Enclosure 6
DNB Methodology Topical Report Slides
(Redacted)

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DNB Methodology Topical Report

December 10, 2013
(Redacted Version)

This material is based upon work supported by the Department of Energy under Award Number DE-NE0000583.

This is a pre-application document and includes preliminary B&W mPower Reactor design or design supporting information and is subject to further internal review, revision, or verification.

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Meeting Objective

- B&W mPower intends to seek NRC's approval of methods for demonstrating adequate protection of the DNB regulatory limit.
- The objective of this meeting is to provide information and elicit feedback from the staff on the proposed content of the B&W mPower™ Reactor DNB Methodology Topical Report.

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Agenda

- Introduction
  - Meeting Objective
  - Fuel Thermal-Hydraulic Topical Reports and DCD Section 4.4
  - Topical Report Table of Contents
  - Introduction to DNB Methodology
  - B&W mPower™ Reactor Characteristics
  - T-H Comparisons to New Reactors
- Background
  - Key Parameters to Consider for DNB
  - Example Power Distributions – Axial
  - Example Power Distributions – Radial
  - Process Parameter Ranges
- Methodology
  - Deterministic Approach
  - Statistical Approach
  - SDL Determination Process
  - ΔDNBR Sample Population
  - SDL Derived From ΔDNBR

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Agenda (cont.)

- Factors Affecting DNB
  - Fuel Rod Bow
  - CRA Misoperation
    - CRA Drop
    - CRA Withdrawal
    - CRA Misalignment
- Core Safety Limit Lines
- Pressure-Temperature Curves
- Summary / Conclusions

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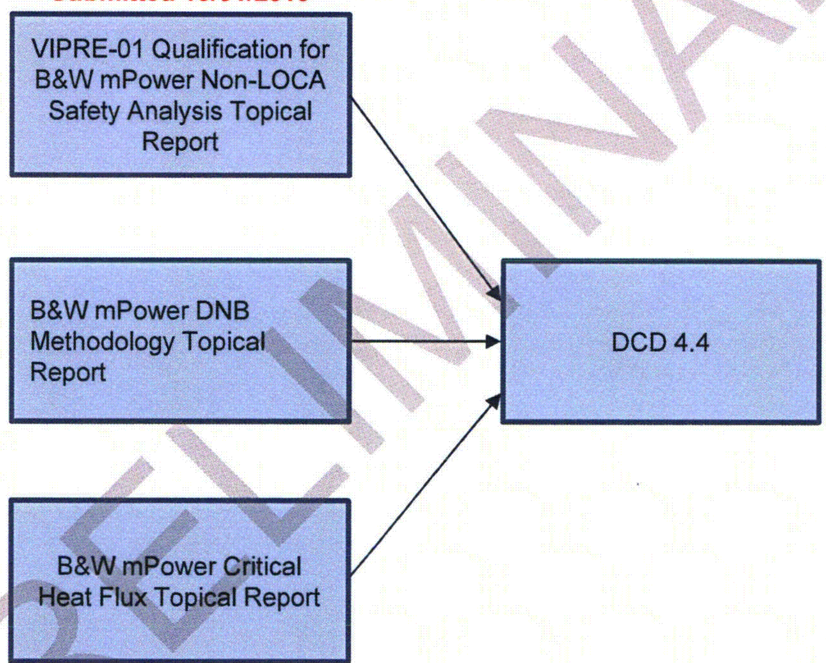
Introduction

Fuel Thermal-Hydraulic Topical Reports and DCD 4.4

Submitted 10/31/2013



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Topical Report Table of Contents

Introduction to DNB Methodology

- Prevention of DNB ensures integrity of the fuel cladding
  - Required by 10 CFR Part 50, Appendix A, General Design Criteria 10 (GDC 10)
  - Required during normal operation (NO) and all anticipated operational occurrences (AOO)
- DNB Methodology describes how DNB is prevented
  - How parameter uncertainties are accounted for
  - How hot channel factors are accounted for
  - Deterministic method and its application
  - Statistical method and its application

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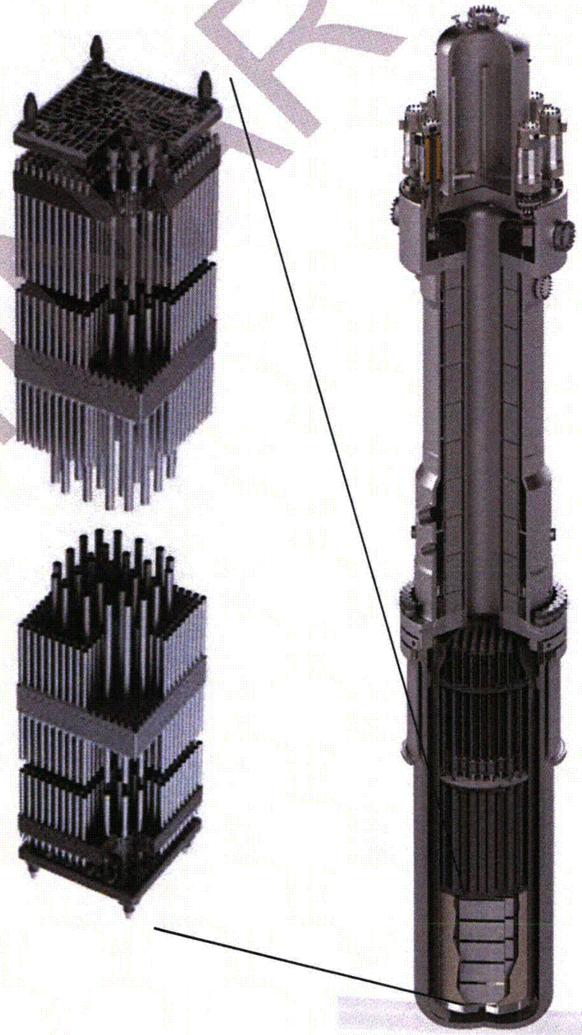
B&W mPower Reactor Characteristics

- Integral PWR (iPWR)
- 530 MWt
- 69 fuel assemblies
  - standard 17x17
  - 95 inch heated length
  - ≤ 5 w/o ^{235}U
- Reactivity control
  - No chemical shim
  - Gd_3O_2 in fuel matrix
  - Discrete BPR in lattice
  - Control rods in every FA



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T-H Comparison to New Reactors

	B&W mPower	AP1000[1]	U.S. EPR[2]	US-APWR[3]	B&W 177[4]
LHGR (kW/ft)	[	5.72	5.22	4.65	5.8
Mass Flux (Mlbm/hr-ft^2)		2.40	2.80	2.25	2.71
Power-to-Flow Ratio	]	**2.38**	**1.86**	**2.07**	**2.14**
System Pressure (psia)	2060	2190	2250	2250	2200
Saturation Temp. (°F)	640	649	653	653	650
Outlet Temp. (°F)	606	612	624	617	606
Outlet Subcooling (°F)	**34**	**37**	**29**	**36**	**44**

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1) AP1000 Design Control Document; Tier 2, Ch. 4
2) U.S. EPR Final Safety Analysis Report; Tier 2, Ch. 4
3) US-APWR Design Control Document; Tier 2, Ch. 4
4) Oconee Nuclear Station Final Safety Analysis Report; Ch. 4

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Background

Key Parameters to Consider for DNB

RCS/Process Parameters

Pressurizer pressure
RCS temperatures
Core flow
Core thermal power

Engineering/Analytical Parameters

Enthalpy rise uncertainty
Local heat flux uncertainty
Fuel rod bow penalty
Fuel assembly bow penalty
Hot channel pitch reduction
Clad outer diameter variations
Radial peaking
Axial Flux Shape
Flux quadrant tilt
$F_{\Delta H}$ augmentations
Core bypass fraction
CHF correlation uncertainty

Key Parameters cover all uncertainties

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Power Distributions – Axial

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AFS varies throughout the cycle

Power Distributions – Axial (cont.)

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Power Distributions – Radial

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$F_{\Delta H}$ varies throughout the cycle

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Process Parameter Ranges

PARAMETER		VALUE	NOTES
Pressure (psia)	Lower	[	]
	Nominal	2060	
	Upper	[	]
Temperature (Hot) (°F)	Lower	[	]
	Nominal	606	
	Upper	[	]
Power (MW)	Lower	0	
	Nominal	530	
	Upper	[	]
Flow (Mlbm/hr)	Lower	[	]
	Nominal	31.0	Inlet
	Upper	[	]

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Methodology

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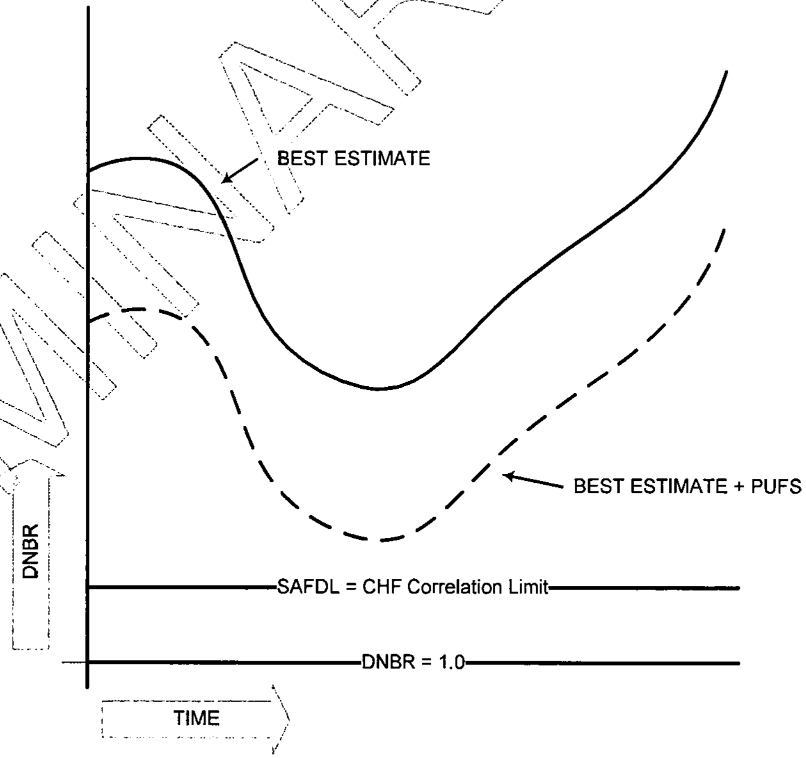
Deterministic Approach

- Conventional methods
- Penalties, uncertainties, and factors (PUFs) compounded at their worst levels in DNBR calculation
- CHF correlation uncertainty added to DNBR = 1.0 to create deterministic SAFDL
- DNBR limiting AFS and $F_{\Delta H}$ are used



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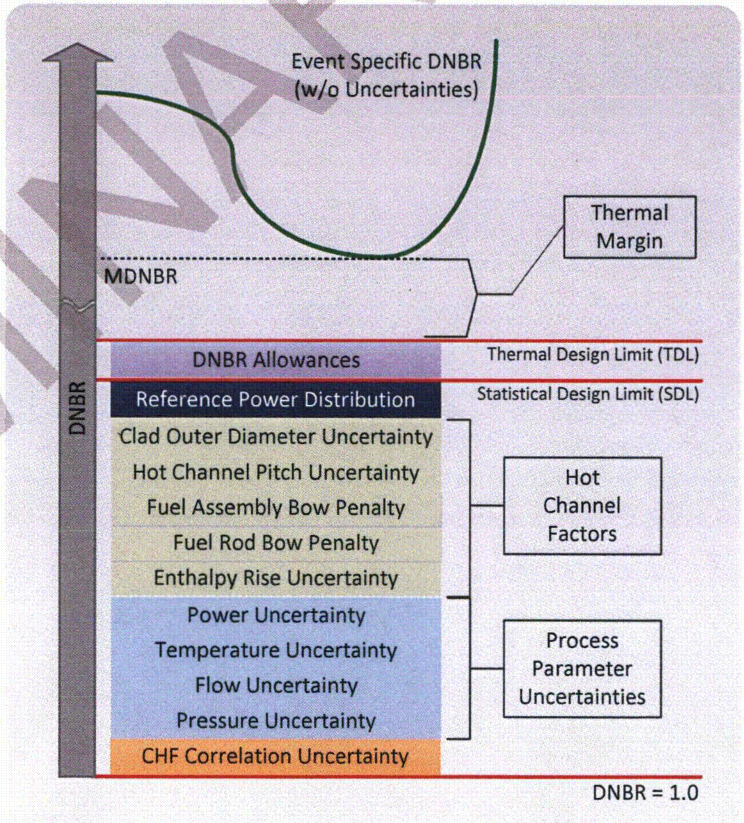
Statistical Approach

- Penalties, uncertainties, and factors (PUFs) treated probabilistically
- Sampling is random
- VIPRE-01 used directly in calculations (No Response Surface Model)
- PUFs added to DNBR = 1.0 to create a Statistical Design Limit (SDL)
- DNBR calculated with Best Estimate (BE) conditions



Uncertainties accommodated statistically in the SDL

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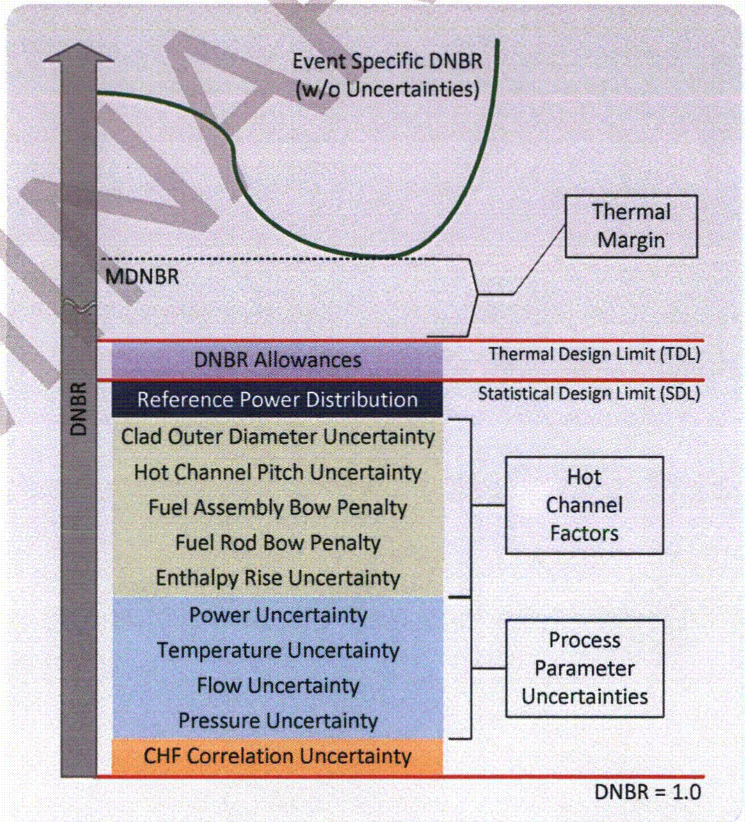
Statistical Approach (cont.)

- Reference power distribution
  - One power distribution for all safety analyses
  - Bias in the SDL
- DNBR allowances
  - Reserved thermal margin
  - Absorb future DNB decrements



Power distribution variations accommodated in SDL

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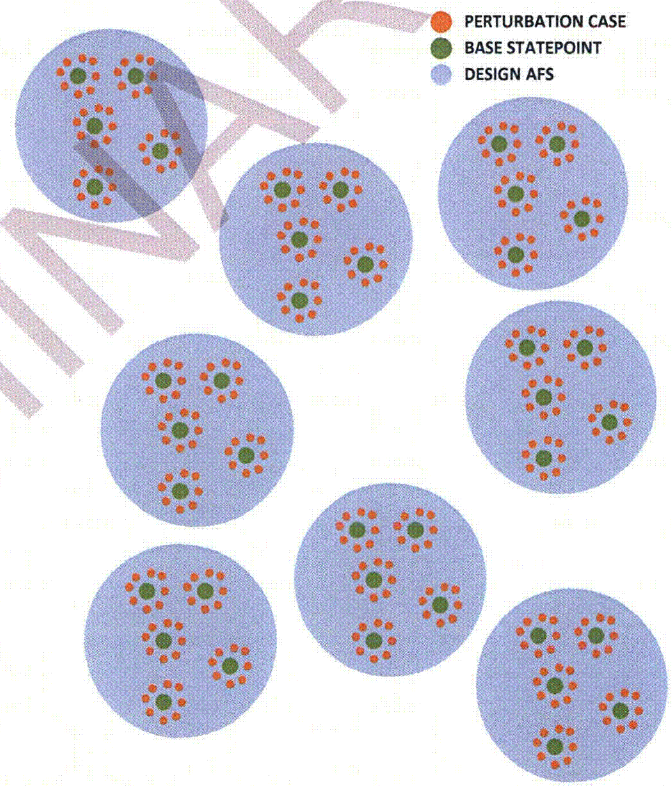
Statistical Approach (cont.)

N_{afs} axial flux shapes

↳ N_{base} base statepoints

↳ N_{pert} perturbed statepoints

→ **ΔDNBR Pool**



Covers a large population of AFSs, reactor states, and PUFs

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SDL Determination Process

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ΔDNBR Sample Population

- ΔDNBR accommodates PUFs and power distributions
- ΔDNBR used to set SDL
- Large ΔDNBR population

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- ΔDNBR are ordered in ascending order
- Tolerance limits are found from order statistics to set a 95/95 limit on ΔDNBR

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Non-Parametric Order Statistics

- Calculate tolerance limits using methods from Wilks, Murphy, Somerville, et. al.

  $$\gamma \leqq I_{1-P}(m, n-m+1) \qquad (1)$$

  where $m = r + s$

- Incomplete beta function:

  $$I_x(p,q) = \frac{\Gamma(p+q)}{\Gamma(p)\Gamma(q)} \int_0^x t^{p-1}(1-t)^{q-1}dt \qquad (2)$$

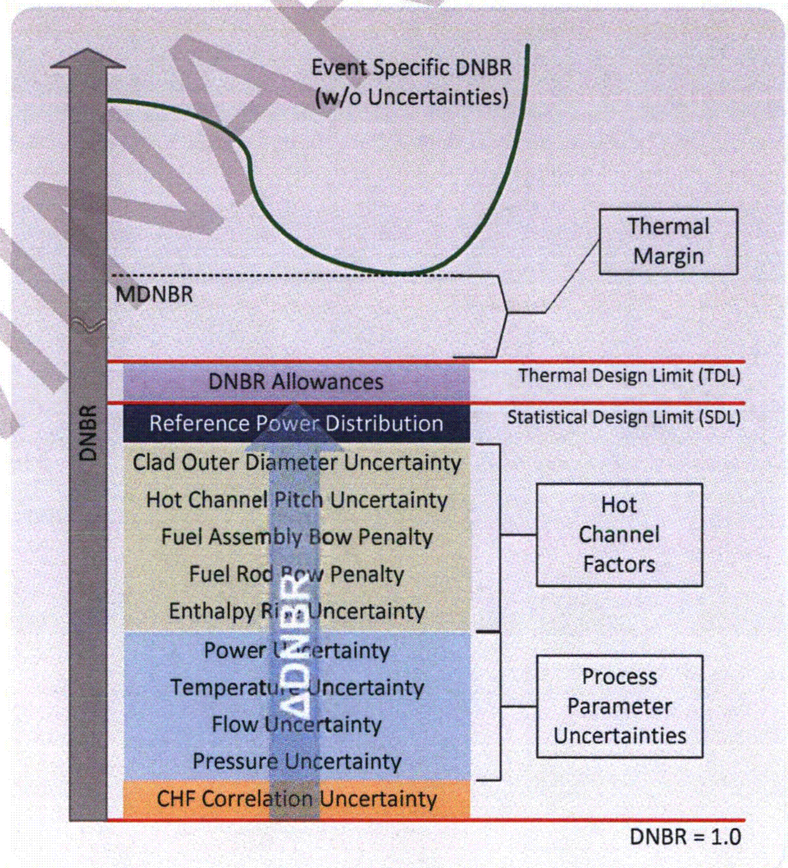
- Find m that satisfies (1) with:

  $\gamma =$ 0.95
  $P =$ 0.95
  $n =$ number of samples

SDL Derived From ΔDNBR

- ΔDNBR accommodates
  - PUFs
  - Reference power distribution
  - CHF correlation uncertainty

- ΔDNBR is added to DNBR = 1.0 to create the SDL



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Factors Affecting DNBR

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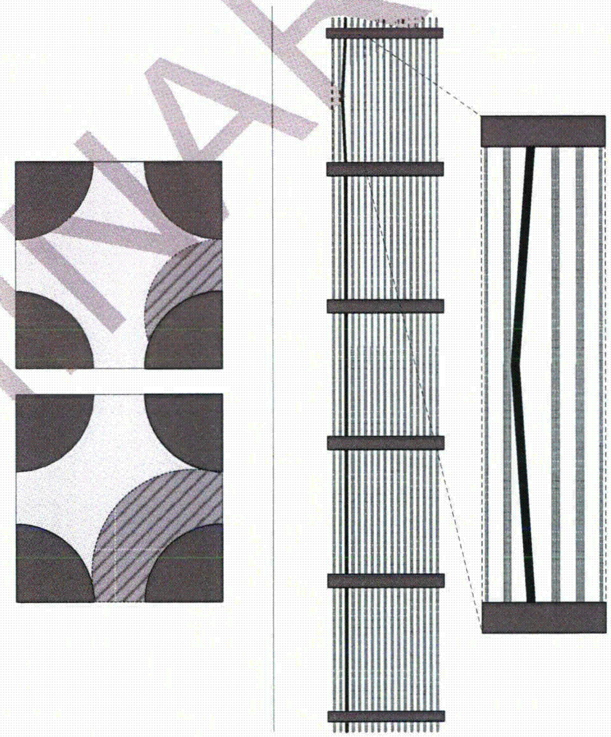
Fuel Rod Bow

- Impacts mid-span channel geometry
- Can reduce flow-affecting DNBR
- Characterized as an augmentation of hot rod $F_{\Delta H}$
- Impact on neutronics is accounted for



Fuel rod bow can provide a significant penalty to DNBR

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CRA Mis-operation (CRA Drop)

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CRA Mis-operation (CRA Withdrawal)

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CRA Mis-operation (CRA Misalignment)

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Core Safety Limit Lines

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Pressure-Temperature Curves

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Summary and Conclusions

- B&W mPower reactor conditions for DNB protection

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- Deterministic approach
  - Conventional
  - Used when DNB is less limiting than other constraints
- Statistical approach
  - Evolutionary but tailored to the B&W mPower reactor
    - Uses subchannel T-H code rather than a Response Surface Model
    - Incorporates reference power distributions into the SDL
  - Used when DNB margins matter the most
- CSLL and P-T curves provide context for reactor operation

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Abbreviations

AFS – Axial Flux Shape
AOO – Anticipated Operational Occurrences
BE – Best Estimate
BPR – Burnable Poison Rod
CHF – Critical Heat Flux
DNB(R) – Departure from Nucleate Boiling (Ratio)
FA – Fuel Assembly
GDC – General Design Criteria
LHGR – Linear Heat Generation Rate
NO – Normal Operation
PUFs – Penalties, Uncertainties and Factors
PWR – Pressurized Water Reactor
RCS – Reactor Coolant System
RSM – Response Surface Model
SAFDL – Specified Allowable Fuel Design Limit
SDL – Statistical Design Limit
TDL – Thermal Design Limit