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LOCA Analysis of Fuel Fragmentation, Relocation, and Dispersal for Westinghouse 2-Loop, 3-Loop, and 4-Loop Plants–Non-Proprietary

Evaluation of Cladding Rupture in High Burnup Fuel Rods Susceptible to Fine Fragmentation

PREPARED UNDER THE NUCLEAR QA PROGRAM

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Evaluation of Cladding Rupture in High Burnup Fuel Rods Susceptible to Fine Fragmentation

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EPRI Project Manager
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ABSTRACT

Nuclear plants are considering the use of higher burnup fuel designs to meet a number of operational objectives. A major technical issue to extending burnup is Fuel Fragmentation, Relocation, and Dispersal (FFRD) during loss-of-coolant-accidents (LOCA). EPRI has developed alternative licensing approaches for utilization of higher burnup fuel rods in pressurized water reactors (PWRs), as described in EPRI Report 3002018457 [1]. One element of the proposed EPRI alternative licensing strategy (ALS) is to evaluate the credibility of fuel dispersal during a postulated Large Break Loss-Of-Coolant Accidents (LBLOCA). Additionally, the EPRI ALS project is evaluating the potential likelihood of cladding rupture and fuel dispersal for higher burnup fuel rods susceptible to fine fragmentation during a small-break and intermediate-break LOCA. This approach is aligned with various alternatives proposed within the U.S. Nuclear Regulatory Commission (NRC)'s regulatory basis for higher enrichment rulemaking per ADAMS accession number ML23032A504 [2].

This report presents the results of cladding rupture calculations for small-break and intermediate-break LOCA, which indicate that cladding rupture would likely not occur in high burnup fuel rods susceptible to fine fragmentation for specific Westinghouse fuel designs utilized in 2-Loop, 3-Loop, and 4-Loop Westinghouse PWRs. If cladding rupture would not occur, finely fragmented fuel would not disperse from the high burnup fuel rods into the reactor coolant during a LOCA. A proprietary version of these results is also published in EPRI Report 3002028674.

Keywords

Alternative Licensing Strategy (ALS)
Cladding Rupture
Fuel Dispersal
Loss-of-Coolant Accident (LOCA)

Redacted proprietary information in this report is indicated by blacked-out, bracketed text with a,c superscripts (for example, [[redacted]][a,c.]**).**

EXECUTIVE SUMMARY

Deliverable Number: 3002028675

Product Type: Technical Report

Product Title: LOCA Analysis of Fuel Fragmentation, Relocation, and Dispersal for Westinghouse 2-Loop, 3-Loop, and 4-Loop Plants – Non-Proprietary: Evaluation of Cladding Rupture in High Burnup Fuel Rods Susceptible to Fine Fragmentation

Primary Audience: Nuclear Regulatory Commission

Secondary Audience: Owners of 2-loop, 3-loop, and 4-loop Westinghouse-designed plants with Westinghouse fuel

KEY RESEARCH QUESTION

The purpose of this analysis is to study whether cladding rupture occurs in specific Westinghouse higher burnup fuel rods during small-break and intermediate-break LOCAs, which could potentially lead to fuel dispersal into the reactor coolant.

RESEARCH OVERVIEW

The analysis framework from the Westinghouse **FULL SPECTRUM**™ LOCA (**FSLOCA**™) evaluation model (EM) (WCAP-16996-P-A, Revision 1 [3]) was adapted in WCAP-18850-P [4] to determine with a high level of probability whether cladding rupture would occur in high burnup fuel during a LOCA. Composite models were then generated for Westinghouse-designed 2-Loop PWRs, 3-Loop PWRs, and 4-Loop PWRs with Westinghouse fuel. Fuel performance data was generated with PAD5 (WCAP-17642-P-A, Revision 1 [5]), and nuclear design data was produced with PARAGON2 (WCAP-18443-P-A [6]). Cladding rupture calculations were performed with each of the composite PWR models covering breaks up to the largest connecting lines to the reactor coolant system (RCS).

KEY FINDINGS

- It was demonstrated with high probability that cladding rupture would not occur in high burnup fuel for breaks up to and including the largest RCS connecting line. As such, fuel dispersal would not occur for LOCA pipe break sizes less than or equal to the largest RCS connecting line.
- Conclusions are applicable to all plants consistent with or bounded by the ranges of analyzed conditions.

WHY THIS MATTERS

One of the largest barriers for the nuclear industry's aspirations to economically achieve 24-month fuel cycles with higher initial fuel rod enrichment and high burnup is the concern with potential fuel dispersal during a LOCA. EPRI's ALS project evaluates potential fuel dispersal in various postulated LOCA scenarios. This report evaluates cladding rupture in Westinghouse-fueled plants under small-break and intermediate-break LOCA conditions and results show that fuel cladding rupture would not occur. These results aid in the achievement of those industry aspirations.

HOW TO APPLY RESULTS

The analysis described in this report can be applied by owners of Westinghouse-designed 2-loop, 3-loop, and 4-loop PWRs with 17x17 or 14x14 Westinghouse fuel arrays. A license amendment request (LAR) would be required to incorporate the approved version of WCAP-18850-P into the technical specification list of methods supporting the LOCA-related parameters. As part of that LAR, licensees would be required to demonstrate that the RCS geometry and plant operating conditions fall within the envelope.

LEARNING AND ENGAGEMENT OPPORTUNITIES

This report provides a high-level description of the LOCA evaluation model and detailed application results of the analysis of cladding rupture resulting from piping breaks as large as the largest RCS connecting line in various Westinghouse-designed reactors. This report, in combination with evaluations of other non-piping component rupture scenarios, is used to address effects of fuel fragmentation, relocation, and dispersal (FFRD) and support the bases for site-specific license amendment requests (LARs) to allow the use of high burnup fuel. Other related EPRI reports include:

- *Loss-of-Coolant-Accident-Induced Fuel Fragmentation, Relocation and Dispersal with Leak-Before-Break Credit – Alternative Licensing Strategy*. EPRI, Palo Alto, CA: 2024. 3002028673. (to be published concurrently)
- *Materials Reliability Program: xLPR Estimation of PWR Loss-of-Coolant Accident Frequencies (MRP-480)*. EPRI, Palo Alto, CA: 2024. 3002023895.

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PROGRAM: Fuel Reliability Program, P41.02.01

IMPLEMENTATION CATEGORY: Reference – Technical Basis

ACRONYMS AND NOMENCLATURE

Acronyms

ADV	atmospheric dump valve
AFD	axial flux difference
ALS	alternative licensing strategy
CCFL	counter-current flow limitation
CE	Combustion Engineering
CFR	Code of Federal Regulations
CHF	critical heat flux
ECC	emergency core cooling
ECCS	emergency core cooling system
EM	evaluation model
EPRI	Electric Power Research Institute
FSLOCA	**FULL SPECTRUM** LOCA
HFP	hot full power
HHSI	high head safety injection
IBLOCA	intermediate-break loss-of-coolant accident
IFBA	integral fuel burnable absorber
L&C	limitation and condition
LBLOCA	large-break loss-of-coolant accident
LHSI	low head safety injection
LOCA	loss-of-coolant accident
LOOP	loss-of-offsite power
LPP	low pressurizer pressure
MSSV	main steam safety valve
MTC	moderator temperature coefficient
MTR	margin to rupture
NRC	Nuclear Regulatory Commission
NSSS	nuclear steam supply system
OPA	offsite power available
PACC	accumulator cover pressure
PAD	performance analysis and design
PCT	peak cladding temperature
PIRT	phenomenon identification and ranking table
PWR	pressurized water reactor

RCP	reactor coolant pump
RCS	reactor coolant system
SAL	safety analysis limit
SBLOCA	small-break loss-of-coolant accident
SG	steam generator
SGTP	steam generator tube plugging
SI	safety injection
SRV	safety relief valve
TBS	transition break size
TMIN	minimum film boiling temperature
UCP	upper core plate
UPI	upper plenum injection
WABA	wet annular burnable absorber
WCAP	Westinghouse Commercial Atomic Power

Nomenclature for Plot Headers

ALPN	void fraction
BST-TMP	burst temperature
FGM	vapor mass flow rate
GT	guide tube
LQ-LEVEL	collapsed liquid level
MX-LEVEL	two-phase mixture level
OMEGA	pump rotational speed
PCT	peak cladding temperature
PN	pressure
POWERF	relative core power
RMVM	total mass flow rate
RVMF	vapor mass flow rate
TFUEL	fuel temperature
VFMASS	vessel fluid inventory

UNIT CONVERSIONS

The units in this report as reflected below are Imperial (British) units. The various conversions required to obtain values in the International System of units (SI units) are as follows.

Area (ft^2)	Area (m^2) = (0.0929 m^2/ft^2)*(Area, ft^2)
Differential Temperature (°F)	Differential Temperature (°C) = (5/9°C/°F)*(Differential Temperature, °F)
Length (ft)	Length (m) = (0.3048 m/ft)*(Length, ft)
Mass (lbm)	Mass (kg) = (0.4536 kg/lbm)*(Mass, lbm)
Mass Flow Rate (lbm/sec)	Mass Flow Rate (kg/sec) = (0.4536 (kg/sec)/(lbm/sec))* (Mass Flow Rate, lbm/sec)
Pressure (psi)	Pressure (MPa) = (6.8948e-03 MPa/psi)*(Pressure, psi)
Resistance (in^{-4})	Resistance (cm^{-4}) = (0.0240 cm^{-4}/in^{-4})*(Resistance, in^{-4})
Resistance (ft/gpm^2)	Resistance (hr^2/m^5) = (5.9086 (hr^2/m^5)/(ft/gpm^2))* (Resistance, ft/gpm^2)
Temperature (°F)	Temperature (°C) = (5/9)*((Temperature, °F) – 32)
Volume (ft^3)	Volume (m^3) = (0.0283 m^3/ft^3)*(Volume, ft^3)
Volumetric Flow Rate (ft^3/sec)	Volumetric Flow Rate (m^3/sec) = (0.0283 (m^3/sec)/(ft^3/sec))* (Volumetric Flow Rate, ft^3/sec)

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1 OVERVIEW OF CLADDING RUPTURE CALCULATIONS

Alternative licensing approaches for higher burnup fuel were considered by the EPRI as described in EPRI Report 3002018457 [1]. One element of the proposed EPRI alternative licensing strategy (ALS) is to evaluate the credibility of fuel dispersal during a postulated Large Break Loss-Of-Coolant Accident (LBLOCA). Additionally, the EPRI ALS project is evaluating the potential likelihood of cladding rupture and fuel dispersal for higher burnup fuel rods susceptible to fine fragmentation during a small-break and intermediate-break LOCA. This approach is aligned with various alternatives proposed within the U.S. Nuclear Regulatory Commission (NRC)'s regulatory basis for higher enrichment rulemaking per ADAMS accession number ML23032A504 [2]. This report presents the results of cladding rupture calculations based on composite 2-Loop, 3-Loop, and 4-Loop Westinghouse pressurized water reactor (PWR) models with Westinghouse fuel which demonstrate that cladding rupture would not occur for break sizes up to the largest reactor coolant system (RCS) connecting line for specific Westinghouse fuel designs. Since results show that the cladding rupture does not occur, then finely fragmented fuel will not disperse from the high burnup fuel rods into the reactor coolant during a LOCA, and the fuel is maintained in a coolable geometry.

The cladding rupture calculations presented in this report are intended to cover the full fleet of Westinghouse-designed 2-loop PWRs with 14x14 fuel array, 3-loop PWRs with 17x17 fuel array, and 4-loop PWRs with 17x17 fuel array that contain Westinghouse fuel. As such, rather than performing the calculations on a plant-specific basis, a composite model was generated for each class of PWRs intended to bound the LOCA transient response of any individual PWR within each class. The cladding rupture calculations were then performed using the composite model for each plant class. In order to apply the composite model analysis on a plant-specific basis, it must be demonstrated that the plant-specific conditions are within the envelope considered for the composite model.

The calculations cover break sizes up to the largest connecting line to the RCS. This is consistent with the definition of the transition break size (TBS) based on the expert elicitation documented in NUREG-1829 [7]. The largest connecting line diameter varies from the hot side to the cold side, and also varies amongst the different plants within the different classes of nuclear steam supply systems (NSSSs) considered. The largest break sizes considered for the various classes of PWRs are presented in Table 1-1.

The methodology used to perform the cladding rupture calculations is discussed in Section 2. Section 3 contains a discussion of the composite PWR models that were developed for each plant class. Section 4 discusses the results of the various cladding rupture analyses that were executed for the various plant classes and break sizes. Section 5 discusses the limitations and conditions on the methodology (Section 7.2 of WCAP-18850) as well as requirements for implementation of the calculations on a plant-specific basis.

Note that the proprietary version of this report is EPRI report 3002028674, and the non-proprietary version of this report is EPRI report 3002028675.

Table 1-1: Maximum Break Sizes Considered within the Cladding Rupture Calculations

Plant Class	Break Location	Break Diameter (in)	Break Area (ft^2)
2-Loop PWR	Cold Side	10.2	0.57
	Hot Side	8.8	0.42
3-Loop PWR	Cold Side	10.5	0.60
	Hot Side	11.2	0.68
4-Loop PWR	Cold Side	8.8	0.42
	Hot Side	11.5	0.72

2 METHODOLOGY FOR CLADDING RUPTURE CALCULATIONS

The methodology utilized for the cladding rupture calculations is described in WCAP-18850-P. The WCAP-18850-P methodology builds on the Westinghouse **FULL SPECTRUM**™ LOCA (**FSLOCA**™) evaluation model (EM), and incorporates various updates required to perform the cladding rupture calculations described herein. Those changes include updates to the fuel rod models (cladding rupture model, transient fission gas release, pre-burst fuel relocation, etc.), the kinetics and decay heat models, and updates related to the change in the figure of merit (from satisfaction of the emergency core cooling system (ECCS) acceptance criteria **[** [redacted]]^{a,c}).

The nuclear design input to the cladding rupture calculations was generated using approved Westinghouse nuclear design codes and methods. Bounding inputs were developed from various fuel cycle designs that include higher enriched fuel rods which achieve high burnup. These inputs are intended to bound the operation of any plants which operate on 24-month cycles to higher fuel rod burnups. The resulting peaking factors that were analyzed are discussed in Section 3 of this report.

It is noted from Table 1-1 that for certain plant classes, the maximum hot leg break to be considered is larger than the maximum cold leg break to be considered. As such, break spectrum studies are performed to confirm that the cold leg breaks remain limiting relative to the hot leg breaks. The break spectrum studies consider the range of intermediate breaks up to the largest break size to be considered per Table 1-1, and the **[** [redacted]]^{a,c} with the methodology in WCAP-18850-P. The results for the 2-loop, 3-loop, and 4-loop PWR composite models are presented in Tables 2-1, 2-2, and 2-3, respectively. It is observed that the cold leg breaks produce a higher peak cladding temperature (PCT) than the hot leg breaks across all the different PWR classes as expected. Therefore, the uncertainty analyses for cladding rupture are performed considering cold leg breaks. The results for the 3-loop PWR studies are presented in Figure 2-1 as an illustration of the results from the break location studies.

The spectrum of possible LOCA break sizes is divided into several different regions as described in WCAP-18850-P. The regions are referred to as Region I, Region IB, and Region II in order of increasing break size. Based on the maximum break sizes to be considered from Table 1-1, **[** [redacted]]^{a,c}

The satisfaction of the limitations and conditions associated with the WCAP-18850-P methodology is discussed in Section 5. However, some additional discussion regarding the fuel rod performance input is warranted in this section. The fuel performance input to the LOCA cladding rupture calculations following WCAP-18850-P is expected to be from a fuel performance code that is Nuclear Regulatory Commission (NRC)-approved for the enrichment and burnup ranges that are analyzed. Currently Westinghouse does not have a fuel performance code that has been approved by the NRC for the analyzed fuel rod discharge burnups. As such, fuel performance input which is expected to bound the fuel rod conditions was utilized in the cladding rupture calculations. Confirmation that the fuel performance input is bounding relative to an NRC-approved fuel performance code will be required as part of the plant-specific implementation of these calculations (discussed further in Section 5.2).

Table 2-1: IBLOCA PCT Results for Composite 2-Loop PWR Model

Break Location	[[redacted]]a,c PCT (F)	[[redacted]]a,c PCT (F)
Cold Leg	1,311	1,353
Hot Leg	739	1,041

Table 2-2: IBLOCA PCT Results for Composite 3-Loop PWR Model

Break Location	[[redacted]]a,c PCT (F)
Cold Leg	1,290
Hot Leg	727

Table 2-3: IBLOCA PCT Results for Composite 4-Loop PWR Model

Break Location	[[redacted]]a,c PCT (F)
Cold Leg	1,245
Hot Leg	1,035

a,c

[redacted]

Figure 2-1: PCT [[redacted]]^{a,c} with Composite 3-Loop PWR Model

3 BOUNDING PWR MODEL DEVELOPMENT

As discussed in Section 1, it is desirable to perform the cladding rupture calculations with composite, bounding PWR models which would bound the design features and boundary conditions for individual plants. This enables utilities to leverage these calculations on a plant-specific basis as long as their design and operating conditions are within the analysis envelope. The development of the composite, bounding PWR models for the 2-loop Westinghouse PWR design with upper plenum injection (UPI), 3-loop Westinghouse PWR design with cold-side injection, and 4-loop Westinghouse PWR design with cold-side injection is discussed in this section.

The approach used to generate the composite, bounding plant models is as follows. First, a review of the **FSLOCA** EM phenomena identification and ranking table (PIRT) is conducted to identify highly-ranked phenomena. Any plant design-specific geometric inputs, boundary conditions, and uncertainty contributors which have a high impact on the small-break LOCA (SBLOCA) and intermediate-break LOCA (IBLOCA) transient results (based on the review of the PIRT) and a clear direction of conservatism are then identified. A survey is completed across existing analyses to determine values for the identified parameters and the bounding values are selected among the fleet of plants surveyed. Finally, the composite PWR models are developed using the bounding parameter values.

Any utility intending to implement these calculations into a plant's licensing basis would be required to confirm that the applicable plant-specific geometry (i.e., geometrical parameters) and operating conditions are consistent with or bounded by the composite model analysis (as discussed later in Section 5.2).

3.1 Identification of Important Phenomena

3.1.1 [[redacted]]a,c

[[redacted]

[redacted]

[redacted]]a,c

3.1.2 [[redacted]]a,c

[[redacted]

[redacted]

[redacted]

[redacted]]a,c

3.1.3 [[redacted]]a,c

[[redacted]]a,c

3.1.4 [[redacted]]a,c

[[redacted]

[redacted]]a,c

3.1.5 [[redacted]]a,c

None

3.1.6 [[redacted]]a,c

None

3.1.7 [[redacted]]a,c

[[redacted]

[redacted]

[redacted]

[redacted]]a,c

3.1.8 [[redacted]]a,c

[[redacted]]a,c See below discussion.

[[redacted]]a,c See below discussion.

[[redacted]]a,c

3.1.9 [[redacted]]a,c

[[redacted]]a,c

3.1.10 [[redacted]]a,c

[[redacted]

[redacted]

[redacted]]a,c

3.1.11 [[redacted]]a,c

[[redacted]]a,c See below discussion.

[[redacted]]a,c See below discussion.

[[redacted]]a,c

3.1.12 [[redacted]]a,c

[[redacted]]a,c

3.1.13 [[redacted]]a,c

None

3.1.14 [[redacted]]a,c

[[redacted]

[redacted]]a,c

3.2 PWR Geometry

Aspects of PWR geometry which are related to the important thermal-hydraulic phenomena identified in the previous Section 3.1 and significant to the development of the composite, bounding PWR models are discussed in this section.

3.2.1 [[redacted]]a,c

[[redacted]]a,c

3.2.2 [[redacted]]a,c

[[redacted]

[redacted]

[redacted]]a,c

[[redacted]][a,c]

3.2.3 [[redacted]][a,c]

[[redacted]][a,c]

3.2.4 [[redacted]][a,c]

[[redacted]][a,c]

3.2.5 [[redacted]][a,c]

[[redacted]

[redacted]][a,c]

3.3 Initial and Boundary Conditions

The various initial and boundary conditions which are significant to the development of the composite, bounding PWR models are discussed in this section.

[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]]a,c

[[redacted]]a,c

3.4 Envelope of Analysis Applicability

The analyzed values of the previously discussed parameters are presented in Tables 3.4-1 through 3.4-8 for the various composite, bounding PWR models. These values comprise the envelope of applicability for the associated cladding rupture calculations. Note that for the 3-loop PWR class, there are [[redacted]]a,c Plants would have to demonstrate that their operating conditions are bounded by [[redacted]]a,c

One important set of input data that is not specified in Tables 3.4-1 through 3.4-8 is the fuel performance data. The fuel performance data analyzed within the cladding rupture calculations is intended to bound any plant-specific fuel performance data that would result from operation to high burnup levels. Per Section 7.2 of WCAP-18850-P, the fuel performance data should be generated using a code that is NRC-approved over the applicable ranges of burnup and enrichment. However, Westinghouse does not currently have a fuel performance code that satisfies that criterion. As such, the analyzed fuel performance data will be treated in a similar manner as the other parameters listed in Tables 3.4-1 through 3.4-8. Any plant desiring to implement these cladding rupture calculations would have to confirm that the plant-specific fuel temperatures and rod internal pressures are less than those analyzed within these calculations. The plant-specific values utilized in such an assessment must be generated with an NRC-approved fuel performance code over the applicable range of burnups and enrichments. The requirement to perform this confirmation is captured in Section 5.2 herein.

If a plant is unable to demonstrate that the envelope of applicability for the cladding rupture calculations is met based on the plant-specific conditions, then there are two different available options in such a circumstance:

- The plant-specific analysis conditions can be compared to the composite bounding model, and analysis can be performed to demonstrate that the composite bounding model remains limiting relative to the plant-specific model (for example, a difference in steam generator flow area and/or resistance could be compensated by a corresponding difference in the tube plugging level), or
- The analysis (analyses) for cladding rupture can be performed on a plant-specific basis, according to the methodology in WCAP-18850-P.

Table 3.4-1: Analysis Values for Various Plant Geometric Quantities

a,c

[redacted]

Table 3.4-2: Analysis Values for Plant Operating Conditions

a,c

[redacted]

[1] For the 3-loop PWR composite model, the [[redacted]]a,c and vice versa.

Table 3.4-3A: 2-Loop PWR Rod Peaking Factors (with uncertainty) for Cladding Rupture Calculations

a,c

Rod Average Burnup (GWd/MTU)	Transient F_Q (-)	$F_{\Delta H}$ (-)
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 3.4-3B: 2-Loop Assembly Peaking Factors (with uncertainty) for Cladding Rupture Calculations

a,c

Assembly Average Burnup (GWd/MTU)	P_{HA} (-)
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Table 3.4-4A: 3-Loop PWR Rod Peaking Factors (with uncertainty) for Cladding Rupture Calculations

a,c

Rod Average Burnup (GWd/MTU)	Transient F_Q (-)	$F_{\Delta H}$ (-)
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 3.4-4B: 3-Loop Assembly Peaking Factors (with uncertainty) for Cladding Rupture Calculations

a,c

Assembly Average Burnup (GWd/MTU)	P_{HA} (-)
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Table 3.4-5A: 4-Loop PWR Rod Peaking Factors (with uncertainty) for Cladding Rupture Calculations

a,c

Rod Average Burnup (GWd/MTU)	Transient F_Q (-)	$F_{\Delta H}$ (-)
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 3.4-5B: 4-Loop Assembly Peaking Factors (with uncertainty) for Cladding Rupture Calculations

a,c

Assembly Average Burnup (GWd/MTU)	P_{HA} (-)
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Table 3.4-6A: Safety Injection Flow for SBLOCA Cladding Rupture Calculations for 2-loop PWRs

[redacted]

a,c

Table 3.4-6B: Bounding Safety Injection Flow for IBLOCA Cladding Rupture Calculations for 2-loop PWRs

[redacted]

a,c

Table 3.4-7A: Bounding Safety Injection Flow for SBLOCA Cladding Rupture Calculations for [[redacted]]a,c

[redacted]

a,c

Table 3.4-7B: Bounding Safety Injection Flow for SBLOCA Cladding Rupture Calculations for [[redacted]]a,c

[redacted]

a,c

Table 3.4-7C: Bounding Safety Injection Flow for IBLOCA Cladding Rupture Calculations for 3-loop PWRs

[[redacted]] a,c

Table 3.4-8A: Bounding Safety Injection Flow for SBLOCA Cladding Rupture Calculations for 4-loop PWRs

[[redacted]] a,c

Table 3.4-8B: Bounding Safety Injection Flow for IBLOCA Cladding Rupture Calculations for 4-loop PWRs

[[redacted]]a,c

3.5 Benchmarking of Bounding PWR Models

The composite, bounding PWR models were created from plant-specific models which tended to already have a number of the bounding characteristics identified. They were further modified to bound all of the different important parameters identified previously in this section. After the composite models for the various classes of PWRs were developed, it was desirable to benchmark those models against existing analysis results to confirm the engineering approach for the development of the composite models.

[[redacted]]a,c The benchmark of the composite model against that existing analysis is presented in Table 3.5-1. It is observed that the composite model produces a slightly more limiting peak cladding temperature (PCT) result than the existing analysis result, which is expected since the composite model is quite similar to the model used in the existing PWR analysis.

The [[redacted]]a,c from the overall composite 3-loop PWR model[2] are compared to the results from various existing 3-loop PWR analyses in Table 3.5-2. The PCT from the composite model is between approximately 130°F and 300°F higher than the existing analysis results for 3-loop PWRs which are enveloped by the 3-loop PWR composite model. This is expected since the composite model contains limiting aspects from various 3-loop PWR designs. The analysis results for a 3-loop PWR with a 15x15 fuel array and limited emergency core cooling (ECC) capability were also included as 3-Loop Plant D in Table 3.5-2. It is observed that the 3-loop PWR composite model results bound even the 3-Loop Plant D analysis results.

[[redacted]]a,c are compared against the composite 4-loop PWR model [[redacted]]a,c in Table 3.5-3. The results from seven different 4-loop PWR analyses are available to compare against the composite 4-loop PWR model results. It is observed that the composite model is more bounding than any plant analysis by approximately 80°F to 300°F. This is expected, because similar to the 3-loop composite model, the 4-loop composite model draws on limiting elements from different plant-specific models.

Overall, it was found that the composite models were bounding relative to plant-specific models across all the different classes of PWRs. This was expected given that the composite models envelope plant-specific design and operating differences for parameters considered highly important as identified by the PIRT review. The degree of conservatism relative to any specific analysis varies as expected due to the varying degree of difference between the composite model and any given plant-specific model.

Table 3.5-1: Benchmark of 2-Loop PWR Composite Model to FSLOCA EM Analysis Results

Plant	PCT (°F)
2-Loop Plant A	965
Composite Model	**972**

Table 3.5-2: Benchmark of 3-Loop PWR Composite Model to FSLOCA EM Analysis Results

Plant	PCT (°F)
3-Loop Plant A	1,362
3-Loop Plant B	1,320
3-Loop Plant C	1,197
3-Loop Plant D*	1,459
Composite Model	**1,496**

* 3-Loop Plant D is a more limiting, 15x15 fuel array plant that is not covered by these cladding rupture calculations. It was included in this benchmark to illustrate that the composite model is even more bounding than this specific analysis.

[2] Since the 3-loop plants are [[redacted]]a,c there would be less difference to the plant-specific results.

Table 3.5-3: Benchmark of 4-Loop PWR Composite Model to FSLOCA EM Analysis Results

Plant	PCT (°F)
4-Loop Plant A	1,307
4-Loop Plant B	1,316
4-Loop Plant C	1,159
4-Loop Plant D	1,205
4-Loop Plant E	1,174
4-Loop Plant F	1,081
4-Loop Plant G	1,132
Composite Model	**1,392**

4 CLADDING RUPTURE ANALYSIS RESULTS

4.1 Introduction

The cladding rupture calculations cover the full fleet of Westinghouse-designed 2-loop PWRs with 14x14 Westinghouse fuel, 3-loop PWRs with 17x17 Westinghouse fuel, and 4-loop PWRs with 17x17 Westinghouse fuel. The largest break sizes considered for the various classes of PWRs were presented in Table 1-1. The maximum break areas to be analyzed from Table 1-1 are all **[** [redacted]]**a,c**

The fuel performance data that was utilized in the cladding rupture analyses was generated with the PAD5 code (WCAP-17642-P-A, Revision 1 [5]). The data was generated with the intent of bounding plant-specific results from a future version of the code which is approved for high burnup (see related implementation requirement #2 in Section 5.2). The nuclear physics data was produced with PARAGON2 (WCAP-18443-P-A [6]).

Sensitivity studies were conducted for the hot leg versus cold leg breaks with the different composite models since the maximum break sizes for the hot leg breaks are larger than the cold leg breaks for 3-loop and 4-loop PWRs (see Section 2). It was confirmed that analysis of the cold leg breaks bounds the results from the hot leg breaks, consistent with the approved **FSLOCA** EM (and by extension the methodology described in WCAP-18850-P).

Note that in the following sub-sections, references to the analysis case, 95/95 case, and 18th ranked case all refer to the same simulation for each analysis.

4.2 Two-Loop PWR Analyses

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

4.2.1 Two-Loop PWR [[redacted]]a,c Cladding Rupture Calculations

[[redacted]

[redacted]]**a,c**

[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]][a,c]

4.2.2 Two-Loop PWR [[redacted]]a,c Cladding Rupture Calculations

[[redacted]

[redacted]

[redacted]

[redacted]

[redacted]]a,c

[[redacted]][a,c]

a,c

[[redacted]]

Figure 4.2-1: [[redacted]][a,c] for the 2-Loop Composite PWR Model

a,c

[redacted]

Figure 4.2-2: [[redacted]][a,c] for the 2-Loop Composite PWR Model

a,c

[redacted]

Figure 4.2-3: Pressurizer Pressure for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-4: Break Flow Void Fraction for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-5: Total Break Mass Flow Rate for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-6: Relative Core Power for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-7: Pumped Safety Injection Mass Flow Rate for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-8: Pressurizer and Steam Generator Secondary-Side Pressure for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-9: Hot Assembly Two-Phase Mixture Level for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-10: Peak Cladding Temperature for All Rods for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-11: Reactor Coolant Pump Speeds for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-12: Vapor Mass Flow Rate through the Crossover Legs for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-13: Accumulator Injection Flow for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-14: Vessel Fluid Inventory for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-15: Cladding Temperature and Rupture Temperature for the Limiting Rod for the Analysis Case from the 2-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-16: Bottom-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 359 from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-17: Top-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 426 from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-18: Middle-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 345 from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-19: Pressurizer Pressure for the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-20: Vapor Mass Flow Rate through the Loop Seal Region for the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-21: Vessel Fluid Inventory for the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-22: Accumulator Injection Mass Flow Rate for the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-23: Vapor Mass Flow Rate at the Bottom of Active Fuel from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-24: Reactor Coolant Pump Speed for both Pumps from the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-25: Pumped Safety Injection for the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-26: Core Channel Collapsed Liquid Levels for the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.2-27: Dummy Rod PCT and Burst Temperature for the Analysis Case from the 2-Loop PWR IBLOCA Cladding Rupture Calculations

4.3 Three-Loop PWR Analyses

The Westinghouse-designed 3-loop PWRs have historically been more challenged in mitigating SBLOCA accidents due to the lower high pressure ECCS capacity. There is also a relatively large span of certain, key boundary conditions across the fleet of 3-loop Westinghouse-designed PWRs. Due to those factors, **[** [redacted]

[redacted]

[redacted]]a,c

4.3.1 Three-Loop PWR [[redacted]]a,c Cladding Rupture Calculations

[[redacted]

[redacted]]a,c

[[redacted]

[redacted]

[redacted]

[redacted]][a,c]

4.3.2 Three-Loop PWR [[redacted]][a,c] Cladding Rupture Calculations

[[redacted]

[redacted]][a,c]

[[redacted]

[redacted]

[redacted]

[redacted]][a,c]

4.3.3 Three-Loop PWR [[redacted]][a,c] Cladding Rupture Calculations

[[redacted]

[redacted]][a,c]

[[redacted]

[redacted]

[redacted]]a,c

a,c

[redacted]

Figure 4.3-1: [[redacted]]a,c for the 3-Loop Composite PWR Model

a,c

[redacted]

Figure 4.3-2: Pressurizer Pressure for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]][a,c]

a,c

[redacted]

Figure 4.3-3: Break Flow Void Fraction for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]]^{a,c}

a,c

[redacted]

Figure 4.3-4: Break Mass Flow Rate for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]][a,c]

a,c

[redacted]

Figure 4.3-5: Relative Core Power for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]]^{a,c}

a,c

[redacted]

Figure 4.3-6: Pumped Safety Injection Mass Flow Rate for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]]^{a,c}

a,c

[redacted]

Figure 4.3-7: Pressurizer and Steam Generator Secondary Side Pressure for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]][a,c]

a,c

[redacted]

Figure 4.3-8: Hot Assembly Two-Phase Mixture Level (Relative to Bottom of Active Fuel) for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-9: Peak Cladding Temperature for all Rods for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-10: Vapor Mass Flow Rate through the Crossover Legs for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-11: Core Collapsed Liquid Levels (Relative to Bottom of Active Fuel) for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]]a,c

a,c

[redacted]

Figure 4.3-12: Accumulator Injection Flow for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-13: Vessel Fluid Inventory for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]][a,c]

a,c

[redacted]

Figure 4.3-14: Cladding Temperature and Rupture Temperature for the Limiting Rod for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]][a,c]

a,c

[redacted]

Figure 4.3-15: Pressurizer Pressure for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]]^{a,c}

a,c

[redacted]

Figure 4.3-16: Break Flow Void Fraction for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-17: Break Mass Flow Rate for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-18: Relative Core Power for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]]a,c

a,c

[redacted]

Figure 4.3-19: Pumped Safety Injection Mass Flow Rate for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]]a,c

a,c

[redacted]

Figure 4.3-20: Pressurizer and Steam Generator Secondary Side Pressure for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted] **]**[a,c]

a,c

[redacted]

Figure 4.3-21: Hot Assembly Two-Phase Mixture Level (Relative to Bottom of Active Fuel) for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]]^{a,c}

a,c

[redacted]

Figure 4.3-22: Peak Cladding Temperature for all Rods for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-23: Vapor Mass Flow Rate through the Crossover Legs for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]]a,c

a,c

[redacted]

Figure 4.3-24: Core Collapsed Liquid Levels (Relative to Bottom of Active Fuel) for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations [[redacted]][a,c]

a,c

[redacted]

Figure 4.3-25: Accumulator Injection Flow for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]][a,c]

a,c

[redacted]

Figure 4.3-26: Vessel Fluid Inventory for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]]a,c

a,c

[redacted]

Figure 4.3-27: Cladding Temperature and Rupture Temperature for the Limiting Rod for the Analysis Case from the 3-Loop PWR SBLOCA Cladding Rupture Calculations **[** [redacted]]^{a,c}

a,c

[redacted]

Figure 4.3-28: Bottom-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 270 from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-29: Top-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 343 from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-30: Middle-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 436 from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-31: Pressurizer Pressure for the Analysis Case from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-32: Vapor Mass Flow Rate through the Loop Seal Region for the Analysis Case from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-33: Vessel Fluid Inventory for the Analysis Case from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-34: Accumulator Injection Mass Flow Rate for the Analysis Case from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-35: Hot Assembly Two-Phase Mixture Level for the Analysis Case from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-36: PCT for all the Fuel Rods from the Analysis Case from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.3-37: Dummy Rod PCT and Burst Temperature for the Analysis Case from the 3-Loop PWR IBLOCA Cladding Rupture Calculations

4.4 Four-Loop PWR Analyses

[[redacted]][a,c]

4.4.1 Four-Loop PWR [[redacted]][a,c] Cladding Rupture Calculations

[[redacted]][a,c]

[[redacted]

[redacted]][a,c]

4.4.2 Four-Loop PWR [[redacted]][a,c] Cladding Rupture Calculations

[[redacted]

[redacted]

[redacted]][a,c]

[[redacted]][a,c]

a,c

[redacted]

Figure 4.4-1: [[redacted]][a,c] for the 4-Loop Composite PWR Model

a,c

[redacted]

Figure 4.4-2: Pressurizer Pressure for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-3: Break Flow Void Fraction for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-4: Break Mass Flow Rate for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-5: Relative Core Power for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-6: Pumped Safety Injection Mass Flow Rate for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-7: Pressurizer and Steam Generator Secondary Side Pressure for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-8: Hot Assembly Two-Phase Mixture Level (Relative to Bottom of Active Fuel) for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-9: Peak Cladding Temperature for all Rods for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-10: Vapor Mass Flow Rate through the Crossover Legs for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-11: Core Collapsed Liquid Levels (Relative to Bottom of Active Fuel) for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-12: Accumulator Injection Flow for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-13: Vessel Fluid Inventory for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-14: Cladding Temperature and Rupture Temperature for the Limiting Rod for the Analysis Case from the 4-Loop PWR SBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-15: Bottom-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 222 from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-16: Top-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 444 from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-17: Middle-Skewed Hot Rod Axial Fuel Pellet Average Temperature Profile at Break Initiation for Run 314 from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-18: Pressurizer Pressure for the Analysis Case from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-19: Vapor Mass Flow Rate through the Loop Seal Region for the Analysis Case from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-20: Vessel Fluid Inventory for the Analysis Case from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-21: Accumulator Injection Mass Flow Rate for the Analysis Case from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-22: Hot Assembly Two-Phase Mixture Level for the Analysis Case from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-23: PCT for all the Fuel Rods from the Analysis Case from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

a,c

[redacted]

Figure 4.4-24: Dummy Rod PCT and Burst Temperature for the Analysis Case from the 4-Loop PWR IBLOCA Cladding Rupture Calculations

5 SUMMARY AND IMPLEMENTATION

The analyses of cladding rupture following the method documented in WCAP-18850-P have been discussed in this report. All of these analyses demonstrate that cladding rupture is not predicted to occur with high probability.

WCAP-18850-P contains various limitations and conditions (L&Cs) associated with the cladding rupture calculation methodology. Note that the term “limitations and conditions” could refer to limitations and conditions imposed by the NRC or defined by Westinghouse. The discussion in Section 5.1 indicates how the L&Cs from WCAP-18850-P are satisfied. There are a few L&Cs which are not addressed by the cladding rupture calculations within this report. For those items, the plant-specific actions required to implement this report are discussed in Section 5.2.

The analyses were completed using composite, bounding PWR models for different plant classes. For a utility to implement these calculations into a plant-specific licensing basis, the plant-specific implementation actions related to the composite models are also discussed in Section 5.2.

5.1 Satisfaction of Limitations and Conditions on the Cladding Rupture Methodology

The L&Cs associated with the cladding rupture methodology described in WCAP-18850-P are documented in Section 7.2 therein. Section 7.2 of WCAP-18850-P includes the limitations from the approved **FSLOCA** EM (WCAP-16996-P-A, Revision 1 [3]) which remain applicable to the cladding rupture methodology. An assessment of the cladding rupture calculations described in this report against the limitations and conditions from Section 7.2 of WCAP-18850-P is discussed in this section.

Limitation Number 1

Summary

The cladding rupture methodology is applicable to Westinghouse-designed 2-loop, 3-loop, and 4-loop PWRs and Combustion Engineering (CE)-designed PWRs. The methodology for the LOCA cladding rupture calculations can only be applied to the Westinghouse 2-loop PWR and CE PWR designs if the **FSLOCA** EM is approved for these designs. Any differences in the approved methodology for these plant designs must be addressed in the cladding rupture calculations.

Analyses should be executed consistent with the approved method, or any deviations from the approved method should be described and justified.

Assessment

The **FSLOCA** EM has not yet been approved for 2-loop PWRs, but cladding rupture calculations are presented in this report for 2-loop PWRs. See the discussion in Section 5.2 for a description of the plant-specific implementation actions required to address this L&C. This limitation is met with the satisfaction of implementation requirement #3 from Section 5.2.

Limitation Number 2

Summary

The decay heat uncertainty multiplier will be **[** [redacted]]^{a,c} The analysis simulations for the cladding rupture calculations will not be executed for longer than 10,000 seconds following reactor trip unless the decay heat model is appropriately justified.

Assessment

The decay heat multiplier was sampled as specified for the cladding rupture calculations, and simulations were not run beyond 10,000 seconds. Therefore, this limitation is met.

Limitation Number 3

Summary

The maximum fuel rod length-average burnup and fuel assembly average burnup permitted with this topical report is **[** [redacted]]^{a,c}

Assessment

The maximum fuel rod length-average burnup and fuel assembly average burnup supported by the cladding rupture calculations is **[** [redacted]]^{a,c} per Tables 3.4-3 through 3.4-5. Therefore, this limitation is met with the satisfaction of implementation requirement #1 from Section 5.2.

Limitation Number 4

Summary

The fuel performance data used to initialize the fuel rods for the cladding rupture calculations should be from a Westinghouse fuel performance code that is NRC-approved through the fuel rod average burnups and initial fuel enrichments that are analyzed. The **[** [redacted]]^{a,c} and the generation of all the fuel performance data should adhere to the NRC-approved methodology.

Assessment

The fuel performance data was generated consistent with the stipulations of this L&C, except for the use of an NRC-approved methodology. The fuel performance data utilized in the cladding rupture calculations is from PAD5, which is not NRC-approved through the burnup and enrichment range of interest. See the discussion in Section 5.2 for a description of the plant-specific implementation actions required to address this L&C. This limitation is met with the satisfaction of implementation requirement #2 from Section 5.2.

Limitation Number 5

Summary

The **[** [redacted] **]^{a,c}** cladding rupture analyses.

Assessment

[[redacted] **]^{a,c}** for the cladding rupture calculations described in this report. Therefore, this limitation is met.

Limitation Number 6

Summary

There are two aspects of this Limitation and Condition, which are summarized below:

- The **[** [redacted]]^{a,c} the analysis seed(s), and the analysis inputs will be declared and documented prior to performing the cladding rupture calculations. The **[** [redacted]]^{a,c} and the analysis seed(s) will not be changed throughout the remainder of the analysis once they have been declared and documented.
- Plant operating ranges which are sampled within the cladding rupture calculations will be provided in the analysis submittal associated with the cladding rupture calculations.

Assessment

The two aspects of this L&C are met as follows:

- The **[** [redacted]]^{a,c} the analysis seed(s), and the analysis inputs were declared and documented prior to performing the cladding rupture calculations. The **[** [redacted]]^{a,c} and the analysis seed(s) were not changed throughout the remainder of the analysis.
- The plant operating ranges which were sampled within the cladding rupture calculations are provided in Section 3 of this report.

Therefore, this limitation is met.

Limitation Number 7

Summary

Any plant-specific applications of the cladding rupture methodology for Region II must be executed twice: once assuming LOOP and once assuming OPA. The results from both analysis executions should be shown to be in compliance with the 10 CFR 50.46 acceptance criteria.

The **[** [redacted]][a,c]

Assessment

Cladding rupture calculations were not performed for **[** [redacted]][a,c] to the calculations described herein. The **[** [redacted]][a,c] as discussed in Section 4 of this report. Therefore, this limitation is met.

Limitation Number 8

L&Cs #3, #12, and #13 from the **FSLOCA** EM must be satisfied.

Limitation and Condition Number 3 from the **FSLOCA** EM

Summary

For Region II, the containment pressure calculation will be executed in a manner consistent with the approved methodology (i.e., the COCO or LOTIC2 model will be based on appropriate plant-specific design parameters and conditions, and engineered safety features which can reduce pressure are modeled). This includes utilizing a plant-specific initial containment temperature, and only taking credit for containment coatings which are qualified and outside of the break zone-of-influence.

Assessment

Cladding rupture calculations were not performed for Region II, so this L&C does not apply to the calculations described herein.

Limitation and Condition Number 12 from the **FSLOCA** EM

Summary

The plant-specific dynamic pressure loss from the steam generator secondary-side to the main steam safety valves must be adequately accounted for in the cladding rupture analyses.

Assessment

Implementation of these cladding rupture calculations on a plant-specific basis requires that the plant-specific dynamic pressure loss from the steam generator secondary-side to the main steam safety valves is bounded by the analyzed value specified in Table 3.4-1. Therefore, this limitation is met with the satisfaction of implementation requirement #1 from Section 5.2.

<u>Limitation and Condition Number 13 from the **FSLOCA** EM</u>

Summary

In plant-specific models for analysis of cladding rupture: 1) the **[** [redacted] **]**[a,c] and 2) the **[** [redacted] **]**[a,c]

Assessment

Implementation of these cladding rupture calculations on a plant-specific basis requires that the **[** [redacted] **]**[a,c] is bounded by the analyzed value specified in Table 3.4-1. The **[** [redacted] **]**[a,c] in the cladding rupture calculations. Therefore, this limitation is met with the satisfaction of implementation requirement #1 from Section 5.2.

Limitation Number 9

Summary

This topical report is applicable to UO_2 or **ADOPT** fuel with **AXIOM** cladding.

Assessment

The fuel pellet materials supported by the cladding rupture calculations are UO_2 and **ADOPT** fuel as specified in Table 3.4-1. The **AXIOM** cladding material is supported by the cladding rupture calculations as specified in Table 3.4-1. Therefore, this limitation is met with the satisfaction of implementation requirement #1 from Section 5.2.

Limitation Number 10

Summary

This topical report is applicable to un-poisoned fuel, fuel with integral fuel burnable absorber (IFBA), and fuel with Gadolinia. This limitation does not preclude the use of wet annular burnable absorbers (WABAs) or other discrete burnable absorbers during the lifetime of an assembly.

Assessment

The burnable absorbers supported by the cladding rupture calculations are un-poisoned fuel rods, IFBA, and Gadolinia as specified in Table 3.4-1. Therefore, this limitation is met with the satisfaction of implementation requirement #1 from Section 5.2.

Limitation Number 11

Summary

A maximum of **[** [redacted]]**a,c** is permitted with this topical report. This limitation results from the maximum enrichment that is supported by the WCOBRA/TRAC-TF2 kinetics and decay heat module.

Assessment

The maximum enrichment supported by the cladding rupture calculations is **[** [redacted]]**a,c** as specified in Table 3.4-1. Therefore, this limitation is met with the satisfaction of implementation requirement #1 from Section 5.2.

5.2 Plant-Specific Implementation Requirements

For a utility to implement these calculations into a plant-specific licensing basis, it must be demonstrated that the calculations are applicable to that particular PWR. There are several requirements to demonstrate the applicability of these cladding rupture calculations to a particular PWR, and to address the L&Cs which are not generically addressed within this report.

- **Implementation Requirement #1**: It must be demonstrated that the plant geometry and operating conditions are consistent with or bounded by the values presented in Tables 3.4-1 through 3.4-8 (where there are two different configurations to consider for 3-loop Westinghouse PWRs).
- **Implementation Requirement #2**: It must be demonstrated that the plant-specific fuel performance data, from a version of a Westinghouse fuel performance code that is NRC-approved through the analyzed fuel rod average burnups and initial fuel rod enrichments, is bounded by the fuel performance data that was utilized in the cladding rupture calculations presented in this report. This condition satisfies L&C #4 from WCAP-18850-P. Note that

higher fuel temperatures and rod internal pressures are considered bounding for the cladding rupture calculations. This is because a higher fuel temperature will result in increased cladding heatup from initial stored energy if the core is uncovered, which increases the likelihood of rupture. The increased fuel rod internal pressure will increase the hoop stress across the cladding, which also increases the likelihood of rupture.

- **Implementation Requirement #3**: If the plant is a 2-loop PWR, then the **FSLOCA** EM must be approved for 2-Loop PWRs and any differences in the approved methodology for 2-Loop PWRs versus 3-Loop and 4-Loop PWRs must be addressed. This condition satisfies L&C #1 from WCAP-18850-P.

The demonstration that these three implementation requirements are met should be included in any plant-specific licensing submittals relying upon these cladding rupture calculations.

6 REFERENCES

1. *Alternative Licensing Approaches for Higher Burnup Fuel: A Scoping Study on Deterministic and Risk Informed Alternatives Supporting Fuel Discharge Burnup Extension*. EPRI, Palo Alto, CA: 2020. 3002018457.
2. Accession Number ML23032A504, "Increased Enrichment of Conventional and Accident Tolerant Fuel Designs for Light-Water Reactors," September 2023.
3. WCAP-16996-P-A, Revision 1, "Realistic LOCA Evaluation Methodology Applied to the Full Spectrum of Break Sizes (FULL SPECTRUM LOCA Methodology)," November 2016.
4. WCAP-18850-P, "Adaptation of the FULL SPECTRUM LOCA (FSLOCA) Evaluation Methodology to Perform Analysis of Cladding Rupture for High Burnup Fuel," February 2024.
5. WCAP-17642-P-A, Revision 1, "Westinghouse Performance Analysis and Design Model (PAD5)," November 2017.
6. WCAP-18443-P-A, "Qualification of the Two-Dimensional Transport Code PARAGON2," July 2021.
7. NUREG-1829, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process," April 2008.

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PROGRAM

Fuel Reliability Program, P41.02.01

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