PRESSURIZED WATER REACTOR OWNERS GROUP

PWROG-16057-NP
Revision 0

AREVA NP NON-PROPRIETARY
WESTINGHOUSE NON-PROPRIETARY CLASS 3

Update to the PWROG 50.46c Margin Assessment

Analysis Committee

PA-ASC-1393 Revision 0

October 2016

Westinghouse

AREVA

PWROG-16057-NP
Revision 0

Update to the PWROG 50.46c Margin Assessment

PA-ASC-1393 Revision 0

Ann Marie DiLullo
AnnMarie DiLullo 10/11/2016
Westinghouse Electric Company LLC

Brittany Smith
10/11/2016
AREVA NP

Approved: Lisa Gerken
AREVA NP
10/11/2016

Mitchell E. Nissley
Westinghouse Electric Company LLC
MENissley 10/11/2016

Approved: James P. Molkenthin
PWR Owners Group PMO
10/11/2016

October 2016

Westinghouse Electric Company LLC
1000 Westinghouse Drive
Cranberry Township, PA 16066, USA

AREVA NP
3315 Old Forest Road
Lynchburg, VA 24501

ACKNOWLEDGEMENTS

This report was developed and funded by the PWR Owners Group under the leadership of the participating utility representatives of the Analysis Committee.

This report was a collaborative effort between technical teams at Westinghouse and AREVA NP.

The authors would like to thank the following people and/or organizations for their valuable contributions to this report:

AREVA NP
Danielle Page Blair

Westinghouse Electric Company LLC
Douglas W. Atkins
Kevin J. Barber
Cherri L. DeVoe
Justin T. Figley
Taylor L. Jedrek
Rosemary T. Null
Jarrett D. Valeri
Mike Volodzko

JOINT AREVA NP AND WESTINGHOUSE ELECTRIC COMPANY LLC NON-PROPRIETARY

LEGAL NOTICE

This report was prepared as an account of work performed by both AREVA NP and Westinghouse Electric Company LLC. Neither AREVA NP, nor Westinghouse Electric Company LLC, nor any person acting on its behalf:

1. Makes any warranty or representation, express or implied including the warranties of fitness for a particular purpose or merchantability, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

2. Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

COPYRIGHT NOTICE

DISTRIBUTION NOTICE

This report was prepared for the PWR Owners Group. This Distribution Notice is intended to establish guidance for access to this information. This report (including proprietary and non-proprietary versions) is not to be provided to any individual or organization outside of the PWR Owners Group program participants without prior written approval of the PWR Owners Group Program Management Office. However, prior written approval is not required for program participants to provide copies of Class 3 Non-Proprietary reports to third parties that are supporting implementation at their plant, and for submittals to the NRC.

PWR Owners Group
United States Member Participation* for PA-ASC-1393 Revision 0

Utility Member	Plant Site(s)	Participant	
		Yes	No
Ameren Missouri	Callaway (W)	X	
American Electric Power	D.C. Cook 1 & 2 (W)	X	
Arizona Public Service	Palo Verde Unit 1, 2, & 3 (CE)	X	
Dominion Connecticut	Millstone 2 (CE)	X	
	Millstone 3 (W)	X	
Dominion VA	North Anna 1 & 2 (W)	X	
	Surry 1 & 2 (W)	X	
Duke Energy Carolinas	Catawba 1 & 2 (W)	X	
	McGuire 1 & 2 (W)	X	
	Oconee 1, 2, & 3 (B&W)	X	
Duke Energy Progress	Robinson 2 (W)	X	
	Shearon Harris (W)	X	
Entergy Palisades	Palisades (CE)	X	
Entergy Nuclear Northeast	Indian Point 2 & 3 (W)	X	
Entergy Operations South	Arkansas 1 (B&W)	X	
	Arkansas 2 (CE)	X	
	Waterford 3 (CE)	X	
Exelon Generation Co. LLC	Braidwood 1 & 2 (W)	X	
	Byron 1 & 2 (W)	X	
	TMI 1 (B&W)	X	
	Calvert Cliffs 1 & 2 (CE)	X	
	Ginna (W)	X	
FirstEnergy Nuclear Operating Co.	Beaver Valley 1 & 2 (W)	X	
	Davis-Besse (B&W)	X	
Florida Power & Light \ NextEra	St. Lucie 1 & 2 (CE)	X	
	Turkey Point 3 & 4 (W)	X	
	Seabrook (W)	X	
	Pt. Beach 1 & 2 (W)	X	
Luminant Power	Comanche Peak 1 & 2 (W)	X	

PWR Owners Group
United States Member Participation* for PA-ASC-1393 Revision 0

Utility Member	Plant Site(s)	Participant	
		Yes	No
Omaha Public Power District	Fort Calhoun (CE)	X	
Pacific Gas & Electric	Diablo Canyon 1 & 2 (W)	X	
PSEG – Nuclear	Salem 1 & 2 (W)	X	
South Carolina Electric & Gas	V.C. Summer (W)	X	
So. Texas Project Nuclear Operating Co.	South Texas Project 1 & 2 (W)	X	
Southern Nuclear Operating Co.	Farley 1 & 2 (W)	X	
	Vogtle 1 & 2 (W)	X	
Tennessee Valley Authority	Sequoyah 1 & 2 (W)	X	
	Watts Bar 1 & 2 (W)	X	
Wolf Creek Nuclear Operating Co.	Wolf Creek (W)	X	
Xcel Energy	Prairie Island 1 & 2 (W)	X	

*Project participants as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWR Owners Group Program Management Office to verify participation before sending this document to participants not listed above.

PWR Owners Group
International Member Participation* for PA-ASC-1393 Revision 0

Utility Member	Plant Site(s)	Participant Yes	Participant No
Asociación Nuclear Ascó-Vandellòs	Asco 1 & 2 (W)	X	
	Vandellos 2 (W)	X	
Axpo AG	Beznau 1 & 2 (W)	X	
Centrales Nucleares Almaraz-Trillo	Almaraz 1 & 2 (W)	X	
EDF Energy	Sizewell B (W)	X	
Electrabel	Doel 1, 2 & 4 (W)	X	
	Tihange 1 & 3 (W)	X	
Electricite de France	58 Units	X	
Eletronuclear-Eletrobras	Angra 1 (W)	X	
Emirates Nuclear Energy Corporation	Barakah 1 & 2	X	
Eskom	Koeberg 1 & 2 (W)	X	
Hokkaido	Tomari 1, 2 & 3 (MHI)	X	
Japan Atomic Power Company	Tsuruga 2 (MHI)	X	
Kansai Electric Co., LTD	Mihama 3 (W)	X	
	Ohi 1, 2, 3 & 4 (W & MHI)	X	
	Takahama 1, 2, 3 & 4 (W & MHI)	X	
Korea Hydro & Nuclear Power Corp.	Kori 1, 2, 3 & 4 (W)	X	
	Hanbit 1 & 2 (W)	X	
	Hanbit 3, 4, 5 & 6 (CE)	X	
	Hanul 3, 4 , 5 & 6 (CE)	X	
Kyushu	Genkai 2, 3 & 4 (MHI)	X	
	Sendai 1 & 2 (MHI)	X	
Nuklearna Electrarna KRSKO	Krsko (W)	X	
Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Shikoku	Ikata 1, 2 & 3 (MHI)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	

*Project participants as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWR Owners Group Program Management Office to verify participation before sending this document to participants not listed above.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION AND PURPOSE

The U. S. Nuclear Regulatory Commission (NRC) has sponsored a test program at Argonne National Laboratory (ANL) which examined the effect of burnup on the embrittlement of various cladding alloys under conditions relevant to loss-of-coolant accidents (LOCAs). The results of these tests demonstrated that the effects are largely due to hydrogen that is absorbed in the cladding during normal operation (Reference 1). In August 2009 the NRC published an advance notice of proposed rulemaking in the Federal Register (Reference 2). As part of this rulemaking package, a change in the oxidation acceptance criterion was proposed based on Reference 1.

To ensure that the current operating fleet maintains margin to the proposed criterion, the NRC completed a preliminary safety assessment of the Emergency Core Cooling System (ECCS) performance. In 2011 and 2013, the Pressurized Water Reactor Owners Group (PWROG) coordinated with the respective fuel vendors to provide plant-specific information and margin assessments in support of more detailed NRC safety assessments (Reference 3 and Reference 4).

The original oxidation margin assessment performed in 2011 (Reference 3) was based on the plants' LOCA licensing basis analysis of record (AOR) results and considered both large break LOCA (LBLOCA) and small break LOCA (SBLOCA) analysis results. The original assessment represents a snapshot of the available post-quench ductility and breakaway oxidation margin at the time the plant-specific analyses were completed. The effect of changes to and errors discovered in ECCS models, as well as planned plant changes, which had been evaluated for peak cladding temperature (PCT) impact (per 10 Code of Federal Regulations (CFR) 50.46(a)(3)(iii)) were not considered in the original assessment.

The 2013 work (Reference 4) updated the original LBLOCA oxidation margin assessment to consider recent AORs and the effects of plant-specific PCT rackup assessments (including fuel thermal conductivity degradation (TCD)). Evaluations assessed on a plant's LBLOCA PCT rackup sheet were considered in this update. The SBLOCA analysis and breakaway oxidation margin assessments were not updated.

The current work described herein updates the 2013 LBLOCA oxidation margin assessment and the original 2011 SBLOCA oxidation margin assessment to consider recent AORs and the effects of plant-specific PCT rackup assessments. This updated margin assessment represents a new snapshot of the available post-quench ductility margin in the plants' LBLOCA and SBLOCA analyses, considering current plant analyses and associated evaluations of changes to and errors in the applicable ECCS evaluation models, as well as evaluated plant changes.

Since the original margin assessment was performed, the following plants have permanently shut down, and therefore, are not included in the updated assessment: Crystal River Nuclear Generating Plant Unit 3, San Onofre Nuclear Generating Station Units 2 and 3, and Kewaunee Power Station.

2 REFERENCES

1. U. S. Nuclear Regulatory Commission, Argonne National Laboratory, NUREG/CR-6967, ANL-07/04, "Cladding Embrittlement During Postulated Loss-of-Coolant Accidents," M. Billone, Y. Yan, T. Burtseva, R. Daum, July 2008 (ML082130389).

2. "10 CFR Parts 50 and 52 Risk-Informed Changes to Loss-of-Coolant Accident Technical Requirements; Proposed Rule," Federal Register Vol. 74, No. 152, August 2009 (ML092250362).

3. OG-11-143, "PWROG 50.46(b) Margin Assessment," April 2011 (ML11139A309).

4. OG-13-407, "Transmittal of Update to the PWROG 50.46c Margin Assessment Report for Information Only (PA-ASC-1094)," November 2013 (ML13329A086).

5. U. S. Nuclear Regulatory Commission, Regulatory Guide 1.224 (Pre-Decisional), "Establishing Analytical Limits for Zirconium-Alloy Cladding Material," January 2016 (ML16005A133).

6. WCAP-12610-P-A & CENPD-404-P-A, Addendum 2-A (Proprietary) and WCAP-14342-A & CENPD-404-NP-A (Non-Proprietary), "Westinghouse Clad Corrosion Model for *ZIRLO* and *Optimized ZIRLO*," October 2013.

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

8. 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, September 2010.

9. WCAP-16009-P-A (Proprietary) and WCAP-16009-NP-A (Non-Proprietary), "Realistic Large-Break LOCA Evaluation Methodology Using the Automated Statistical Treatment Of Uncertainty Method (ASTRUM)," January 2005.

10. WCAP-12945-P-A Volume 1 Revision 2 and Volumes 2-5 Revision 1 (Proprietary) and WCAP-14747 (Non-Proprietary), "Code Qualification Document for Best Estimate LOCA Analysis," March 1998.

11. WCAP-16996-P, Revision 1 (Proprietary) and WCAP-16996-NP, Revision 1 (Non-Proprietary), "Realistic LOCA Evaluation Methodology Applied to the Full Spectrum of Break Sizes (FULL SPECTRUM LOCA Methodology)," April 2015 (Volume I), June 2015 (Volume II), and October 2015 (Volume III).

12. U. S. Nuclear Regulatory Commission, Advisory Committee on Reactor Safeguards, "Topical Report WCAP-16996-P, Volumes I, II and III, Revision 1, 'Realistic Loss-of-Coolant Accident Evaluation Methodology Applied to the Full Spectrum of Break Sizes'," July 2016 (ML16201A103).

13. SECY-16-0033, "Draft Final Rule – Performance-Based Emergency Core Cooling System Requirements and Related Fuel Cladding Acceptance Criteria (RIN 3150-AH42)," April 2016 (ML15238A947).

3 ASSESSMENT CRITERIA

The results of the ANL test program show that irradiation (burnup) can have a significant impact on cladding post-quench ductility as a consequence of hydrogen absorption during normal operation (Reference 1). To account for this, the NRC-acceptable limit for the proposed 10 CFR 50.46c local oxidation criterion (Reference 13) is expected to be in the form of allowable equivalent cladding reacted (ECR) versus hydrogen concentration. Figure 1 (Reference 5, Figure 2) shows the allowable ECR versus hydrogen concentration for this updated margin assessment. Figure 1 is hereafter referred to as the proposed local oxidation criterion or limit.

As part of assessing plants' margin to the proposed local oxidation criterion, the calculation of the cladding hydrogen content as a function of burnup, the associated burnup selected to perform the plant assessments, and the treatment of oxygen diffusion into the interior cladding surface are described in this section of the report.

Breakaway oxidation is a new criterion added to the proposed 10 CFR 50.46c regulation; the assessment for this criterion is also described in this section of the report.

3.1 WESTINGHOUSE CLADDING HYDROGEN CONCENTRATION

The hydrogen concentrations for cladding used in Westinghouse-fueled Westinghouse (W) and Combustion Engineering (CE) nuclear steam supply system (NSSS) plant designs (either **ZIRLO®**[1] or **Optimized ZIRLO™**[1] high performance fuel cladding materials) are based on Figure 3.3-3 of Reference 6, which shows cladding hydrogen concentration as a function of oxide thickness. An oxide thickness versus burnup curve for a representative limiting pressurized water reactor (PWR) core was developed considering the maximum allowable volume-averaged clad hydrogen content given by the NRC final safety evaluation included in Section A of Reference 6. The oxide thickness versus burnup curve was used with Figure 3.3-3 of Reference 6 and Figure 1 to determine an allowable ECR versus burnup.

For Westinghouse-fueled CE-NSSS plants, a plant-specific oxide thickness versus burnup was used in order to capture the limiting allowable ECR for a given plant. As such, the cladding hydrogen content corresponding to a certain burnup may differ from group-to-group.

---

[1] Optimized ZIRLO and ZIRLO are trademarks or registered trademarks of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. Other names may be trademarks of their respective owners.

3.2 AREVA CLADDING HYDROGEN CONCENTRATION

The plants for which AREVA provides reload fuel use either **M5**®[2] or Zircaloy-4 cladding. The FRAPCON-3 cladding hydrogen concentration versus burnup for **M5**® cladding is based on Figure 16 of Reference 7, while Figure 5 of Reference 8 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 noted in the 2011 and 2013 margin assessments (Reference 3 and Reference 4) there is a substantial drop in power for typical fuel assemblies in the 3rd cycle of residence in a reactor core in typical U. S. PWR 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 is necessary. **M5**® cladding was analyzed to a burnup of 62 GWD/MTU since there is minimal difference in the hydrogen content between the two burnup points.

For certain plants, discrete burnup steps from beginning-of-life to 50 GWD/MTU were evaluated in this assessment.

3.4 OXYGEN DIFFUSION AT CLADDING INNER DIAMETER

Similar to the 2011 and 2013 margin assessments, all calculated oxidation results which are single-sided are doubled for all burnups as a conservative surrogate to account for oxygen diffusion at the cladding inner diameter (also referred to as interior oxidation). This is conservative with respect to guidance provided in Reference 5, Section C.3.B, which recommends considering burnups greater than 30 GWD/MTU.

3.5 BREAKAWAY OXIDATION

10 CFR 50.46c(g)(1)(iii) requires that an analytical time limit that has been shown to preclude breakaway oxidation using an NRC-approved experimental technique must be determined and specified for each Zirconium-based cladding alloy. As testing programs are not established, the breakaway oxidation assessment is performed consistent with the 2011 assessment. SBLOCA analyses are reviewed to assess the time that the cladding temperature is above 800°C and compared to a limit of 5000 seconds. LBLOCA events have shorter times-at-temperature than the SBLOCA events and do not pose a challenge for breakaway oxidation.

---

[2] M5 is a trademark of AREVA registered in the USA and in other countries.

4 GROUPING PROCESS

The process utilized to group the plants is described in this section.

The plants are assessed with respect to margin to the proposed limit (Figure 1). The groupings are established separately for LBLOCA and SBLOCA. 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 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, rather than physical characteristics (e.g., loop configuration, core size, and ECCS differences). This approach is consistent with the 2011 and 2013 margin assessments.

The detailed information for all the plants included in this report is available to the NRC for audit at the vendor offices.

5 LARGE BREAK LOCA ADJUSTMENTS

The adjustments applied in the updated assessment of plants' LBLOCA analyses are discussed in this section. Several plants need no adjustments to show a positive margin of safety to the proposed 10 CFR 50.46c local 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.

Adjustments to show margin to the proposed ECR criterion were determined and justified based on conservatisms in the specific licensing basis analysis methodologies under consideration.

The LBLOCA adjustments which were used in this assessment, explained in more detail in the sub-sections, are as follows:

1. Improved Statistics in Westinghouse Best-Estimate Analysis Evaluation Models
2. Burst Modeling Improvements in Westinghouse Best-Estimate Analysis Evaluation Models
3. Translation of **ZIRLO** Oxidation to Cathcart-Pawel Oxidation
4. CQD Evaluation Model MLO Calculation Improvements
5. Plant-specific Cladding Temperature Benefit
6. Plant-specific Transition from CQD to ASTRUM Evaluation Model
7. Translation of Baker-Just Oxidation to Cathcart-Pawel Oxidation
8. Reload Power History

While not explicitly used to show margin in this updated assessment, and depending on the specific evaluation model, plants may also be able to credit additional benefits such as conservatism in how the inner cladding oxidation was assessed, conservatism in how PCT evaluations were used to estimate the plant rebaseline maximum local

oxidation (MLO) results, credit for a lower temperature transient due to the Cathcart-Pawel reaction rate (compared to the **ZIRLO** or Baker-Just reaction rate), burnup dependence in the allowable ECR limit, and other conservatisms in the evaluation models or approach for this assessment, which would show an increase in margin to the limit.

5.1 IMPROVED STATISTICS IN WESTINGHOUSE BEST-ESTIMATE ANALYSIS EVALUATION MODELS

The Westinghouse ASTRUM methodology (Reference 9) uses the limiting results from 124 runs to determine the 95th percentile PCT, MLO, and core-wide oxidation (CWO) with 95% confidence (95/95 values). However, a lower ranking analysis result can be used to estimate the result for one parameter of interest (such as local oxidation) at a high level of probability. As a result, the explicitly calculated oxidation resulting from the 3rd most limiting case may be taken as a credit for existing ASTRUM analyses. Alternatively, TCD evaluation results for plants with ASTRUM analyses were used to conservatively estimate a 12% reduction in oxidation, which may be used if plant-specific oxidation results are not available. For example, with the Westinghouse Code Qualification Document (CQD) evaluation model (Reference 10) MLO calculation improvements, it was shown that the MLO as a function of PCT results benchmark well into ASTRUM results (considering TCD); therefore, a group which credits the CQD evaluation model MLO calculation improvements may then also credit the improved statistics for best-estimate analysis if additional margin is needed.

5.2 BURST MODELING IMPROVEMENTS IN WESTINGHOUSE BEST-ESTIMATE ANALYSIS EVALUATION MODELS

As part of other development efforts, improvements to hot rod burst modeling in the ASTRUM and CQD evaluation models have been developed. These model improvements are outside of the current as-approved ASTRUM and CQD evaluation models. These changes are expected to more appropriately represent the hot rod burst response when burst during the blowdown period is predicted, which has been observed when effects of TCD are explicitly accounted for.

Fully separate from this margin assessment, these model improvements are included in the **FULL SPECTRUM**™[3] LOCA (Reference 11) evaluation model, which is approved by the Advisory Committee on Reactor Safeguards (ACRS) (Reference 12).

---

[3] FULL SPECTRUM is a trademark of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited. Other names may be trademarks of their respective owners.

The magnitude of this adjustment is determined on a plant-specific basis and is consistent with the approach taken for the 2013 assessment.

5.3 TRANSLATION OF ZIRLO OXIDATION TO CATHCART-PAWEL OXIDATION

For plants with **ZIRLO** or **Optimized ZIRLO** cladding, the Westinghouse ASTRUM and CQD evaluation models use the **ZIRLO** oxidation kinetics model 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, for a given temperature transient based on the limiting local oxidation results and accounting for effects of PCT rackup assessments, the local oxidation is calculated using both the **ZIRLO** correlation and the Cathcart-Pawel correlation. The difference between these results may be used to quantify the benefit.

Since the cladding temperature transient is based on the limiting local oxidation results determined based on the use of the **ZIRLO** correlation oxidation kinetics, this conversion of **ZIRLO** correlation local oxidation to Cathcart-Pawel correlation 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.

The magnitude of this adjustment is determined on a plant-specific basis and is consistent with the approach taken for the 2013 assessment.

5.4 CQD EVALUATION MODEL MLO CALCULATION IMPROVEMENTS

In the original margin assessment, a generic margin for evaluation model transition from CQD to ASTRUM was quantified. The magnitude of this margin was based on comparison of MLO results for plants which had been analyzed with both the CQD and ASTRUM evaluation models. Subsequently, plant-specific evaluations for the effect of TCD and peaking factor burndown were completed. The estimated PCT impact of TCD varied depending on the evaluation model, fuel assembly design, and other plant-specific aspects. Therefore, the magnitude of the margin originally assessed for transition from the CQD to the ASTRUM evaluation model may be different after explicitly accounting for the effects of TCD. With consideration of plant-specific evaluations following the completed analyses, it was determined that it was not feasible to justify a generic evaluation model transition benefit as was done in the original assessment. Therefore, a different approach was taken to quantify known conservatisms in the CQD evaluation model MLO calculations.

In the CQD evaluation model, the MLO results accounting for effects of local hot rod uncertainties are calculated in HOTSPOT using thermal-hydraulic boundary conditions from an appropriate WCOBRA/TRAC calculation. The CQD evaluation model specified that the WCOBRA/TRAC transient for the MLO calculation be such that the nominal cladding temperature results already exceed the analysis final 95% PCT results. Then,

a timescale stretching factor was applied to conservatively bound observed behavior in some validation calculations, and the final MLO results were calculated at the 95% probability level. As part of the ASTRUM evaluation model licensing, it was justified that application of such a timescale stretching factor was no longer required. Due to the timescale stretching and calculation of MLO at the 95% level, and also depending on how much the nominal PCT for the MLO calculation exceeded the 95% analysis PCT result, plant MLO results calculated per the CQD evaluation model could be considerably more conservative than results from ASTRUM calculations for the same PCT. When CQD plant average MLO results from the MLO calculation without timescale stretching, as a function of the nominal PCT, were compared to ASTRUM calculation results of MLO as a function of PCT, it was observed that the improved CQD results benchmarked well into the ASTRUM results.

Therefore, the CQD evaluation model improvements benefit is estimated by calculating the MLO following the CQD evaluation model approach, except that timescale stretching is not applied and the average MLO result for the MLO calculation is used.

The magnitude of this adjustment is determined on a plant-specific basis and is consistent with the approach taken for the 2013 assessment.

5.5 PLANT-SPECIFIC CLADDING TEMPERATURE BENEFIT

This margin is applicable to plants with LBLOCA analyses performed using the Westinghouse CQD evaluation model. There are two sources of cladding temperature benefit potentially available for CQD plants:

- Conservatism in the MLO calculation if the nominal PCT is substantially higher than the analysis PCT (see also discussion in Section 5.4).
- Cladding temperature benefit due to peaking factor burndown assumed as part of the TCD evaluations.

As discussed in Section 5.4, in the CQD evaluation model the WCOBRA/TRAC transient for the MLO calculation was such that the nominal cladding temperature results already exceed the analysis final 95% PCT results. If the 95% PCT results are significantly exceeded, the corresponding benefit on MLO may be estimated.

The second possible source of margin is due to peaking factor burndown. From the TCD evaluation work, it was observed that typically CQD plants were PCT-limited around middle of life; with peaking factor burndown credited at higher burnups, the PCT results at higher burnups were typically lower compared to middle of life results. Therefore, the TCD evaluation PCT rackup line items generally reflect the middle of life PCT estimates. If additional margin to the allowable ECR limit is needed at higher burnup, the benefit of this cladding temperature reduction may be estimated from the plant's TCD evaluation results or equivalent calculations.

As discussed in Section 5.4, after CQD evaluation model improvements are applied, the improved CQD MLO results benchmark well into ASTRUM results. To estimate the MLO benefit due to cladding temperature benefit, a best fit to the ASTRUM calculation results which intersects the plant's improved CQD MLO benchmark point is drawn. The fit line is then used to estimate the MLO benefit due to cladding temperature reduction.

The magnitude of this adjustment is determined on a plant-specific basis and is consistent with the approach taken for the 2013 assessment.

5.6 PLANT-SPECIFIC TRANSITION FROM CQD TO ASTRUM EVALUATION MODEL

As discussed in Section 5.4, sufficient data are not available at this time to support a generic CQD to ASTRUM evaluation model benefit, when accounting for the PCT rackup items. However, if an ASTRUM analysis was completed for a plant whose current licensing basis analysis of record was performed with the CQD evaluation model, the ASTRUM analysis may be used as the basis for the updated margin assessment. In this case, the applicability of the ASTRUM analysis to represent the plant's current operating conditions, and the PCT impact of known issues which would affect the ASTRUM analysis results, are considered in the assessment.

5.7 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. For Westinghouse-fueled W-NSSS plants, the local oxidation is calculated using both the Baker-Just correlation and the Cathcart-Pawel correlation for a given temperature transient based on the limiting local oxidation results and accounting for the effects of PCT rackup assessments. The difference between these results is used to quantify the benefit. For Westinghouse-fueled CE-NSSS plants, 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.

The magnitude of this adjustment is determined on a plant-specific basis and is consistent with the approach taken for the 2013 assessment.

5.8 RELOAD POWER HISTORY

As part of the reload process for Westinghouse-fueled CE-NSSS plants, 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).

The magnitude of this adjustment is determined on a plant-specific basis and is consistent with the approach taken for the 2013 assessment.

6 SMALL BREAK LOCA ADJUSTMENTS

The adjustments applied in the updated assessment of plants' SBLOCA analyses are discussed in this section. Most plants need no adjustments to show positive margin of safety to the proposed 10 CFR 50.46c local oxidation criterion shown in Figure 1; however, there were two plants that were required to credit conservatisms to show a positive margin of safety to the proposed limit.

Adjustments to show margin to the proposed ECR criterion were determined and justified based on conservatisms in the specific licensing basis analysis methodologies under consideration.

The SBLOCA adjustments used in this assessment and explained in more detail in the sub-sections are as follows:

1. Hot Assembly Peaking Factor Burndown
2. Translation of Baker-Just to Cathcart-Pawel Oxidation
3. Reload Power History

While not explicitly used to show margin in this updated assessment, and depending on the specific evaluation model, plants may also be able to credit additional benefits such as conservatism in how the inner cladding oxidation was assessed, conservatism in how PCT evaluations were used to estimate the plant rebaseline MLO results, credit for a lower temperature transient due to the Cathcart-Pawel reaction rate (compared to the **ZIRLO** or Baker-Just reaction rate), burnup dependence in the allowable ECR limit, and other conservatisms in the evaluation models or approach for this assessment, which would show an increase in margin to the limit.

6.1 HOT ASSEMBLY PEAKING FACTOR BURNDOWN

As fuel accrues burnup, the maximum power that it can achieve is reduced. Therefore, the peaking factors at end-of-life (EOL) conditions for a fuel assembly are lower than for a fresh assembly, resulting in lower cladding temperatures and reduced oxidation accrual for the burned fuel compared to fresh fuel. The magnitude of this adjustment is determined on a plant-specific basis.

6.2 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. For Westinghouse-fueled CE-NSSS plants, 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.

The magnitude of this adjustment is determined on a plant-specific basis.

6.3 RELOAD POWER HISTORY

The reload power history adjustment for SBLOCA licensing basis analyses is the same as described in Section 5.8 with the exception that the reload power history produces a change in the 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 is 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 and summarized in Table 1. A detailed breakdown of the application of adjustments (identified in Section 5 of the report) is also provided for an example plant in each group.

Consistent with the 2011 and 2013 assessments (References 3 and 4), 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.

Table 1: Summary of LBLOCA Plant Grouping

Group	# of Units	Credits
1	34	None
2	8	Improved Statistics
3	2	Improved Statistics Burst Modeling Improvements
4	2	Improved Statistics Translation of **ZIRLO** Oxidation to Cathcart-Pawel Oxidation
5	1	CQD Evaluation Model Improvements
6	1	Improved Statistics CQD Evaluation Model Improvements
7	4	Improved Statistics Translation of **ZIRLO** Oxidation to Cathcart-Pawel Oxidation CQD Evaluation Model Improvements Plant-Specific Cladding Temperature Benefit
8	2	Improved Statistics Burst Modeling Improvements CQD Evaluation Model Improvements Plant-Specific Cladding Temperature Benefit
9	1	Improved Statistics Plant-Specific Transition from CQD to ASTRUM Evaluation Model
10	5	Translation of Baker-Just to Cathcart Pawel Oxidation
11	6	Translation of Baker-Just to Cathcart Pawel Oxidation Reload Power History
Total	66	

7.1 GROUP 1

Group 1 contains 34 units; this plant grouping is comprised of plants whose licensing bases use Westinghouse or AREVA best-estimate or Appendix K LBLOCA evaluation models. The plants in this group need no adjustments to show a margin of safety to the proposed ECR criterion. The amount of available margin to the proposed limit varies on a plant-specific basis.

7.2 GROUP 2

Group 2 contains 8 units; this plant grouping is comprised of plants which have a licensing basis using the ASTRUM methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustment:

- Improved statistics (Section 5.1)

Since these plants currently utilize the ASTRUM evaluation model, explicit analytical results for each plant are used to show a margin of safety to the proposed ECR criterion.

For the example plant for this group, the rebaseline MLO, considering PCT rackup items, is 10.88% ECR.

The third ranked case can be used for the statistical benefit. Therefore, the processed MLO is:

10.88%*(1-0.49) = 5.55% ECR

The processed MLO is lower than the allowable ECR limit for the evaluated burnup. Therefore, no additional margins are applied.

7.3 GROUP 3

Group 3 contains 2 units; this plant grouping is comprised of plants which have a licensing basis using the ASTRUM methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustments:

- Improved statistics (Section 5.1)
- Burst modeling improvements (Section 5.2)

Since these plants currently utilize the ASTRUM evaluation model, explicit analytical results for each plant are used to show a margin of safety to the proposed ECR criterion.

For the example plant for this group, the rebaseline MLO, considering PCT rackup items, is 8.77% ECR.

From plant-specific calculation results for limiting cases, the fractional benefit from the first to third ranked cases accounting for the burst modeling improvements is 0.366.

Therefore, the processed MLO is:

8.77*(1-0.366) = 5.56% ECR

The processed MLO is lower than the allowable ECR limit for the evaluated burnup. Therefore, no additional margins are applied.

7.4 GROUP 4

Group 4 contains 2 units; this plant grouping is comprised of plants which have a licensing basis using the ASTRUM methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustment:

- Improved statistics (Section 5.1)
- Translation of **ZIRLO** oxidation to Cathcart-Pawel oxidation (Section 5.3)

For the example plant in this group, the rebaseline MLO, considering PCT rackup items, is 6.89% ECR.

The fractional benefit for translation to Cathcart-Pawel oxidation was estimated as 0.081. Therefore, the processed MLO is:

$$6.89*(1-0.081) = 6.33\%\ ECR$$

Using the fractional benefit from the first to third rank cases, the processed MLO of the first rank MLO is calculated:

$$6.33*(1-0.086) = 5.79\%\ ECR$$

The processed MLO is lower than the allowable ECR limit for the evaluated burnup. Therefore, no additional margins are applied. It is noted that for the plants in this group, considering the details of their analyses and PCT rackup items, it was more straightforward to estimate and apply the benefit for translation from **ZIRLO** oxidation to Cathcart-Pawel oxidation, as compared to estimating the benefit for burst improvements that was typically the second margin applied to other plants licensed with the ASTRUM evaluation model.

7.5 GROUP 5

Group 5 contains 1 unit; this plant grouping is comprised of a plant whose licensing basis uses the CQD methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustment:

- CQD evaluation model MLO calculation improvements (Section 5.4)

For the plant in this group, the rebaseline MLO, considering PCT rackup items, is 6.6% ECR.

From plant-specific calculations, applying evaluation model improvements reduces the MLO to 5.18% ECR.

The processed MLO is lower than the allowable ECR limit for the range of evaluated burnup. Therefore, no additional margins are applied.

7.6 GROUP 6

Group 6 contains 1 unit; this plant grouping is comprised of a plant which has a licensing basis using the CQD methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustment:

- Improved statistics (Section 5.1)
- CQD evaluation model MLO calculation improvements (Section 5.4)

For the plant in this group, the rebaseline MLO, considering PCT rackup items, is 7.1% ECR.

From plant-specific calculations, applying evaluation model improvements reduces the MLO to 5.99% ECR, which is a 15.6% benefit. With the generic 12% benefit for improved statistics, then, the final processed MLO is:

7.1*(1-0.156)*(1-0.12) = 5.3% ECR

The processed MLO is lower than the allowable ECR limit for the range of evaluated burnup. Therefore, no additional margins are applied.

7.7 GROUP 7

Group 7 contains 4 units; this plant grouping is comprised of plants whose licensing bases use the CQD methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustments:

- Improved statistics (Section 5.1)
- Translation of **ZIRLO** oxidation to Cathcart-Pawel oxidation (Section 5.3)
- CQD evaluation model MLO calculation improvements (Section 5.4)
- Plant-Specific cladding temperature benefit (Section 5.5)

For the example plant in this group, the rebaseline MLO, considering PCT rackup items, is 12.5% ECR.

From plant-specific calculations, applying evaluation model improvements reduces the MLO to 9.2% ECR, or a 26% benefit.

The estimated benefit for the cladding temperature margin due to conservatism in the MLO calculation for this plant was 20%. With the generic 12% benefit for improved statistics, then, the processed MLO is:

12.5*(1-0.26)*(1-0.20)*(1-0.12) = 6.5% ECR

The fractional benefit for translation to Cathcart-Pawel oxidation was estimated as 0.12. Therefore, the final processed MLO is:

6.5*(1-0.12) = 5.7% ECR

The final processed MLO is lower than the allowable ECR limit for the range of evaluated burnup. Therefore, no additional margins are applied.

7.8 GROUP 8

Group 8 contains 2 units; this plant grouping is comprised of plants whose licensing bases use the CQD methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustments:

- Improved statistics (Section 5.1)
- Burst modeling improvements (Section 5.2)
- CQD evaluation model MLO calculation improvements (Section 5.4)
- Plant-Specific cladding temperature benefit (Section 5.5)

For the example plant in this group, the rebaseline MLO, considering PCT rackup items, is 13.0% ECR.

From plant-specific calculations, applying evaluation model improvements reduces the MLO to 10.6% ECR, or an 18% benefit.

From plant-specific calculations, applying the burst modeling improvements provides an additional 12% benefit.

With these benefits, and the generic 12% benefit for improved statistics, the processed MLO applicable for middle of life conditions is:

13.0*(1-0.18)*(1-0.12)*(1-0.12) = 8.3% ECR

This processed MLO is lower than the allowable ECR limit near middle of life burnups (30 GWD/MTU); however, additional margin is needed for higher burnups. From plant-specific calculations to assess the effect of peaking factor burndown between 30-50 GWD/MTU, a cladding temperature benefit of 100°F was estimated. This was estimated as a 36% benefit on the plant MLO. Then, the final processed MLO appropriate for 50 GWD/MTU is:

13.0*(1-0.18)*(1-0.12)*(1-0.12)*(1-0.36) = 5.3% ECR

The processed MLO is lower than the allowable ECR limit at 50 GWD/MTU. Using a linear fit between the processed MLO points, the allowable ECR limit is not exceeded at interim burnups. Therefore, no additional margins are applied.

7.9 GROUP 9

Group 9 contains 1 unit; this plant grouping is comprised of a plant whose current licensing basis uses the CQD methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from the following Large Break LOCA Adjustment:

- Improved statistics (Section 5.1)
- Plant-specific transition from CQD to ASTRUM evaluation model (Section 5.6)

For the plant in this group, the rebaseline MLO based on the plant's ASTRUM analysis results, and accounting for the PCT impact of known issues which would affect the ASTRUM analysis results, is 7.23% ECR.

From the plant calculation results, the fractional benefit from the first to third ranked case is 0.59. Therefore, the processed MLO is:

7.23*(1-0.59) = 2.96% ECR

The MLO is lower than the allowable ECR limit for the evaluated burnup. Therefore, no additional margins are applied.

7.10 GROUP 10

Group 10 contains 5 units; this plant grouping is comprised of Westinghouse-fueled W-NSSS plants which are licensed with Appendix K methodology. A margin of safety to the proposed ECR criterion is shown by crediting the estimated benefit from the translation of Baker-Just oxidation to Cathcart-Pawel oxidation (Section 5.7) for a range of burnups from beginning-of-life to the maximum evaluated burnup of 50 GWD/MTU.

For the example plant in this group, the rebaseline MLO is 15.92% between 0 and 30 GWD/MTU, 11.00% between 30 and 40 GWD/MTU, and 6.66% between 40 and 50 GWD/MTU.

The estimated benefit from the translation of Baker-Just oxidation to Cathcart-Pawel oxidation is 2.48 %ECR for 0 to 30 GWD/MTU; the benefit is not required for burnups between 30 and 50 GWD/MTU.

The final MLO is 13.44% between 0 and 30 GWD/MTU, 11.00% between 30 and 40 GWD/MTU, and 6.66% between 40 and 50 GWD/MTU. The final MLO is lower than the allowable ECR limit over each segment of the range of evaluated burnup. Therefore, no additional margins are applied.

7.11 GROUP 11

Group 11 contains 6 units; this plant grouping contains Westinghouse-fueled CE-NSSS 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 5.7 and 5.8 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 conditions.

The result of evaluating the CE-NSSS plants is that the minimum reported oxidation margin is 1.95% and was calculated for **ZIRLO** high performance fuel cladding material.

8 SMALL BREAK LOCA GROUPING

As discussed in Section 4 of this report, the plant grouping process is based on analysis margin and applied adjustments. The result of this grouping process and the number of units in each group are discussed in this section and summarized in Table 2. A detailed breakdown of the application of adjustments (identified in Section 6 of the report) is also provided for an example plant in each group.

Consistent with the LBLOCA assessment, 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.

Table 2: Summary of SBLOCA Plant Grouping

Group	# of Units	Credits
1	64	None
2	1	Hot Assembly Peaking Factor Burndown
3	1	Translation of Baker-Just to Cathcart-Pawel Oxidation Reload Power History
Total	66	

8.1 GROUP 1

Group 1 contains 64 units; this plant grouping is comprised of plants whose licensing bases use Westinghouse or AREVA Appendix K SBLOCA evaluation models. The plants in this group need no adjustments to show a margin of safety to the proposed ECR criterion. The amount of available margin to the proposed limit varies on a plant-specific basis.

8.2 GROUP 2

Group 2 contains 1 unit; this plant grouping is comprised of a plant whose current licensing basis uses the NOTRUMP methodology. A margin of safety to the proposed ECR criterion was shown by crediting the estimated benefits from hot assembly peaking factor burndown.

For the plant in this group, the rebaseline MLO is 6.27% ECR. Crediting hot assembly peaking factor burndown results in an estimated MLO of less than 5.99%. The final MLO is lower than the allowable ECR limit; therefore, no additional margins are applied.

8.3 GROUP 3

Group 3 contains 1 unit; this plant grouping contains Westinghouse-fueled CE-NSSS 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 conditions.

The result of evaluating the CE-NSSS plants is that the minimum reported oxidation margin is 1.79% and was calculated for **Optimized ZIRLO** high performance fuel cladding material.

9 BREAKAWAY OXIDATION

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

10 CONCLUSION

The previous margin assessments have been updated to take into account more recent plant AORs and evaluations currently assessed against a plant's LBLOCA and SBLOCA PCT rackup sheet. Many of the PWRs in the survey need no credit to show a margin of safety to the proposed local oxidation criterion; the remaining PWRs credited the described conservatisms. It is shown in this updated assessment that all currently operating PWRs maintain a margin of safety to the proposed criteria.

Some plants are in the process of transitioning fuel vendors and/or fuel designs at the time of this report, or have other planned plant changes. For the purposes of grouping and assessing margin to the proposed limit, oxidation data from the analyses and evaluations which support the most recent core loading and current plant operation are

used in this report. While not a factor in the present grouping, analyses and evaluations which support the future fuel design and/or planned plant changes were also considered. Detailed information for all the plants addressed in this report, including conclusions for future core loadings and/or plant operations, are available to the NRC for audit at the vendor offices.

11 FUTURE UPDATE PROCESS

A future fleet-wide assessment sponsored by the PWROG will be considered with respect to the timing of the final 10 CFR 50.46c rulemaking. In the interim, fuel vendor support of the annual NRC fleet-wide safety assessment can be provided at the request of NRC.

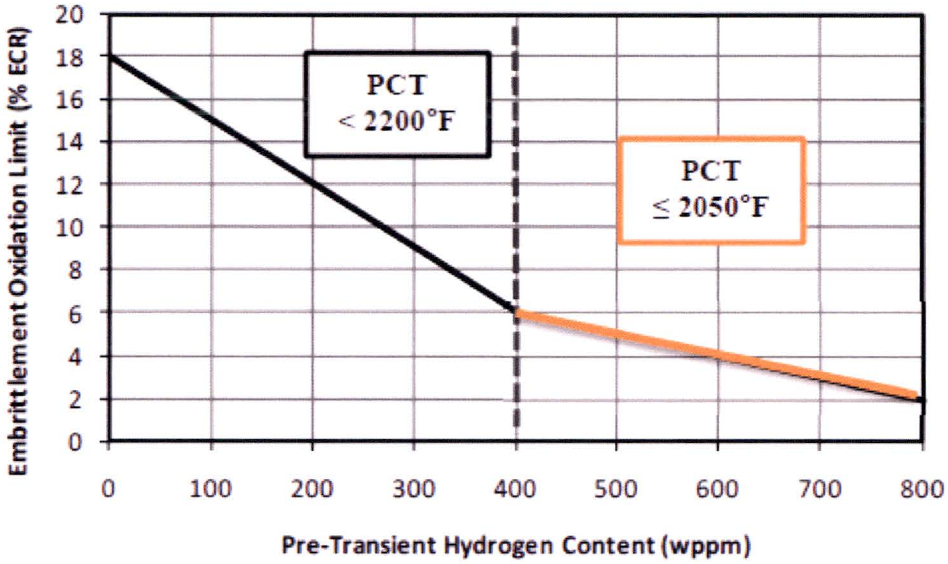

Figure 1: Proposed Acceptance Criteria for Local Oxidation

(Figure 2 of Reference 5)

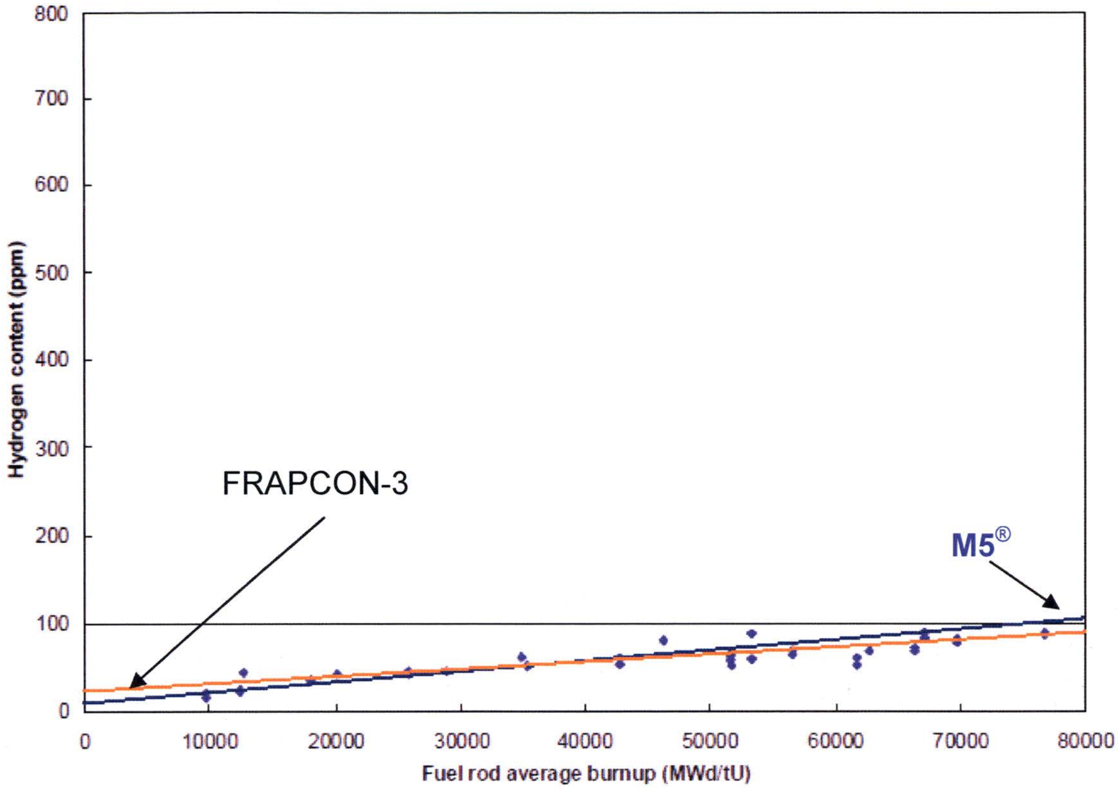

Figure 2: M5® Hydrogen Pickup versus Burnup

(FRAPCON-3, orange curve, was used for survey)

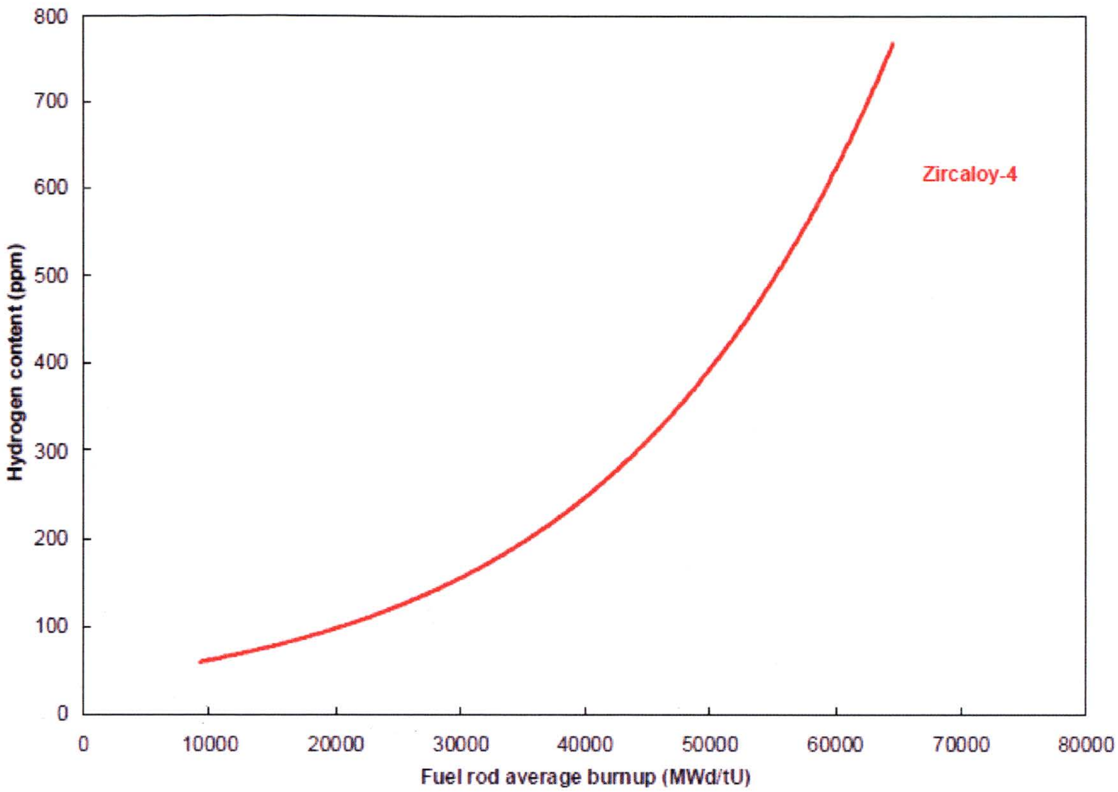

Figure 3: Zr-4 Hydrogen Pickup versus Burnup

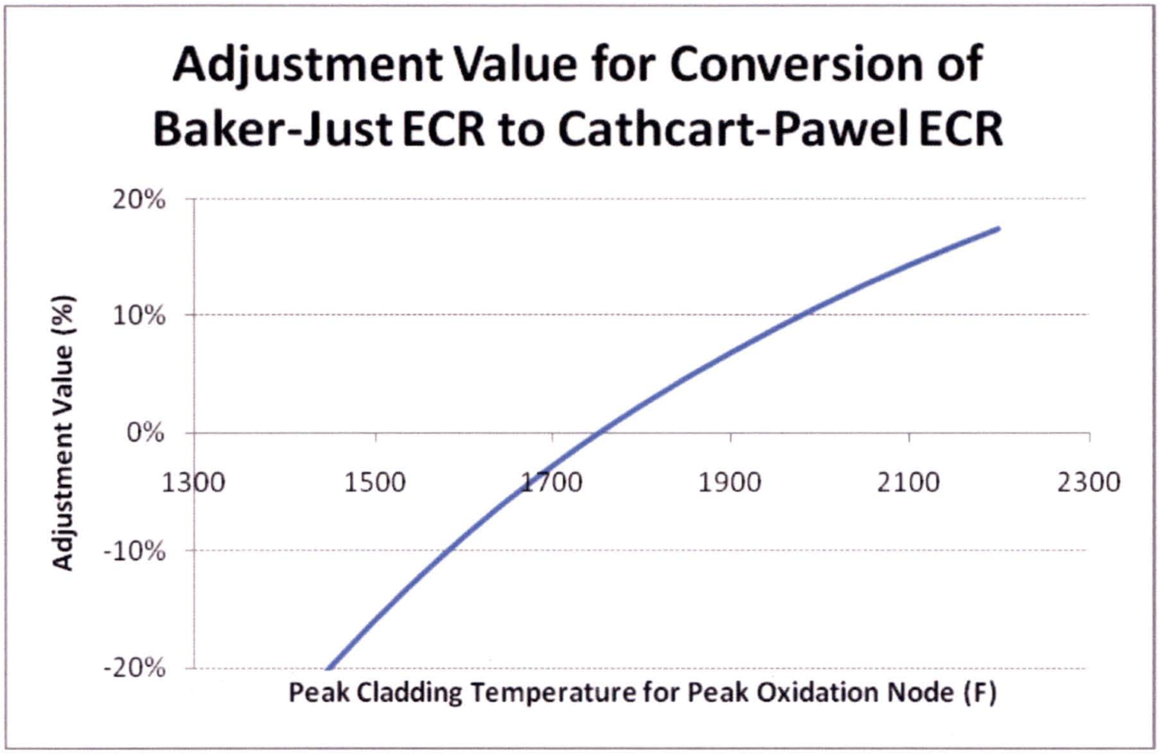

Figure 4: Adjustment Factor for Conversion of Baker-Just ECR to Cathcart-Pawel ECR

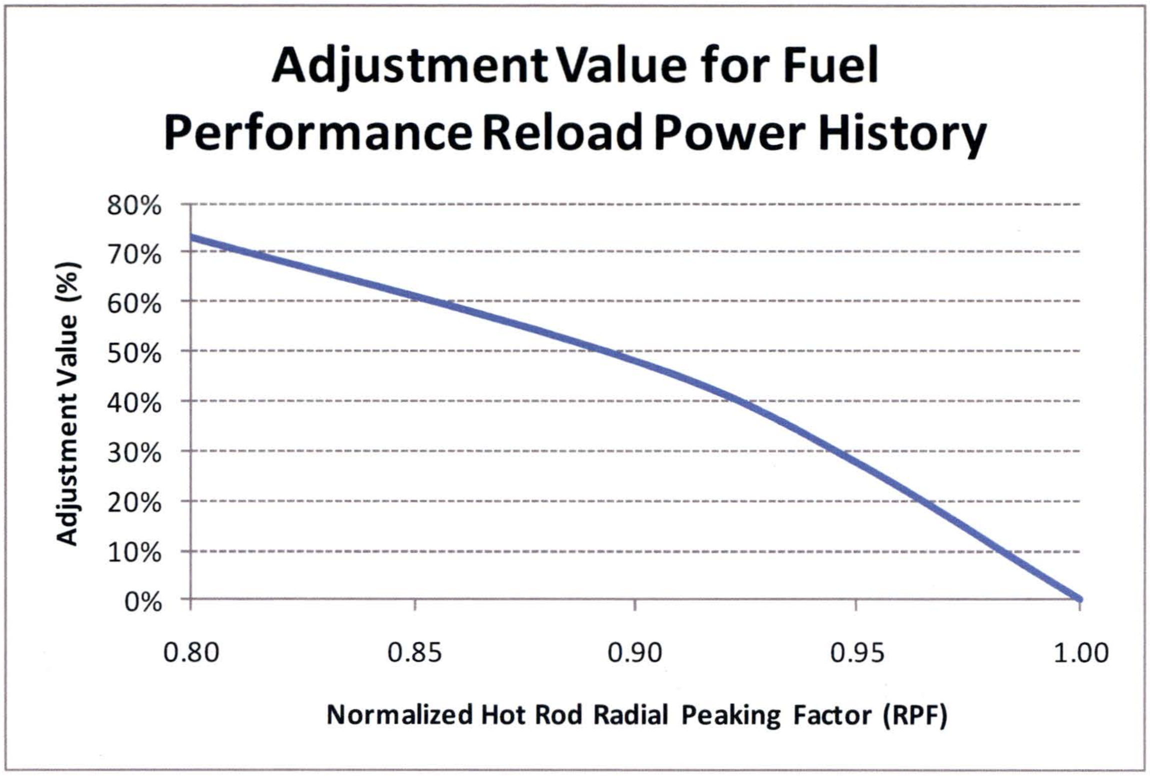

Figure 5: Adjustment Value for Fuel Performance Reload Power History