLO™ lots is consistent. Further, the irradiation growth of PRXA Optimized ZIRLO™ and Standard ZIRLO™ is comparable.

ZIRLO Diameter Irradiation Growth
Vogtle 2 Cycle 10 (Samples open to coolant water), 305-315 C

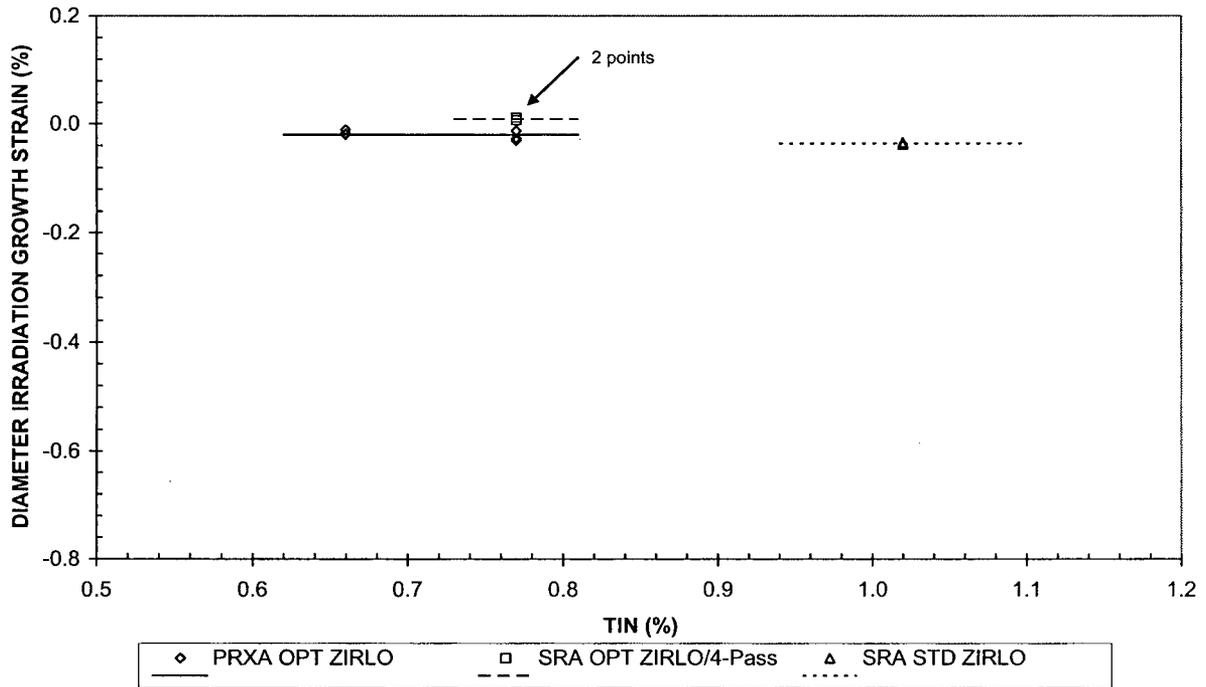


Figure 9 – ZIRLO™ Irradiation Growth after 1 Cycle (Test Assembly A1)



a,b,c

Figure 10 – ZIRLO™ Irradiation Growth after 2 Cycles (Test Assembly A3)

3.3.2 Irradiation Creep

The irradiation creep was measured using samples filled with helium gas. The internal gas pressure was either below or above system pressure so that the samples were in either compression or tension hoop stress, respectively. The irradiation creep diameter strain, $\Delta D/D_o(ic)$, was calculated from the total measured strain, $\Delta D/D_o(total)$, and the average irradiation growth strain, $\Delta D/D_o(ig)$, according to,

$$\Delta D/D_o(ic) = \Delta D/D_o(total) - \Delta D/D_o(ig)$$

Figures 11 and 12 presents the diameter irradiation creep data for Standard ZIRLO™, PRXA Optimized ZIRLO™ (tube samples from two lots) and SRA Optimized ZIRLO™ tubes fabricated by a []^{a,c} 4-pass tube reduction sequence from TREX to final size tubing. Each marker in Figures 11 and 12 represents one sample. The irradiation creep of all of the materials is comparable. This shows that 1) the irradiation creep of PRXA Optimized ZIRLO™ and Standard ZIRLO™ are comparable, and 2) Optimized ZIRLO™ with the same irradiation creep may be fabricated with either a PRXA or SRA final microstructure by changing the tube reduction process. Comparison of Figures 11 and 12 with Figures 9 and 10 shows that the irradiation growth of PRXA Optimized ZIRLO™ and Standard ZIRLO™ is more than an order of magnitude less than the irradiation creep.

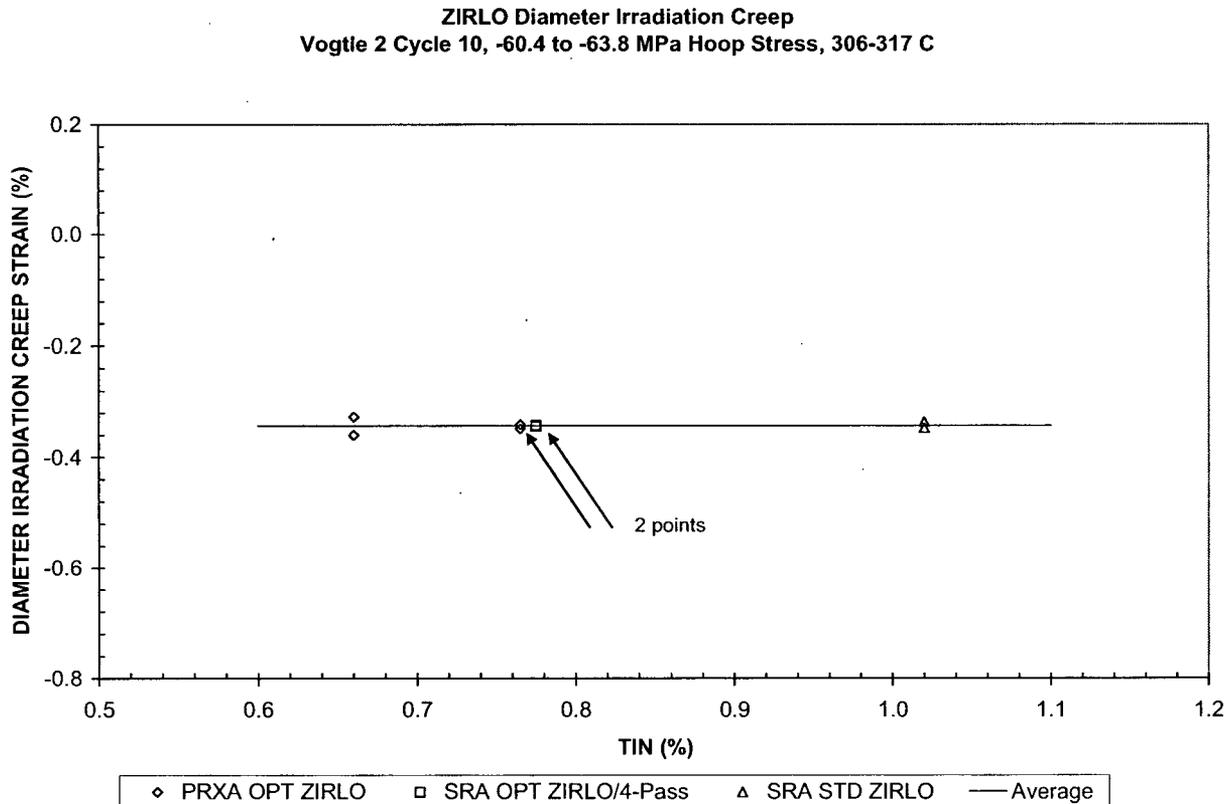


Figure 11 – ZIRLO™ Irradiation Creep after 1 Cycle (Test Assembly A1)



Figure 12 – ZIRLO™ Irradiation Creep after 2 Cycles (Test Assembly A3)

Figures 13 to 15 present the irradiation creep data for Standard ZIRLO™ for tension and compression hoop stresses. The stress ranges are from about []^{a,b,c} hoop stress. This hoop stress range approximately envelopes the range of hoop stresses experienced by fuel rods during normal operation. Each marker in Figures 13 to 15 represents one sample. In the case of test assembly A1, compression hoop stress data are available for []^{a,b,c} and tension hoop stress data are available for []^{a,b,c}. In the case of test assembly A5, compression hoop stress data are available for []^{a,b,c} and tension hoop stress data are available for []^{a,b,c}. In the case of test assembly A3, compression hoop stress data are available for []^{a,b,c} and tension hoop stress data are available for []^{a,b,c}. Most of the stress levels include duplicate samples to confirm strain level consistency. Figures 13 to 15 show that the scatter of duplicate samples is negligible. Further, Figures 13 to 15 show that the data are very consistent between stress levels, and that the behavior is linear as a function of hoop stress. The non-zero $\Delta D/D_0$ intercept at zero stress is attributed to the effect of internal stresses as discussed in Reference 2.



Figure 13 – Irradiation Creep in Tension and Compression after 1 Cycle (Test Assembly A1)



Figure 14 – Irradiation Creep in Tension and Compression after 1 Cycle (Test Assembly A5)



Figure 15 – Irradiation Creep in Tension and Compression after 2 Cycles (Test Assembly A3)

3.4 Discussion of the OD Strain Components

Figures 13 to 15 present the Standard ZIRLO™ irradiation creep strain for compressive and tensile hoop stresses. The currently available Creep/Growth data are not sufficient to separate the total strain into transient and steady state components. However, Halden measurements on Standard ZIRLO™ samples are available (Tests IFA-663 and IFA-617) that allow the separation of the total strain into transient and steady state components. The duration of the transient component is,

298 FPH at a flux of 2.7×10^{13} n/cm²-s (E>1) for Halden Test IFA-663, and
 243 FPH at a flux of 4.5×10^{13} n/cm²-s (E>1) for Halden Test IFA-617.

In terms of fluence, the average duration of the transient is,

$$\begin{aligned} 2.7 \times 10^{13} \text{ n/cm}^2\text{-s} * 298 \text{ h} * 3600 \text{ s/h} &= 0.029 \times 10^{21} \text{ n/cm}^2 \\ 4.5 \times 10^{13} \text{ n/cm}^2\text{-s} * 243 \text{ h} * 3600 \text{ s/h} &= 0.039 \times 10^{21} \text{ n/cm}^2 \\ \hline &0.034 \times 10^{21} \text{ n/cm}^2 \text{ average} \end{aligned}$$

The fluence for the Creep/Growth test assemblies are [

] ^{a,c}.

Based on the Halden data, the test assembly samples are in steady state creep for [] ^{a,c} of their irradiation period. Therefore, a significant fraction of the total irradiation creep strains presented in Figures 13 to 15 is steady state irradiation creep.

According to the original reported evaluation of Halden test IFA-585 (Reference 3), the steady state irradiation creep rate in tension is 50% higher than in compression. The original evaluation has been updated (Reference 4). Reference 4 showed that the Halden test is most likely in transient and not in steady state irradiation creep. Hence, firm conclusions cannot be reached on the behavior of steady state irradiation creep with the Halden IFA-585 test. Further, note that these results were based on testing with fully recrystallized Zr-2. If Standard ZIRLO™ steady state irradiation creep rate in tension was significantly greater than compression, then the compression and tension irradiation creep data shown in Figures 13 to 15 could not be described by one linear equation because []^{a,c} of the irradiation period is in steady state creep. Instead, the data would have to be described by two linear equations, one in the compression stress range and the second with a higher slope in the tension stress range. Since the Creep/Growth compression and tension hoop stress data are described by one linear equation and not two, the steady state irradiation creep is the same in tension and compression for the Standard ZIRLO™ and Optimized ZIRLO™ fuel cladding produced according to Westinghouse processes.

3.5 Fuel Performance Models

The PAD 4.0 irradiation growth and irradiation creep models were benchmarked using Standard ZIRLO™. The FATES code uses the same creep model as PAD. The Creep/Growth data presented above confirm that irradiation growth and irradiation creep are comparable for Standard ZIRLO™ and PRXA Optimized ZIRLO™. This meets Condition 7b of the SER to Reference 1.

The current fuel performance model has the same irradiation creep in tension and compression. The Standard ZIRLO™ data presented above show that irradiation creep is the same for tension and compression hoop stresses. Therefore, the current fuel performance model assumption of the same irradiation creep in tension and compression is consistent with the available Vogtle data.

4.0 Summary

In compliance with Conditions 6 and 7 of Section 5.0 of the SER to topical report WCAP-12610-P-A & CENPD-404-P-A Addendum 1-A (Reference 1), the following information has been provided:

- Visual, oxidation of fuel rods, profilometry, fuel rod length, and fuel assembly length data for Optimized ZIRLO™ LTAs.
- Confirmation of the applicability of currently approved fuel performance models to Optimized ZIRLO™ based on available LTA data. Specifically, the model predictions of steady state creep are in very good agreement with profilometry measurements.
- Irradiation creep and irradiation growth data available from the Vogtle Creep/Growth tests.
- Confirmation of the applicability of currently approved fuel performance models to Optimized ZIRLO™ based on available Vogtle Creep/Growth data. Specifically, the irradiation creep of Standard ZIRLO™ is comparable to PRXA Optimized ZIRLO™, the stress dependence of the irradiation creep strain is linear, and steady state irradiation creep in tension and compression are the same for Westinghouse fuel cladding.

The Vogtle Creep/Growth measured data, LTA measured data, and favorable results from visual examinations of once-burned and twice-burned LTAs confirm, for at least two cycles of operation, that the current fuel performance models are applicable for Optimized ZIRLO™ fuel rods. Furthermore, since there is essentially no difference in the key performance parameters between Standard ZIRLO™ and Optimized ZIRLO™, it is expected that the existing fuel performance models will remain applicable for Optimized ZIRLO™ fuel rods to the licensed fuel burnup limit.

Additional data from the on-going Optimized ZIRLO™ LTA and Creep/Growth programs will be provided after new data for higher burnup/fluence become available.

5.0 References

1. WCAP-12610-P-A & CENPD-404-P-A Addendum 1-A, "Optimized ZIRLO™," July 2006.
2. C. N. Tomé et al., "Role of Internal Stresses in the Transient of Irradiation Growth of Zircaloy-2," *Journal of Nuclear Materials*, Volume 227, 1996, pages 237-250.
3. M. McGrath, "In-reactor Creep Behavior of Zircaloy Cladding," International Topical Meeting on Light Water Reactor Fuel Performance, American Nuclear Society, Park City Utah, April 10-13, 2000.
4. J. Foster and M. McGrath, "In-Reactor Creep Behavior of Zircaloy Cladding," International Topical Meeting on Light Water Reactor Fuel Performance, American Nuclear Society, San Francisco CA, September 30-October 3, 2007.