Letter Report: OG-11-143

PWROG 50.46(b) Margin Assessment

PWROG

PWR Owners Group

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PWROG 50.46(b) Margin Assessment

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1 Background

Approximately 10 years ago, the Nuclear Regulatory Commission (NRC) commissioned an experimental program at Argonne National Laboratory (ANL) to validate two of the five 10 CFR 50.46 Loss-of-Coolant Accident (LOCA) acceptance criteria. These criteria, 2200°F peak cladding temperature (PCT) limit and 17 percent local oxidation limit, had been developed in 1973 based on experiments with fresh, unirradiated cladding material, and had never been validated for irradiated cladding.

The ANL program performed post LOCA ductility, termed post-quench ductility (PQD), testing on fresh cladding, irradiated cladding, and pre-hydrided cladding. The results show that irradiation has a significant impact on post-quench ductility and that this impact is the consequence of hydrogen absorption during normal operation. During operation, corrosion releases hydrogen which is absorbed by the cladding. The main embrittlement process for high temperature oxidation is oxygen embrittlement. Hydrogen, to the extent present in the cladding, increases the diffusivity of oxygen into the cladding and the solubility of oxygen in the cladding at high temperatures.

Another observation of the ANL program is the occurrence of breakaway oxidation at moderately high cladding temperatures. This phenomenon occurs at singularity temperatures of 1000°C and 800°C and requires only relatively low amounts of oxidation. When cladding remains at these temperatures for an extended period of time, the crystalline structure of the oxide changes from a protective layer which does not allow significant hydrogen absorption to an oxide layer which is much looser and allows rapid hydrogen absorption.

The third item of significance resulting from the ANL program is that some oxygen absorption on the inside of the cladding can occur even without cladding rupture. The source of oxygen is from an operationally developed interior corrosion layer, due to fission product oxygen, and oxygen extracted from the pellet uranium oxide molecule. Because extraction from the pellet is the dominant mechanism, this process is only important after cladding creep produces hard contact between the pellet and the cladding.

2 PWROG Margin Assessment

In August 2009 the NRC published an advance notice of proposed rulemaking in the federal register (Reference 1). As part of this rule making package, a change in the oxidation acceptance criterion was proposed based on testing that was done at ANL (Reference 2). To ensure that the current operating fleet maintains some margin to this new criterion, the NRC began the process of gathering plant-specific information related to Emergency Core Cooling System (ECCS) performance. The Pressurized Water Reactor Owners Group (PWROG) and Boiling Water Reactor Owners Group (BWROG) proposed performing a survey of plant information for transmittal to the NRC via Nuclear Energy Institute (NEI). The process for the PWROG involved the fuel vendors surveying the plant-specific LOCA analyses, collecting licensing basis analysis results, and comparing the current results against the proposed acceptance criterion.

The NRC proposed an equivalent cladding reacted (ECR) criterion as a function of cladding hydrogen content. Industry discussions concluded that for the current effort, the criterion should be modified to: 1) Reduce the allowable ECR from 18% to 17% at 0 ppm cladding hydrogen content to be consistent with current regulations, and 2) continue past 600 ppm hydrogen at a continuous slope based on the industry interpretation of current test data. This modified criterion is presented as Figure 1, and is hereafter referred to as the proposed criterion.

The approach of the PWROG margin assessment was presented to the NRC during two public meetings. The first occurred on August 12, 2010 (Reference 3) and the second on December 2, 2010 (Reference 4). The approach presented to the NRC and approved by the PWROG was one in which plant licensing basis analyses are surveyed, the plants are then grouped, the group results are compared to the proposed hydrogen-based local oxidation acceptance criterion, and adjustments for conservatism are applied as necessary to show that groups have margin to the proposed limit. Additionally, breakaway oxidation is addressed via comparison of transient time-at-temperature versus established breakaway times.

The necessary plant information was gathered and sent to individual utilities for confirmation. In parallel to the utility confirmation of the information, sensitivity studies and data extraction were initiated to determine the magnitude of possible adjustments. The representative hydrogen concentration versus burnup curves for each cladding material was also generated as discussed in the following section.

3 Cladding Hydrogen Concentration

The calculation of the cladding hydrogen content as a function of burnup, and the associated burnup selected to perform the plant licensing basis analysis assessments are described in this section of the report.

3.1 Westinghouse Cladding Hydrogen Concentration

The hydrogen concentrations for cladding used in Westinghouse and Combustion Engineering (CE) Nuclear Steam Supply System (NSSS) plant designs (either ZIRLO® or Optimized ZIRLO™ cladding)[1] are based on Figure 3.3-3 of Reference 5, which shows cladding hydrogen concentration as a function of oxide thickness. The hydrogen concentration as a function of burnup was generally determined by using an oxide

[1] Optimized ZIRLO and ZIRLO are trademarks of the Westinghouse Electric Company LLC in the United States and may be registered in other countries throughout the world.

thickness vs. burnup curve for a limiting Pressurized Water Reactor (PWR) core which was modified to achieve a 100 micron oxide thickness at 62 GWD/MTU burnup. The hydrogen content for ZIRLO® cladding at about 50 GWD/MTU is 432 ppm based on this curve. Since ZIRLO® cladding supports higher fuel duty; the oxide thickness and therefore hydrogen concentration of the cladding are higher than that of Zircaloy-4 for cores with high fuel duty. (Note that the use of Zircaloy-4 would not give acceptable results for those core designs.)

A plant-specific maximum calculated oxide thickness versus burnup was used for certain plants (as available) in order to capture the limiting oxidation for a given plant. As such, the cladding hydrogen content corresponding to a certain burnup may differ from group-to-group.

3.2 AREVA Cladding Hydrogen Concentration

The plants for which AREVA provides reload fuel use either M5® or Zircaloy-4 cladding. The FRAPCON3 cladding hydrogen concentration versus burnup for M5® cladding is based on Figure 16 of Reference 6, while Figure 5 of Reference 7 is used for plants that use Zircaloy-4 cladding. These two figures are reproduced herein for the convenience of the reader as Figure 2 and Figure 3, respectively.

3.3 Evaluated Burnup

A key input to the concentration of hydrogen in the cladding is the burnup for which the hydrogen concentration is evaluated. As discussed in the August 12, 2010 public meeting, there is a substantial drop in power for typical fuel assemblies in the 3rd cycle of residence in a reactor core in typical core designs. Because of the reduced power, these assemblies cannot produce substantial oxidation and therefore will not be evaluated by this assessment. Thus, no additional evaluation for burnup above approximately 50 GWD/MTU was performed.

Where available for certain plants, the evaluated burnup may deviate slightly from 50 GWD/MTU, in order to capture the limiting point corresponding to a plant-specific core design and operating condition.

As discussed in Section 1 of this report, oxygen absorption from the fuel into the inside of the cladding can occur after cladding creep produces hard contact between the pellet and the cladding, which is estimated to occur prior to burnup of 50 GWD/MTU. Since the evaluated burnup is approximately 50 GWD/MTU, all calculated oxidation results which are single-sided are doubled as a conservative surrogate to account for interior oxidation resulting from fuel-to-clad bonding.

4 Grouping Process

In an effort to communicate plant margins to the NRC while maintaining the plant-specific information as proprietary, the plant results are grouped and the most limiting plant information for each group is presented in this report. The detailed information for all the plants included in this report is available to the NRC for audit at the vendor offices. The process utilized to group the plants is described in this section.

In this report, the plants are grouped by margin to the proposed limit (Figure 1). All the plants which can currently meet the requirements are placed in one group, and any plants that need to take adjustments for conservatisms in their licensing basis analysis are grouped together by the type of adjustments applied. The grouping of plants by physical characteristics (i.e. core size, loop configuration, and ECCS differences) was initially proposed for this report. However, upon implementation of the grouping process it quickly became apparent that the initially proposed method of grouping plants by physical characteristics would be difficult. Since the analysis methodology and/or cladding alloy are among key contributors to the plant margins, and these parameters define the plant eligibility for a number of adjustments, the grouping criterion was based on these factors rather than physical characteristics. Some groups are characterized by plants which show margin to the proposed ECR criterion crediting the benefit for transitioning from one evaluation methodology (EM) to an improved version of that EM or to a completely new EM. However, one group is characterized by plants which presently need to show margin to the proposed ECR criterion based on Appendix K methodology.

The limiting result from among all plants within each grouping is defined to be the plant with the lowest oxidation margin. Once a group showed positive margin to the proposed limit, no additional adjustments were applied to that group. It should be noted that with this approach, the amount of positive margin is under-estimated.

5 Large Break LOCA Adjustments

The adjustments applied to plants' Large Break LOCA analyses-of-record are discussed in this section. The majority of plants needed no adjustments to show a positive margin of safety to the proposed 10 CFR 50.46(b) oxidation criterion shown in Figure 1; however, there were several plants that were required to credit conservatisms to show a positive margin of safety to the proposed limit.

The adjustments which were used in this assessment, explained in more detail later, are as follows:

- Transition from Appendix K to Best-Estimate Evaluation Model
- Transition from Code Qualification Document (CQD) to Automated Statistical Treatment of Uncertainty Method (ASTRUM) Evaluation Model
- Translation of Baker-Just Oxidation to Cathcart-Pawel Oxidation
- Reload Power History
- Improved Statistics in Best-Estimate Analysis Evaluation Model
- Burnup Study
- Increase in Allowed ECR for Reduced PCT

While not explicitly used to show margin in this analysis, plants may also be able to credit additional benefits such as peaking factor burndown, changing to new cladding materials, the ongoing 10 CFR 50.46(a) rulemaking, and other unspecified benefits all of which would show a significant increase in margin.

5.1 Transition from Appendix K to Best-Estimate Methods

Since the development of best-estimate LOCA methods, a large number of plants have reanalyzed and replaced their licensing basis analysis with one utilizing the updated methods. With the oxidation values for both analysis methodologies readily available, the benefits of changing from Appendix K to best-estimate methods was estimated for such instances based on the available plant information. The estimated benefit from this change in methodology is approximately a 60% reduction in oxidation.

5.2 Transition from CQD to ASTRUM Evaluation Model

This credit is specific to Westinghouse analyses, and involves the change from a response-surface best-estimate LOCA methodology (CQD) to a newer Westinghouse best-estimate LOCA methodology which is based on order statistics (ASTRUM). Since the development of newer LOCA analysis methods, a large number of plants have updated their licensing basis analyses. With the oxidation values for both types of analyses readily available, a list of plants which have transitioned between these methodologies was created and the benefits of changing from the CQD to ASTRUM best-estimate methodology was quantified for each instance. The resulting benefit estimated from this change in methodology is approximately a 50% reduction in oxidation.

5.3 Translation of Baker-Just to Cathcart-Pawel Oxidation

Appendix K evaluation models are required to utilize Baker-Just oxidation kinetics models for local oxidation and exothermic reaction rates for fuel rod heat balance calculations. For accurate comparison to the research data used for the new NRC post-quench ductility criterion, local oxidation calculations must be performed using the Cathcart-Pawel correlation. Therefore, the limiting local oxidation calculated using the Baker-Just correlation with the Appendix K Evaluation Model is converted to local oxidation using the Cathcart-Pawel correlation by applying a simple temperature-dependent ratio, which is shown in Figure 4.

Since the cladding temperature transient from the licensing basis analysis is unchanged and still based on the use of Baker-Just oxidation kinetics, this conversion of Baker-Just local oxidation to Cathcart-Pawel local oxidation does not credit the lower exothermic reaction rate and lower heat addition that would lead to lower local oxidation in an evaluation model fully utilizing the Cathcart-Pawel correlation. Moreover, this conversion of Baker-Just to Cathcart-Pawel local oxidation also accounts for the cladding metal corrosion resulting from plant operation. The magnitude of this adjustment is determined on a plant-specific basis.

5.4 Reload Power History

As part of the reload process, core power histories are analyzed along with associated fuel performance evaluations. The burnup-dependent fuel performance rod power histories and rod internal pressure calculations are based on bounding core reload depletions with established thermal-mechanical rod power operating limits for no-clad-liftoff and power-to-melt. These operating limits are validated and confirmed for each fuel cycle. The magnitude of this adjustment is determined on a plant-specific basis. In other words, the ECR at the hot rod peak linear heat generation rate is converted to the ECR at the linear heat rate of the evaluated burnup by applying a normalized radial peaking factor dependent ratio. Figure 5 shows how this adjustment varies as a function of normalized radial peaking factors (RPFs).

5.5 Improved Statistics for Best-Estimate Analyses

The Westinghouse ASTRUM methodology uses the limiting result from 124 runs to determine the 95th PCT, ECR, and core-wide oxidation (CWO) with 95% confidence. However, a lower ranking analysis result can be used to estimate the 95th percentile for one parameter of interest (such as oxidation) with 95% confidence. As a result, the explicitly calculated oxidation resulting from the 3rd most limiting case may be taken as a credit for existing analyses. Alternatively, a conservatively estimated 23% reduction in oxidation may be used in lieu of the specific oxidation results for a group which utilizes the change to ASTRUM methodology (i.e. specific ASTRUM analysis results are not available).

5.6 Burnup Study

In certain circumstances plants have explicitly evaluated pre-transient plus transient ECR to address concerns raised in the NRC Information Notice 98-29 (Reference 8). As part of these assessments, explicit transient calculations were executed at an increased burnup. The results of these transient cases are available as an estimate of the maximum transient ECR that would occur at higher burnup, similar to the burnups evaluated in this report. As such, these transient oxidation results can be credited and used for comparison against the proposed ECR limit (Figure 1). The exact magnitude of this credit is determined on a group-specific basis, and was estimated as a 40% reduction in transient oxidation for the group to which it was applied.

5.7 Increase in Allowed ECR for Reduced PCT

The testing performed by ANL which serves as a basis for the 10 CFR 50.46(b) rulemaking was generally conducted at a cladding temperature of 2200°F. However, oxygen is less soluble in cladding which oxidizes at lower temperatures. As such, more oxidation is required to embrittle the cladding if it is oxidized at a lower temperature.

Preliminary results of ongoing, Electric Power Research Institute (EPRI)-sponsored testing show that at reduced temperatures (below 2200 °F) a higher oxidation limit can be supported for a given cladding hydrogen concentration. The increase in allowable ECR is dependent on the hydrogen concentration of the cladding material being evaluated and the maximum temperature during oxidation, and is therefore determined on a group-specific basis. The magnitude of the credit taken is consistent with the current test data. It should be noted that the high temperature oxidation testing is an ongoing activity, with results to be provided to the NRC.

6 Small Break LOCA Adjustments

The adjustments applied to plants' Small Break LOCA (SBLOCA) licensing basis analyses are discussed in this section. The majority of plants needed no adjustments to show a positive margin of safety to the proposed 10 CFR 50.46(b) oxidation criterion shown in Figure 1; however there are several plants that were required to credit conservatism to show a positive margin of safety to the proposed limit as described in Section 6.1.

Additionally, while not used to show margin in the assessment discussed herein, plants may have various other sources of margin available including, but not limited to, the following:

- Operator Actions to Cooldown Plant
- Transition to Improved Clad Materials
- Peaking Factor Burndown
- Improved Evaluation Models

6.1 ANS-1979 Decay Heat Plus 2 Sigma Uncertainty

In accordance with Appendix K to 10 CFR Part 50, Small Break LOCA analyses utilize ANS-1971 Decay Heat plus 20% uncertainty. However, crediting a more realistic (yet conservative) decay heat (e.g., ANS-1979 Decay Heat plus 2 sigma) has been used to show that a number of plants maintain a margin of safety to the proposed 10 CFR 50.46(b) oxidation criterion shown in Figure 1. The magnitude of the change in oxidation assuming the ANS-1979 Decay Heat plus 2 sigma is dependent on the specific model that is being considered, and was determined on an evaluation model-specific basis.

6.2 Translation of Baker-Just to Cathcart-Pawel Oxidation

The conversion of Baker-Just local oxidation to Cathcart-Pawel local oxidation for SBLOCA licensing basis analyses is the same as that described in Section 5.3.

6.3 Reload Power History

The reload power history adjustment for SBLOCA licensing basis analyses is the same as described in Section 5.4 with the exception that the reload power history produces a change in rod internal pressure which modifies the cladding rupture strain and wall thickness for ECR adjustment. The estimated benefit from this adjustment is approximately 28% reduction in oxidation.

7 Large Break LOCA Grouping

As discussed in Section 4 of this report, the plant grouping process was based on analysis margin and applied adjustments. The results of this grouping process and the number of units in each group are discussed in this section. A detailed breakdown of the application of adjustments (identified in Section 5 of the report) is also provided in this section. The limiting plant information for each group is presented later via tables referenced in the following discussion.

7.1 Group 1

Group 1 contains 41 units; this plant grouping is comprised of all plants which need no adjustments to show a margin of safety to the proposed ECR criterion. The details of the most limiting plant are shown in Table 1. While the limiting plant shows 0.2% margin to the proposed limit it should be noted that 20 plants have margin in excess of 5%.

7.2 Group 2

Group 2 contains 2 units; this plant grouping is comprised of plants which show a margin of safety to the proposed ECR criterion crediting the benefit for transitioning from the CQD methodology to the ASTRUM methodology. A 50% reduction in oxidation was estimated for this credit in Section 5.2 of this report. The limiting plant information for this group is shown in Table 2. The application of this credit is as follows: The licensing basis ECR for this plant is 8.4%, and the estimated reduction in ECR for this credit is 50%. When this credit is applied the resulting ECR is: 8.4*(1-0.50) = 4.2%, which is lower than the limit of 5.7% at a conservative hydrogen concentration of 432 ppm for the evaluated burnup.

7.3 Group 3

Group 3 contains 6 units; this plant grouping is comprised of plants which show a margin of safety to the proposed ECR criterion crediting the benefit for transitioning from an Appendix K methodology to a best-estimate methodology. A 60% reduction in oxidation was estimated for this credit in Section 5.1 of this report. The limiting plant information for this group is shown in Table 3. The application of this credit is as follows: The licensing basis ECR for this plant is 7.0% based on a single-sided calculation away from the burst node; therefore, this result is doubled to account for interior oxidation resulting from pellet-to-clad bonding. In this instance a Best-Estimate analysis has been performed resulting in an explicit oxidation reduction of 72% ECR. When this credit is applied the resulting ECR is: 7*2*(1-0.72) ≈ 4.0%, which is lower than the limit of 6.0% at a conservative hydrogen concentration of 400 ppm for the evaluated burnup.

7.4 Group 4

Group 4 contains 4 units; this plant grouping is comprised of plants which have best-estimate licensing basis methodology but would benefit from improved statistics as described in Section 5.5 of this report. Since these plants currently utilize the ASTRUM evaluation model, the explicit analytical results from the analyses-of-record are used to show a margin of safety to the proposed ECR criterion. The limiting plant information is shown in Table 4. The application of this credit is as follows: The licensing basis ECR for this plant is 9.2%, and the explicitly calculated ECR of the 3^{rd} most limiting case is 5.5%. The explicitly calculated ECR of 5.5% is lower than the limit of 5.7% at a conservative hydrogen concentration of 432 ppm for the evaluated burnup.

7.5 Group 5

Group 5 contains 1 unit; this plant grouping is comprised of a plant which has a licensing basis using a best-estimate methodology. An explicit calculation of transient ECR at increased burnup was calculated for this plant as described in Section 5.6 of this report. The plant information is shown in Table 5. The application of this credit is as follows: The licensing basis ECR for this plant is 9.7%, and the explicitly calculated ECR around the evaluated burnup is 4.3%. The explicitly calculated ECR of 4.3% is lower than the limit of 5.7% at a conservative hydrogen concentration of 432 ppm for the evaluated burnup.

7.6 Group 6

Group 6 contains 7 units; this plant grouping is comprised of plants which have a licensing basis using the CQD methodology. A margin of safety to the proposed ECR criterion was shown crediting the estimated benefits from: 1) Transitioning from the CQD to ASTRUM methodology; 2) Taking credit for improved statistics in the ASTRUM methodology; and 3) Increasing the allowable ECR as discussed in Report Sections 5.2, 5.5, and 5.7, respectively. The limiting plant information is shown in Table 6. The application of adjustments is as follows: The licensing basis ECR for this plant is 10% based on a single-sided calculation away from the burst node; therefore, this result is doubled to account for interior oxidation resulting from pellet-to-clad bonding. The benefit of changing from CQD to ASTRUM was estimated as a 50% reduction in oxidation, and the credit for improved statistics was estimated as a further 23% reduction in oxidation. Crediting the estimated increase in allowable ECR resulting from a maximum cladding temperature below 2200°F raises the proposed limit from 5.7% to 8.2% at a hydrogen concentration of 432 ppm. The resulting calculation is: 10*2*(1-0.50)*(1-0.23) = 7.7% ECR which is less than the increased limit of 8.2% ECR, note that due to round off the result may differ from Table 6.

7.7 Group 7

Group 7 contains 8 units; this plant grouping contains plants which are licensed with Appendix K methodology. A margin to the proposed ECR criterion was developed based on Appendix K methodology and by accounting for: 1) The translation of Baker-Just to

Cathcart-Pawel, and 2) reload power histories as discussed in sections 5.3 and 5.4 respectively, with the magnitude for both adjustments being determined on a plant-specific basis. The cladding hydrogen concentration for each plant in this group represents the maximum calculated corrosion thickness versus burnup corresponding to the plant-specific core design, cladding type, and operating condition. For the plant representing this group, the hydrogen concentration for the burnup evaluated is 267 ppm. The limiting plant information is shown in Table 7. The application of the adjustments is as follows: The licensing basis ECR for this plant is 14.4%, the estimated reduction from transition from Baker-Just to Cathcart-Pawel is 12%, and the estimated further reduction in oxidation from using reload verified power histories is 32%. Since these adjustments are additive when used together for this purpose the resulting calculation for this group is 14.4*(1-0.12-0.32) = 8.1% ECR, which is lower than the limit of 10% at a conservative hydrogen concentration of 267 ppm for the evaluated burnup. This group of plants needed to show margin to the NRC-proposed ECR criterion based on Appendix K methodology, however, a significant benefit can be realized if these plants also transition to best-estimate methods.

8 Small Break LOCA Grouping

As discussed in Section 4, the grouping process was performed according to the adjustments required to show a margin of safety to the proposed oxidation limit. The results of this process and breakdown of adjustments are shown in Tables 8, 9, and 10 with the limiting plant information in each group shown. It should be noted that Group 1 contains the plants which need no adjustments to show a margin of safety to the proposed acceptance criterion, and no distinction of the amount of existing margin to the proposed limit has been determined for this group.

8.1 Group 1

Group 1 contains 59 units; this plant grouping is comprised of all plants which need no adjustments to show a margin of safety to the proposed ECR criterion for SBLOCA. The details of the most limiting plant are shown in Table 8. No distinction of the amount of existing margin to the proposed limit has been made within this group.

8.2 Group 2

Group 2 contains 5 units; this plant grouping is comprised of all plants which credit 1979+2 sigma decay heat to show a margin of safety to the proposed ECR criterion for SBLOCA. The details of the most limiting plant are shown in Table 9. No distinction of the amount of existing margin to the proposed limit has been made within this group.

8.3 Group 3

Group 3 contains 5 units; this plant grouping contains plants which are licensed with Appendix K methodology. A margin to the proposed ECR criterion was developed based on Appendix K methodology and by accounting for: 1) The translation of Baker-Just to

Cathcart-Pawel, and 2) reload power histories as discussed in sections 6.2 and 6.3 respectively, with the magnitude for both adjustments being determined on a plant-specific basis. The cladding hydrogen concentration for each plant in this group represents the maximum calculated corrosion thickness versus burnup corresponding to the plant-specific core design, cladding type, and operating condition. For the plant representing this group, the hydrogen concentration for the burnup evaluated is 194 ppm. The limiting plant information is shown in Table 10. The application of the adjustments is as follows: The licensing basis ECR for this plant is 14.2%, the estimated reduction from transition from Baker-Just to Cathcart-Pawel is 1%, and the estimated further reduction in oxidation from using reload verified power histories is 28%. Since these adjustments are additive when used together for this purpose the resulting calculation for this group is 14.2* (1-0.01-0.28) = 10.1% ECR.

9 Breakaway Oxidation

It has been determined that all PWRs show significant margin to the allowable breakaway time (5000 seconds) above 800°C without taking any adjustments. Therefore, breakaway oxidation is not a concern for any PWR.

10 Conclusion

In conclusion, the majority of PWRs need no credit to show a margin of safety to the proposed oxidation criterion. It was shown that all PWRs maintain some margin of safety to the proposed oxidation criterion by crediting various conservatisms in their analyses-of-record. All PWRs were also shown to meet the breakaway oxidation criterion without any adjustments.

There are several plants which are in the process of transitioning fuel vendors at the time of this report. For the purposes of grouping and assessing margin to the proposed limit, the oxidation data from the analyses which support the most recent core loading are used in the evaluation. However, consideration was also given to analyses which support the future fuel design.

11 References

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3. "08/12/2010 Industry Slides for August 12th ECCS Performance Assessments Public Meeting," August 2010 (ML102250415).

4. "Industry Slides from December 2, 2010 Category 3 Public Meeting to Discuss ECCS Performance Assessments," December 2010 (ML103410136).

5. WCAP-12610-P-A & CENPD-404-P-A Addendum 2, "Westinghouse Clad Corrosion Model for ZIRLO™ and Optimized ZIRLO™," November 2008.

6. Ken Geelhood and Carl Beyer, "Corrosion and Hydrogen Pickup Modeling in Zirconium Based Alloys," 2008 Water Reactor Fuel Performance Meeting, Paper No. 8145.

7. J.P. Mardon, G.L. Garner and P.B. Hoffmann, "M5® a breakthrough in Zr Alloy," Proceedings of 2010 LWR Fuel Performance/TopFuel/WRFPM, Paper 069.

8. "NRC Information Notice 98-29: Predicted Increase in Fuel Rod Cladding Oxidation," August 1998 (ML031050107).

Figure 1 Current and Proposed Acceptance Criterion for Local Oxidation

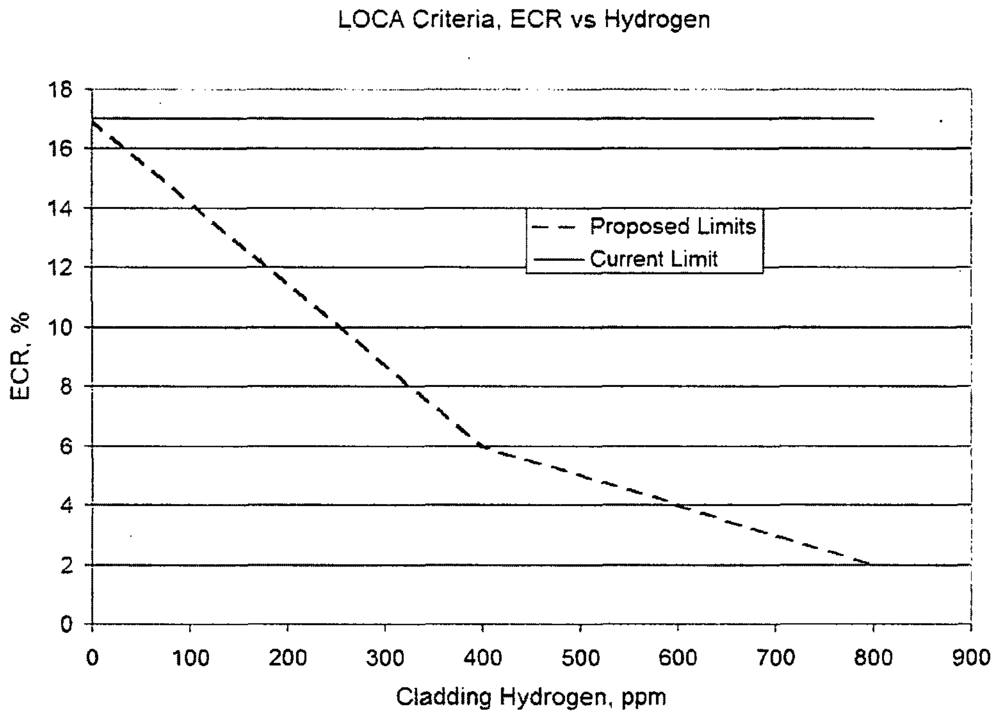

Figure 2 M5® Hydrogen Pickup versus Burnup (FRAPCON, orange curve, will be used for survey)

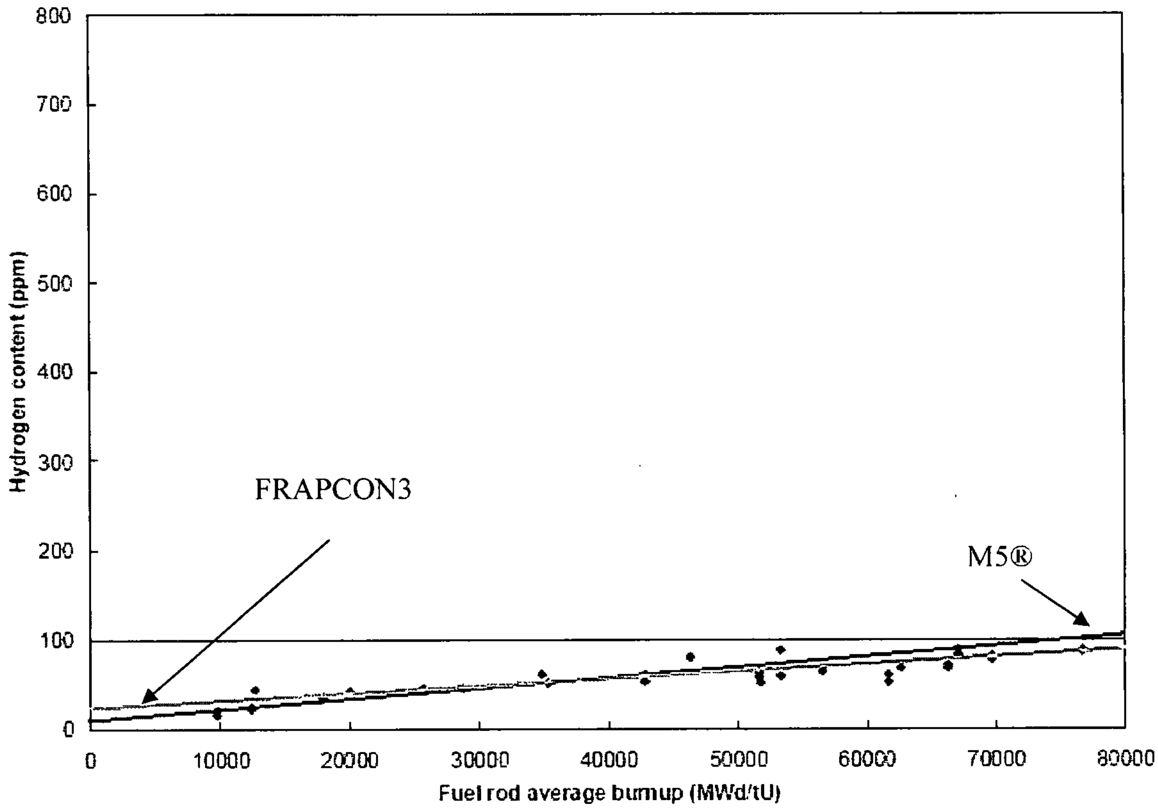

Figure 3 Zr-4 Hydrogen Pickup versus Burnup

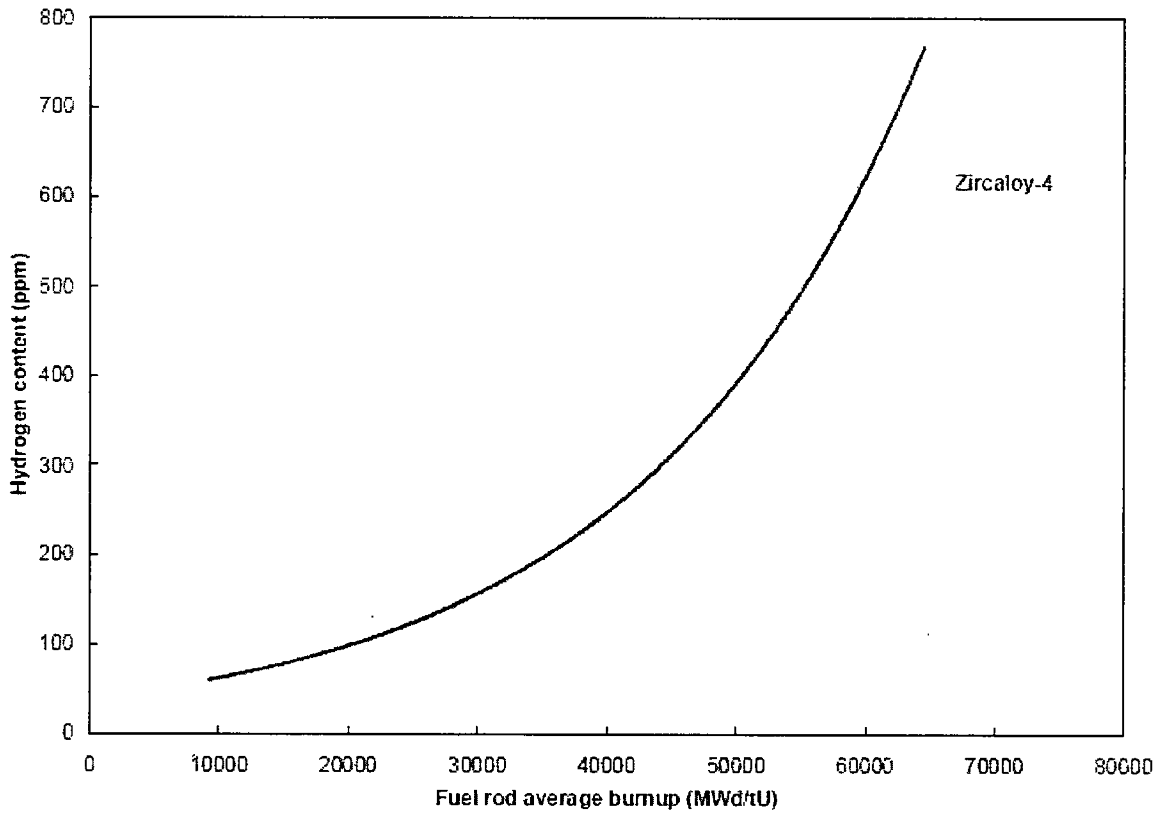

Figure 4 Adjustment Value for Conversion of Baker-Just ECR to Cathcart-Pawel ECR

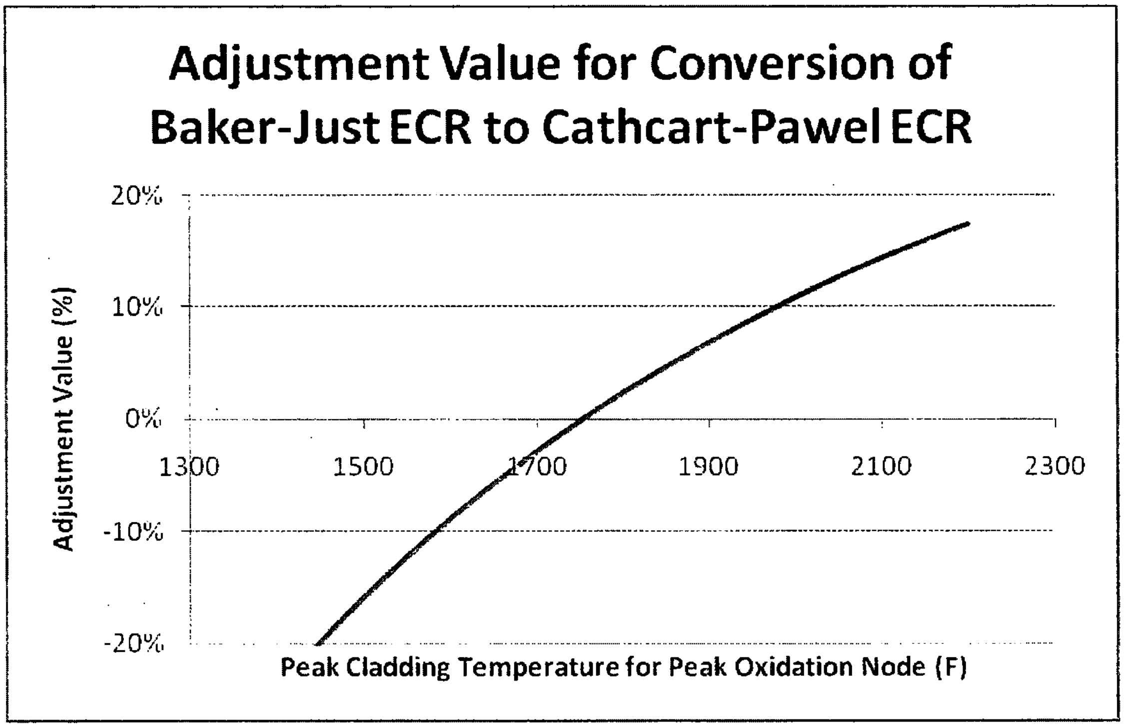

Figure 5 Adjustment Value for Fuel Performance Reload Power History

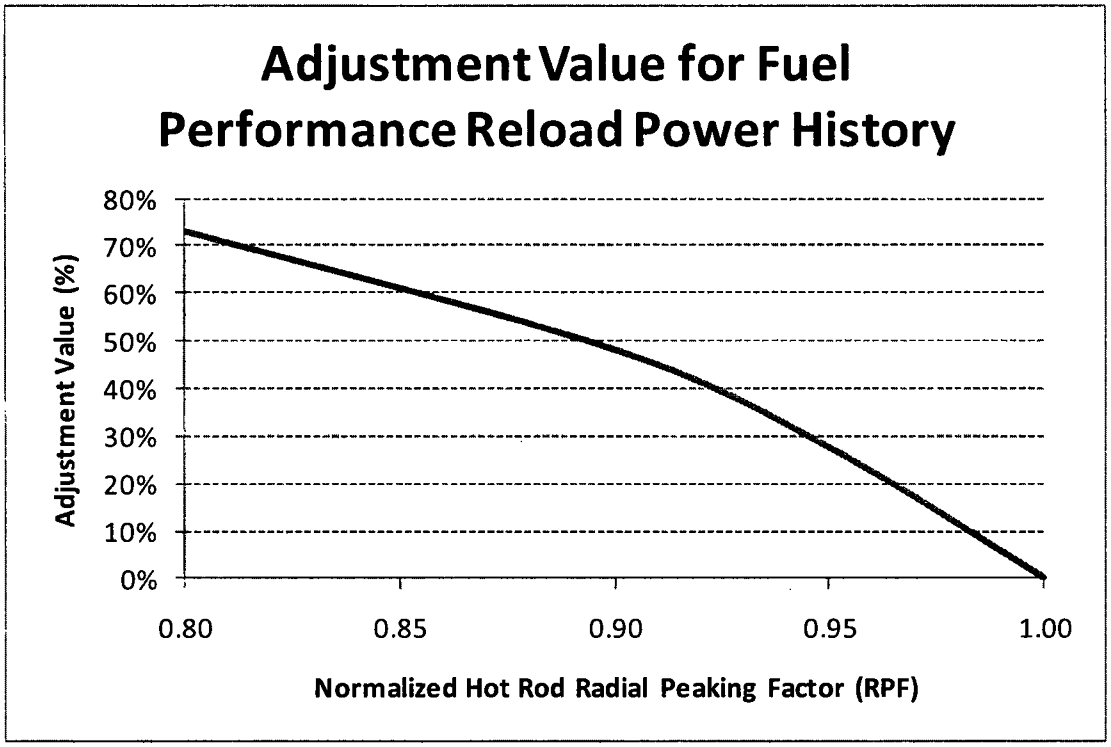

Table 1 Group 1 Limiting Plant

LBLOCA Plant: Group 1 Limiting Plant — Fuel Vendor: Westinghouse

Licensing Basis Trans. Ox/Case	Licensing Basis PCT & Case	Licensing Basis Ox 1 Ox 1 or 2 Sided	Cladding	Fuel Pin Latice	EM Type App K/BE	EM Reference	Licensing Basis Case Burnup	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
% ECR	F						GWd/mtU	GWd/mtU	ppm	%	%
5.5	1913	2	ZIRLO®	17x17	BE (ASTRUM)	WCAP-16009-P-A	12	50	432	5.7	0.2

Filled in from survey

Calculated in survey

Adjustments		
LBLOCA	Value	Type

Table 2 Group 2 Limiting Plant

LBLOCA Plant: Group 2 Limiting Plant — Fuel Vendor: Westinghouse

Licensing Basis Trans. Ox/Case	Licensing Basis PCT & Case	Licensing Basis Ox 1 Ox 1 or 2 Sided	Cladding	Fuel Pin Latice	EM Type App K/BE	EM Reference	Licensing Basis Case Burnup	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
% ECR	F						GWd/mtU	GWd/mtU	ppm	%	%
8.4	2084	2	ZIRLO®	14x14	BE (CQD)	WCAP-14449 R1-P-A	BOL	50	432	5.7	-2.7
4.2		2	CQD to ASTRUM					50	432	5.7	1.5

Filled in from survey

Calculated in survey

Adjustments		
LBLOCA	Value	Type
CQD to ASTRUM	50%	ECR reduction

Table 3 Group 3 Limiting Plant

LBLOCA | Plant: Group 3 Limiting Plant | Fuel Vendor: AREVA

Licensing Basis Trans. Ox/Case	Licensing Basis PCT & Case	Licensing Basis Ox 1 Ox 1 or 2 Sided	Cladding	Fuel Pin Latice	EM Type App K/BE	EM Reference	Licensing Basis Case Bumup	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
% ECR	F						GWd/mtU	GWd/mtU	ppm	%	%
7.0	2081	1[(a)]	Zr-4	17x17	App K	SEMPWR-98	< 62	50	400	6.0	-8.0
2.0	1930	1[(a)]	App K to Best Estimate				< 30	50	400	6.0	2.0

Filled in from survey

Calculated in survey

Adjustments		
LBLOCA	Value	Type
App K to Best-Estimate *	72%	ECR reduction

*Note the magnitude of this credit is larger than 60% because a full RLBLOCA calculation for this plant has been performed

[(a)]Because licensing basis oxidation is single sided the %ECR is multiplied by 2 to account for interior oxidation

Table 4 Group 4 Limiting Plant

LBLOCA | Plant: Group 4 Limiting Plant | Fuel Vendor: Westinghouse

Licensing Basis Trans. Ox/Case	Licensing Basis PCT & Case	Licensing Basis Ox 1 Ox 1 or 2 Sided	Cladding	Fuel Pin Latice	EM Type App K/BE	EM Reference	Licensing Basis Case Bumup	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
% ECR	F						GWd/mtU	GWd/mtU	ppm	%	%
9.2	2161	2	ZIRLO®	17x17	BE (ASTRUM)	WCAP-16009-P-A	7	50	432	5.7	-3.5
5.5		2	Improved Statistics, limiting 3rd case ECR					50	432	5.7	0.2

Filled in from survey

Calculated in survey

Adjustments		
LBLOCA	Value	Type
Improved Statistics, limiting 3rd case ECR	5.5%	Calculated ECR

Table 5 Group 5 Limiting Plant

LBLOCA | Plant: Group 5 Limiting Plant | Fuel Vendor: Westinghouse

Licensing Basis Trans. Ox/Case	Licensing Basis PCT & Case	Licensing Basis Ox 1 Ox 1 or 2 Sided	Cladding	Fuel Pin Latice	EM Type App K/BE	EM Reference	Licensing Basis Case Bumup	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
% ECR	F						GWd/mtU	GWd/mtU	ppm	%	%
9.7	2107	2	ZIRLO®	17x17	BE (ASTRUM)	WCAP-16009-P-A	18	50	432	5.7	-4.0
4.3		2	Burnup Study					50	432	5.7	1.4

Adjustments		
LBLOCA	Value	Type
Burnup Study	4.33%	Calculated ECR

Filled in from survey

Calculated in survey

Table 6 Group 6 Limiting Plant

LBLOCA | Plant: Group 6 Limiting Plant | Fuel Vendor: Westinghouse

Licensing Basis Trans. Ox/Case	Licensing Basis PCT & Case	Licensing Basis Ox 1 Ox 1 or 2 Sided	Cladding	Fuel Pin Latice	EM Type App K/BE	EM Reference	Licensing Basis Case Bumup	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
% ECR	F						GWd/mtU	GWd/mtU	ppm	%	%
10.0	2028	1*	ZIRLO®	17x17	BE (CQD)	WCAP-12945-P-A	BOL	50	432	5.7	-14.3
5.0		1*	CQD to ASTRUM					50	432	5.7	-4.3
3.9		1*	Improved Statistics					50	432	5.7	-2.1
3.9		1*	Increased Allowed ECR					50	432	8.2	0.4

Adjustments		
LBLOCA	Value	Type
CQD to ASTRUM	50%	ECR reduction
Improved Statistics	23%	ECR reduction
Increased Allowed ECR	+2.5%	Limit Increase

Filled in from survey

Calculated in survey

*Because licensing basis oxidation is single sided the %ECR is multiplied by 2 to account for interior oxidation

Table 7 Group 7 Limiting Plant

LBLOCA | Plant | Group 7 Limiting Plant | Fuel Vendor: Westinghouse

Licensing Basis Trans. Ox/Case	Licensing Basis PCT & Case	Licensing Basis Ox 1 Ox 1 or 2 Sided	Cladding	Fuel Pin Latice	EM Type App K/BE	EM Reference	Licensing Basis Case Burnup	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
% ECR	F					1999 EM	GWd/mtU	GWd/mtU	ppm	%	%
14.4	2087	2	ZIRLO®	16x16 Standard	App K	CENPD-132 Supp. 4-P-A	0.5	50	267	10.0	-4.4
12.7[a]		2	BJ-ECR to CP-ECR @ Ref Burnup					50	267	10.0	-2.7
8.1[a]		2	Reload Power History @ Burnup Evaluated					50	267	10.0	2.0

Filled in from survey

Calculated in survey

Adjustments		
LBLOCA	Value	Type
BJ-ECR to CP-ECR @ Burnup Evaluated	12%	ECR reduction
Reload Power History @ Burnup Evaluated	32%	ECR reduction

[a]Due to the nature of these adjustments they are additive i.e. 14.4*(1-0.12-0.32)

Table 8 Small Break LOCA Group 1 Limiting Plant Data

SBLOCA Plant: Group 1 Limiting Plant Fuel Vendor: Westinghouse

Adjustments	
SBLOCA:	Value:

Licensing Basis Break Range & ID	PCT	Time span above 800 C	Licensing Basis Tran Ox	Licensing Basis Ox 1 or 2 Sided	EM Type App K/BE	EM Reference	Cladding	Burnup Evaluated	Tran Ox. at BU Eval.	Hydrogen	Allowed Ox	Ox Margin No Adj.
inches, ft^2	F	s	%					GWd/mtU	%	ppm	%	%
2-inch	986	-	0.04	1	App K	NOTRUMP	ZIRLO®					
2.25-inch	1455	-	0.88	1	App K	NOTRUMP	ZIRLO®					
2.5-inch	1571	500	1.06	1	App K	NOTRUMP	ZIRLO®					
2.75-inch	**1904**	**1000**	**8.38**	2	App K	NOTRUMP	ZIRLO®	50	4.9	432	5.7	**0.8**
3-inch	1835	800	7.6	2	App K	NOTRUMP	ZIRLO®					
3.25-inch	1702	500	1.78	1	App K	NOTRUMP	ZIRLO®					
4-inch	1457	-	0.3	1	App K	NOTRUMP	ZIRLO®					

Margin to time above 800 C	4000

Note: The "Licensing Basis Tran Ox" is the limiting time-in-life transient oxidation value. The "Tran Ox at BU Eval." is the explicit licensing basis transient oxidation result at 50 GWD/MTU.

Table 9 Small Break LOCA Group 2 Limiting Plant Data

SBLOCA Plant: Group 2 Limiting Plant Fuel Vendor: Westinghouse

Adjustments	
SBLOCA:	Value:
1979 Decay Heat + 2σ	90%(1)

(1). Minimum credit calculated for Group 2 plant type 0 - 50 GWD/mtU

Licensing Basis Break Range & ID	PCT	Time span above 800 C	Licensing Basis Tran Ox	Licensing Basis Ox 1 or 2 Sided	EM Type App K/BE	EM Reference	Cladding	Burnup Evaluated	Tran Ox. at BU Eval.	Hydrogen	Allowed Ox	Ox Margin No Adj.
inches, ft^2	F	s	%					GWd/mtU	%	ppm	%	%
2-inch	1753	<1500	3.83	1	App K	NOTRUMP	ZIRLO®					
2.25-inch	1846	<1500	4.3	1	App K	NOTRUMP	ZIRLO®					
2.50-inch	1882	<2000	**13.42**	2	App K	NOTRUMP	ZIRLO®	50	10.1	432	5.7	-4.4
2.75-inch	1829	<2000	4.74	1	App K	NOTRUMP	ZIRLO®					
3-inch	**1917**	~1000	8.47	2	App K	NOTRUMP	ZIRLO®					
3.25-inch	1712	<500	1.9	1	App K	NOTRUMP	ZIRLO®					
4-inch	1456	-	0.37	1	App K	NOTRUMP	ZIRLO®					
6-inch	900	-	0.01	1	App K	NOTRUMP	ZIRLO®					
2.50-Inch - With Credits								50	1	432	5.7	4.7

Margin to time above 800 C	3000

Note: The "Licensing Basis Tran Ox" is the limiting time-in-life transient oxidation value. The "Tran Ox at BU Eval." is the explicit licensing basis transient oxidation result at 50 GWD/MTU.

Table 10 Small Break LOCA Group 3 Limiting Plant Data

SBLOCA Plant: Group 3 Limiting Plant | Fuel Vendor: Westinghouse

AOR Break Range & ID	PCT	Time span above 800 C	AOR Trans Ox	AOR Ox 1 or 2 Sided	EM Type App K/BE	EM Reference	Cladding	Burnup Evaluated	Hydrogen	Allowed Ox	Ox Margin No Adj.
inches, ft^2	F	s	%			S2M		GWd/mtU	ppm	%	%
0.055 ft2	1973	900	14.24	2	App K	CENPD-137	Optimized ZIRLO™	50	194	12.2	-2.1
						Supp. 2-P-A					
			% CP-ECR		Adjustments			Burn Adj			With Adj.
			14.06[a]	2	(1)			50	194	12.2	-1.9
			10.04[a]	2	(2)			50	194	12.2	2.1

Adjustments	Value
SBLOCA	
(1) BJ-ECR to CP-ECR @ Burn Eval	1%
(2) Reload Power History @ Burn Eval	28%

[a] Due to the nature of these adjustments they are additive i.e. 14.24*(1-0.01-0.28)