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Assessment of Existing CHF Correlations for the Operating Conditions and Design Region of the i-SMR

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Background

❑ i-SMR

- Key differences from large PWRs: compact core, soluble boron-free operation, fully passive safety
- Standard design approval (SDA) requires reliable thermal margin evaluation under i-SMR conditions



	Details
Technology developer	i-SMRDA, KHNP&KAERI
Reactor type	Integral PWR
Thermal/Electrical capacity	520 MWt / 170 MWe
NSSS Operating Pressure	15.5 MPa
Fuel type/assembly array	UO_2, 17 x 17 square, 69 fuel assemblies & 49 control rod assemblies
Active fuel length	2.4 m
Reactivity control	Control rod, burnable absorber rods, moderator temperature coefficient
Primary circulation	Forced circulation
Approach to safety systems	Fully passive
Distinguishing features	Boron-free operation At least 72 hours for core cooling without any safety grade DC/AC power

IAEA SMR Catalogue (2024); IAEA ARIS i-SMR Design Description (2024)

Standard Design
2019 ~ 2025

SDA review
2026.02

SDA
2028

Construction permit
2030 (target)

First i-SMR completion
2035 (target)

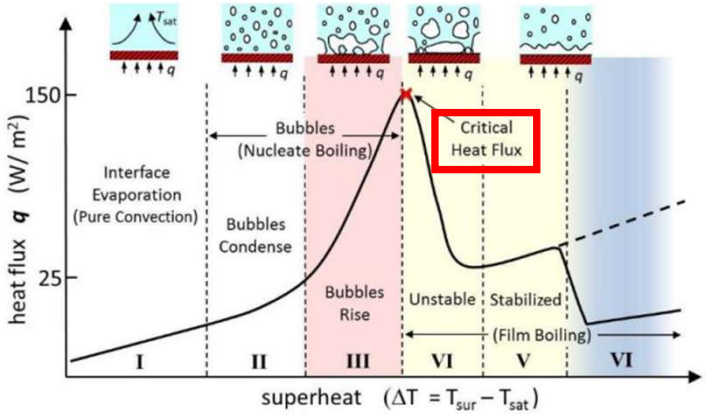
NSSC (2026); IAEA SMR Catalogue (2024)

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Background

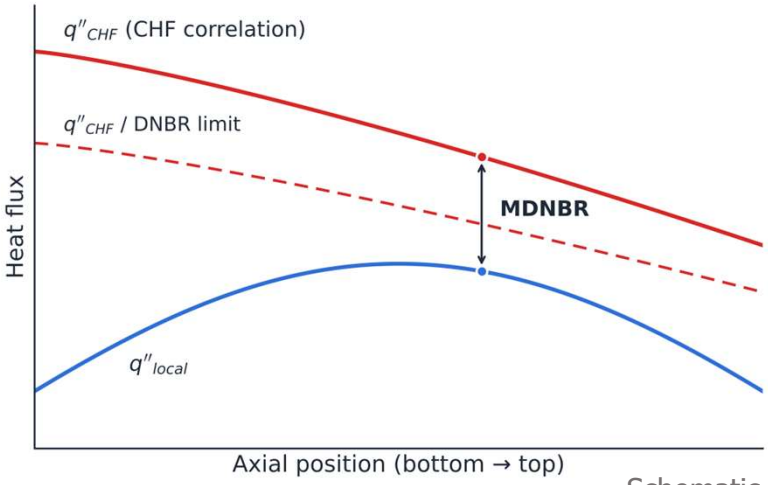
❑ Critical Heat Flux (CHF) is the primary limit determining core thermal margin

- Beyond CHF, heat transfer deteriorates abruptly, leading to cladding temperature excursion and potential fuel failure
- CHF is predicted by empirical correlations reflecting fuel design and operating conditions
- Minimum DNBR must remain above the limit during normal operation and Anticipated Operational Occurrences (AOOs)









Schematic

$$\mathrm{DNBR} = \frac{q''_{CHF}}{q''_{local}}$$

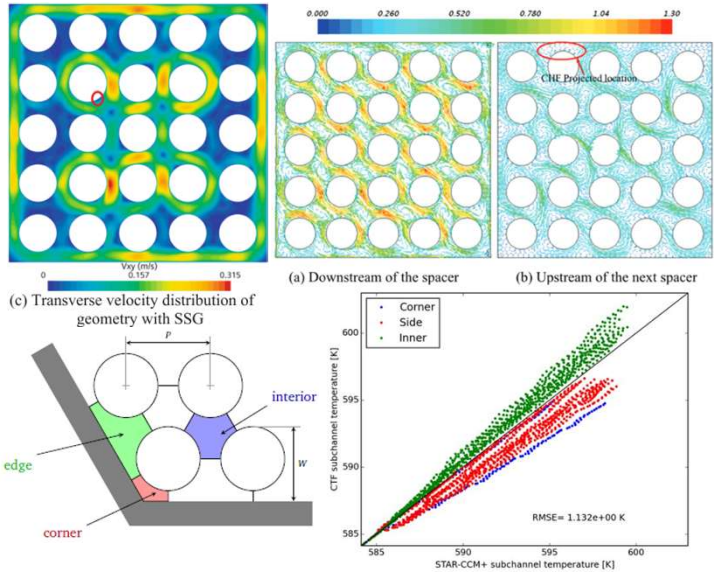
Background

❑ Challenges in Rod Bundle CHF Prediction

- Unlike round tubes, rod bundles are strongly affected by inter-subchannel interaction and local thermal-hydraulic fields

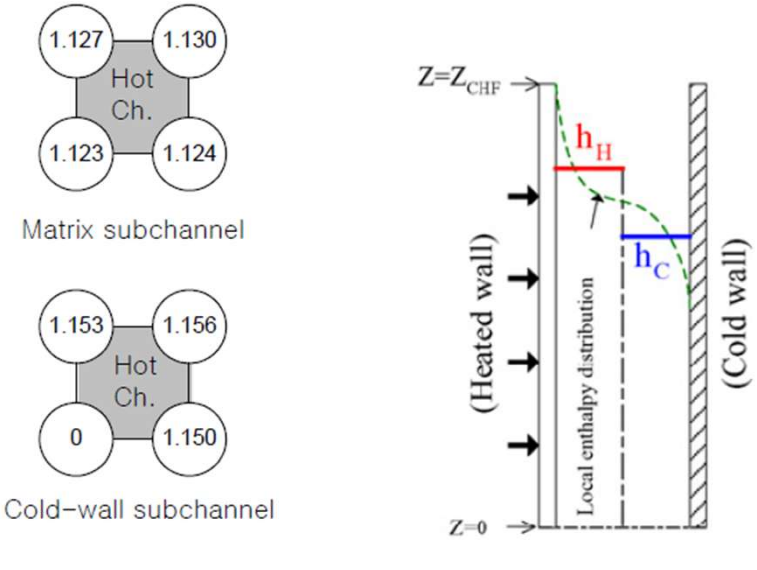
→ CHF correlations based on global parameters are difficult to develop

Geometry-dependent local flow distribution



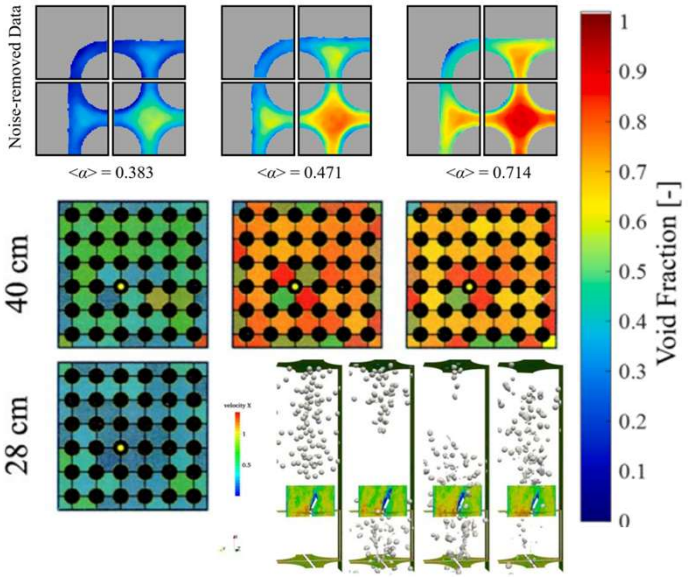
Non-uniform flow area and pressure drop (fuel rods, guide tubes, corner/edge subchannels)

Lateral mixing and incomplete enthalpy exchange



Asymmetric enthalpy distribution

Non-uniform two-phase flow distribution



Asymmetric void distribution and bubble clustering

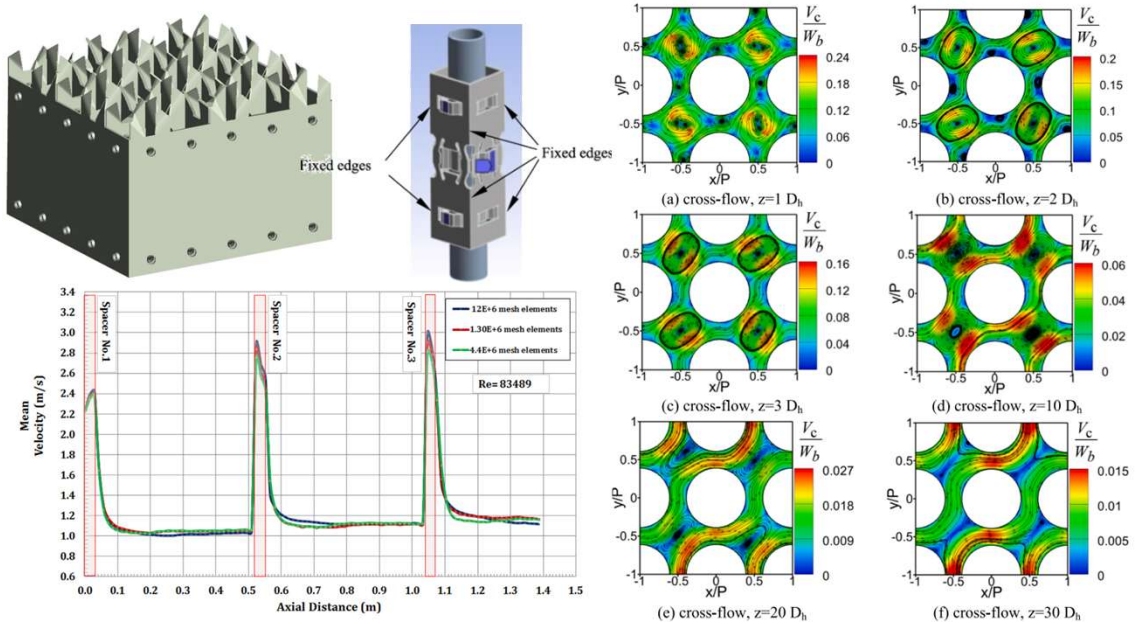
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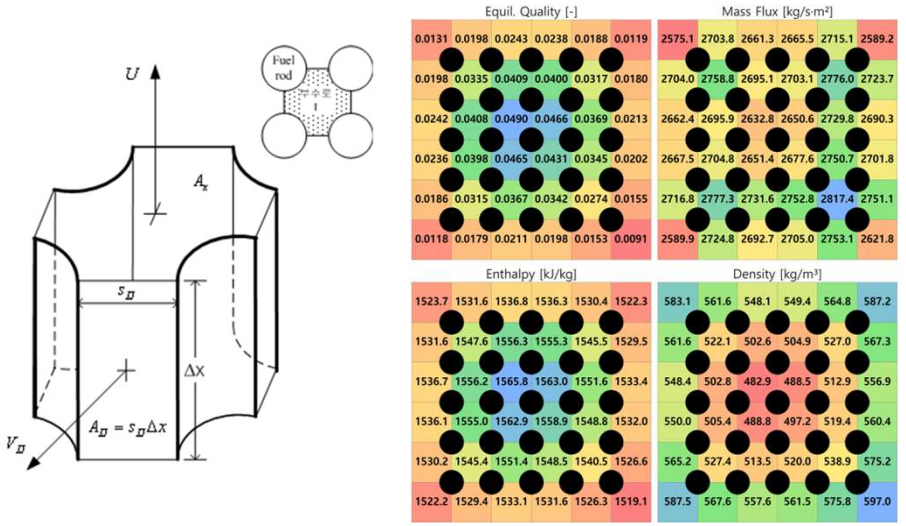
→ **CHF correlations based on global parameters are difficult to develop**

Spacer grid effect



Cross-flow, turbulence enhancement, liquid replenishment to the wall

Subchannel analysis



→ **Bundle CHF is predicted by subchannel analysis code with CHF correlations**

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Background

❑ CHF Correlations: Different Development Bases Centered on Large PWR

- Developed from distinct databases, primarily under conventional **large PWR conditions**
- **No publicly available i-SMR-specific CHF correlation**
- **Limited CHF test data for the i-SMR-specific design**

→ Accuracy and conservatism of existing correlations under i-SMR remain unknown

	W-3	B&W-2	WRB-1
Developer	Westinghouse	Babcock & Wilcox	Westinghouse
Development basis	Single heated tube CHF data + correction factors for bundle application	3×3 rod bundle CHF data at high-pressure PWR conditions	Mixing vane grid bundle CHF data
Range of applicability			
Pressure	6.9 ~ 15.8 MPa	13.68 ~ 16.6 MPa	9.93 ~ 17.17 MPa
Mass flux	1,356 ~ 6,781	1,044 ~ 5,425	1,221 ~ 5,018
Quality	-0.25 ~ +0.15	-0.03 ~ +0.22	-0.20 ~ +0.30
Equivalent diameter	5.08 ~ 17.78 mm	5.08 ~ 12.70mm	9.40 ~ 15.24 mm
Heated length	250 ~ 3,660 mm	1,829 mm	~ 4,267 mm
DNBR limit (95/95)	1.30	1.30	1.17

B&W-2 correlation

$$q''_{CHF} = \frac{1.155 - 0.407(D_h)}{(12.71)(3.053 \times 10^6 G)^A} \times [(0.3702 \times 10^8) \times (0.59137 \times 10^{-6} G)^B - 0.15208 h_{fg} \cdot G]$$

$$A = 0.71186 + (2.0729 \times 10^{-4}) \cdot (P - 1000)$$

$$B = 0.834 + (6.8479 \times 10^{-4})(P - 2000)$$

W-3 correlation

$$q''_{CHF} = q''_{CHF,tube} \times \frac{F_{CW} F_{GRID}}{F_{APK}}$$

$$F_{CW} = 1 - \left(1 - \frac{D_{hy}}{D_h}\right)\left[13.76 - 1.372 e^{1.78x} - 4.732 (10^{-6} G)^{-0.0535} - 0.0619 \left(\frac{p}{1000}\right)^{0.14} - 8.509 D_h^{0.107}\right]$$

$$F_{GRID(S)} = 1.0 + 0.03 \times 10^{-6} G \left(\frac{TDC}{0.019}\right)^{0.35}$$

$$F_{GRID(RL)} = F_g \times \left[(1.445 - 0.0371 L)\left(\frac{p}{225.896}\right)^{0.5} [e^{(x+0.2)^2} - 0.73] \& + K_S \times 10^{-6} G \left(\frac{TDC}{0.019}\right)^{0.035}\right]$$

WRB-1 correlation

$$q''_{WRB1} = A - Bx$$

$$A = A(P, G, L_h, g_{sp}, d_g)$$

$$B = B(P, G, L_h)$$

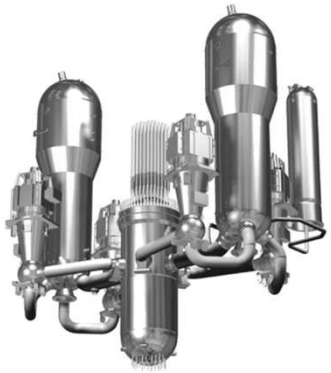
Background

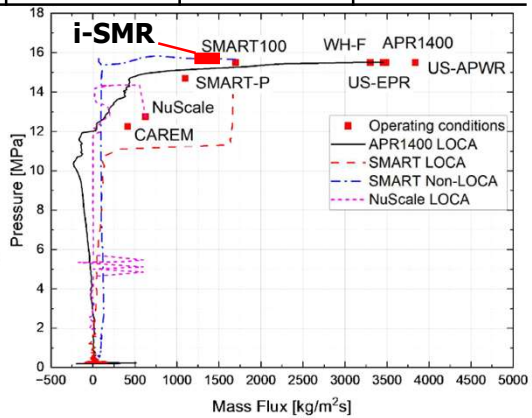
❑ i-SMR Conditions: Distinct from Large PWRs

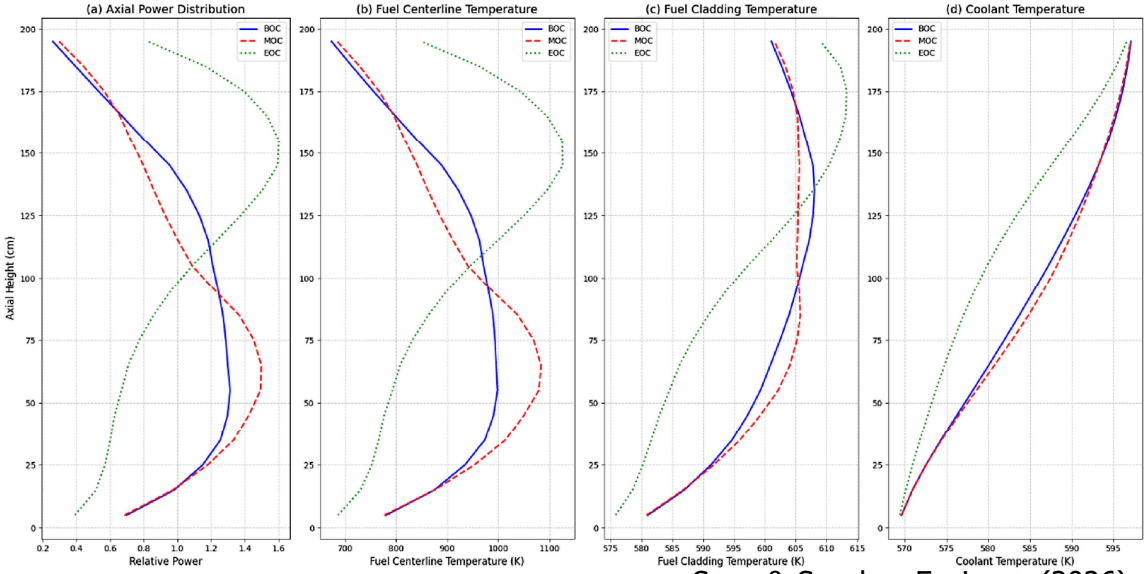
- Relatively short heated length: **2.4 m** (vs. **3.81 m** for APR1400)
- Low-to-intermediate mass flux: **~1,650 kg/m²·s** (vs. **~3,600 kg/m²·s** for APR1400)
- Soluble boron-free (SBF) operation: **wider Axial Offset(AO) variation** and more diverse axial power shapes



NSSS design parameters		Unit	i-SMR	APR1400
Power	Core power	MWt	520	3983
	Power/FA	MWt	7.54	~16.5
	Avg. q'	KW/ft	3.681	~5.5-6.5







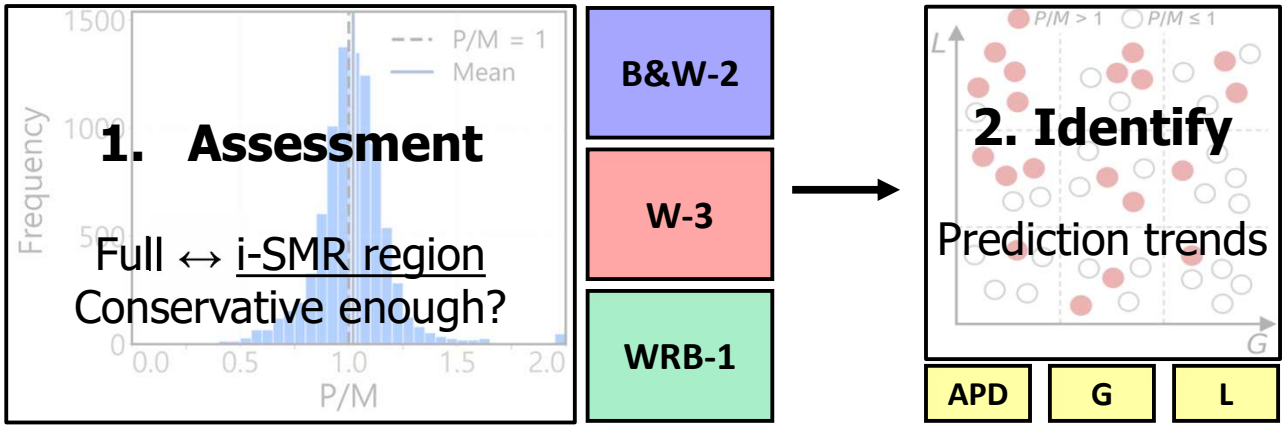
Song & Sanchez-Espinoza (2026)

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→ **Limited assessment of existing CHF correlations under these i-SMR conditions**

Objective

- **Large-PWR-based CHF correlations: applicability to i-SMR conditions not established**
  - → Assess **prediction accuracy** of existing CHF correlations in the i-SMR region
  - → Examine whether the existing methodology remains **conservative** for i-SMR design characteristics
  - i-SMR region: **1,200 ≤ G ≤ 1,650 kg/m²·s** & **L = 2.0~2.4 m** & **P = 12.0~16.5 MPa**
  - Correlations: W-3, B&W-2, WRB-1
- Identify regions and key parameters where prediction accuracy or conservatism may degrade under i-SMR conditions
  - → Examine the **effects** of Axial power distribution (APD), G, and L on prediction accuracy and conservatism with focus on the i-SMR region

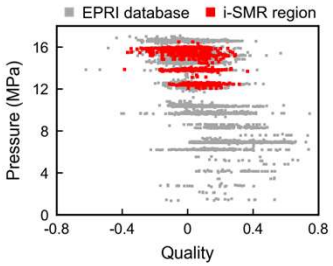


Method

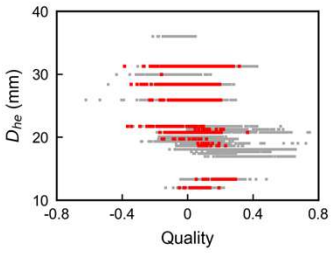
❑ EPRI Rod-Bundle CHF database

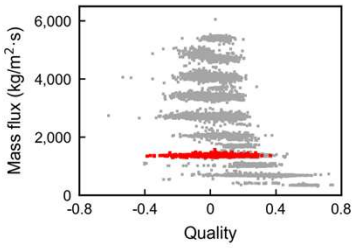
- No publicly available i-SMR-specific CHF correlation & limited rod-bundle experimental data

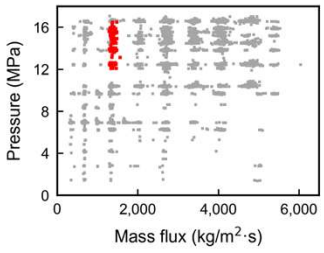
→ In the absence of i-SMR-specific data, correlations are assessed in the i-SMR region using the EPRI database spanning a wide range of LWR conditions



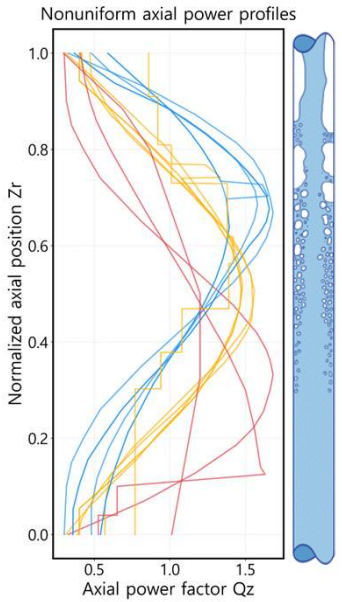
Variables	Range
Inlet mass flux	305 ~ 6046 kg/m²·s
Inlet temperature	359.3 ~ 614.8 K
Outlet pressure	1.35 ~ 17.06 MPa
Heated rod diameter	9.5 ~ 14.3 mm
Heated length	762 ~ 4,267 mm
Gap	3.10~ 4.45 mm



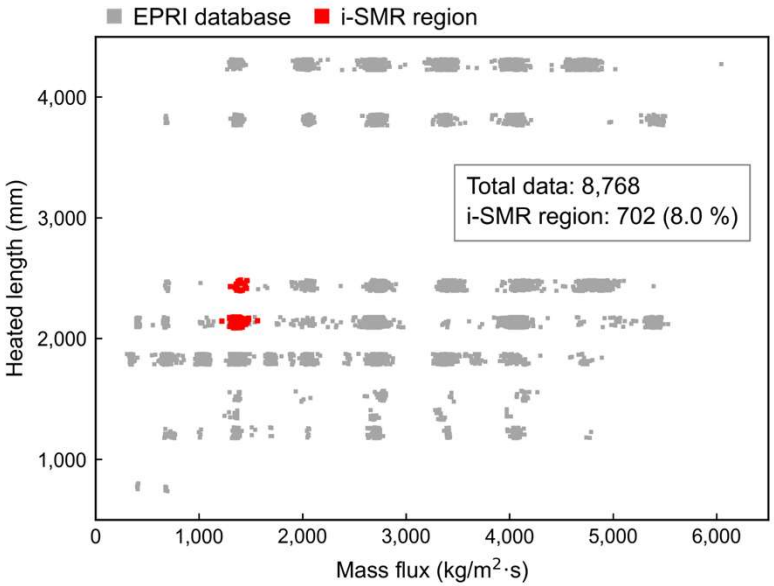




▲ **Various rod length, diameter, mass flux, quality**



Axial power distribution ▲

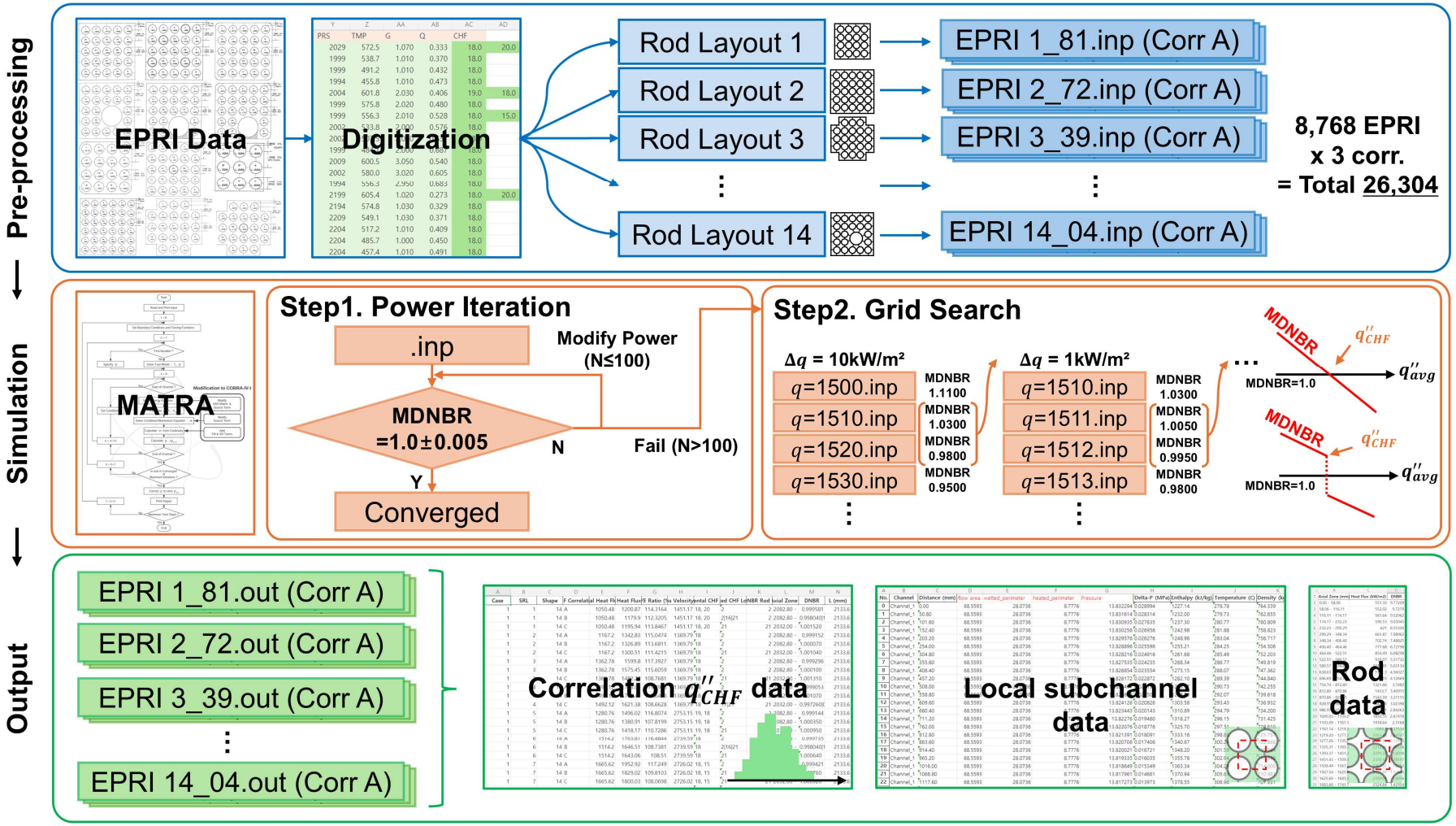


G–L data distribution ▲

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Method

❑ Data Collection and Processing Procedure Using MATRA and EPRI CHF Database

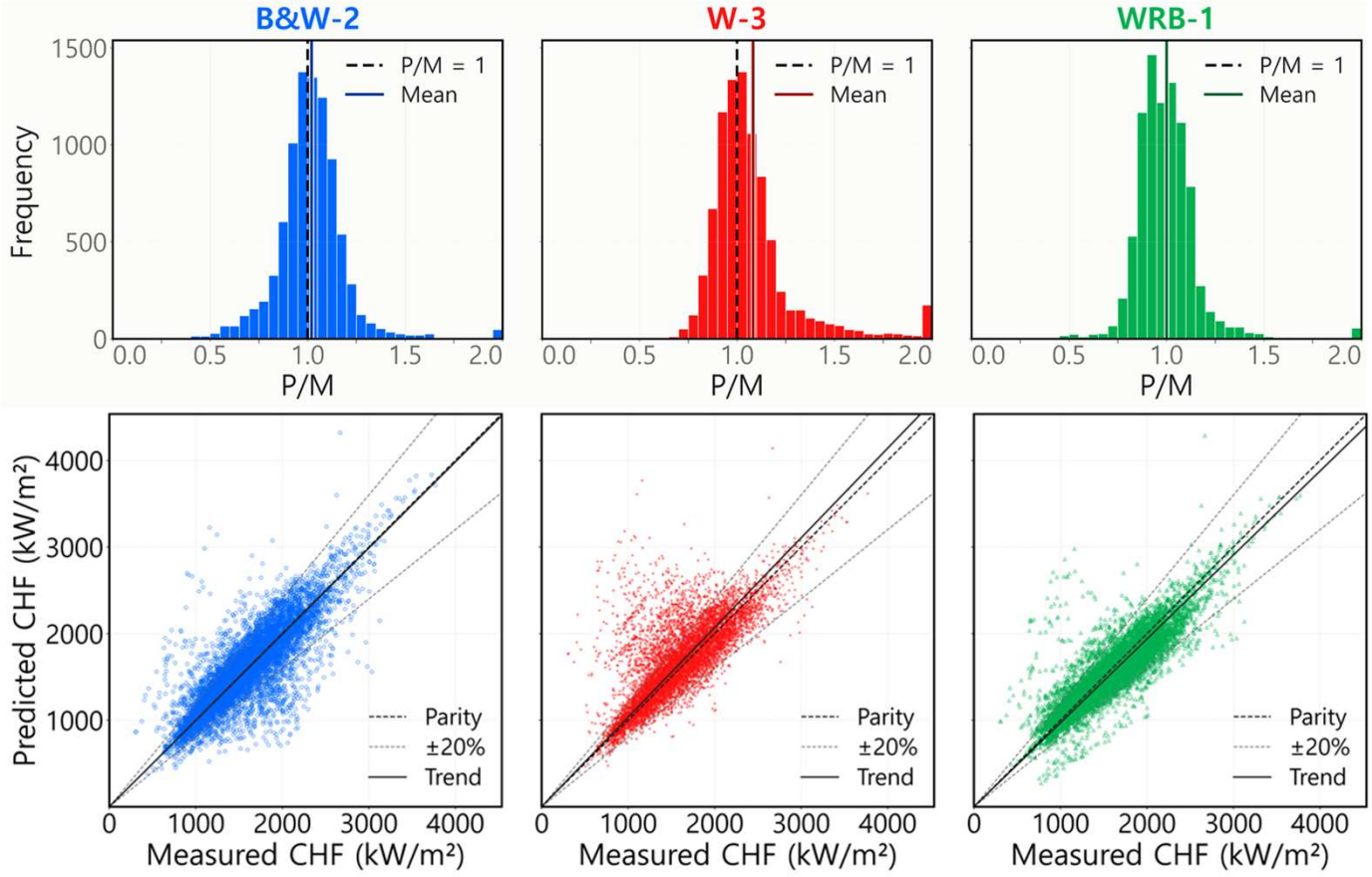


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Result & Discussion

❑ Full sample performance assessment: B&W-2, W-3, WRB-1

- Mean P/M within 1.00~1.08 for all correlations: measured CHF level generally reproduced
- Prediction accuracy: WRB-1 > B&W-2 > W-3

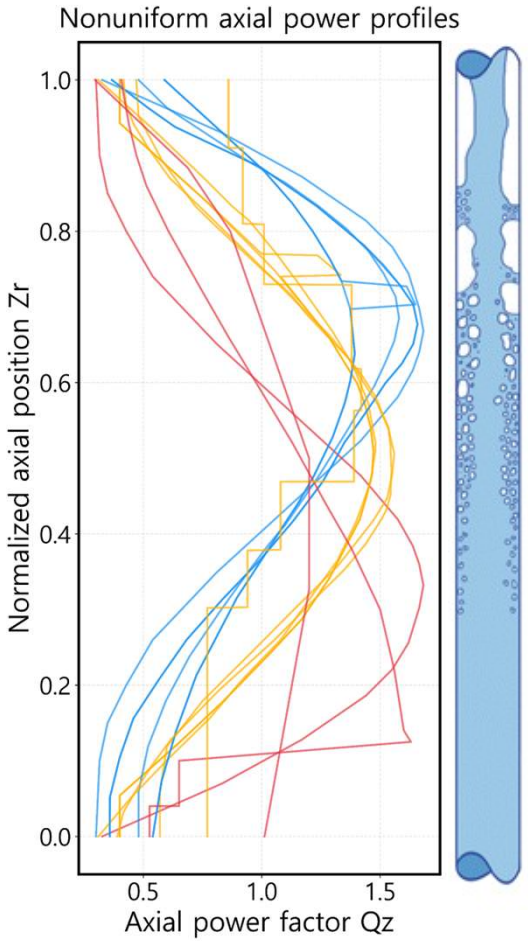


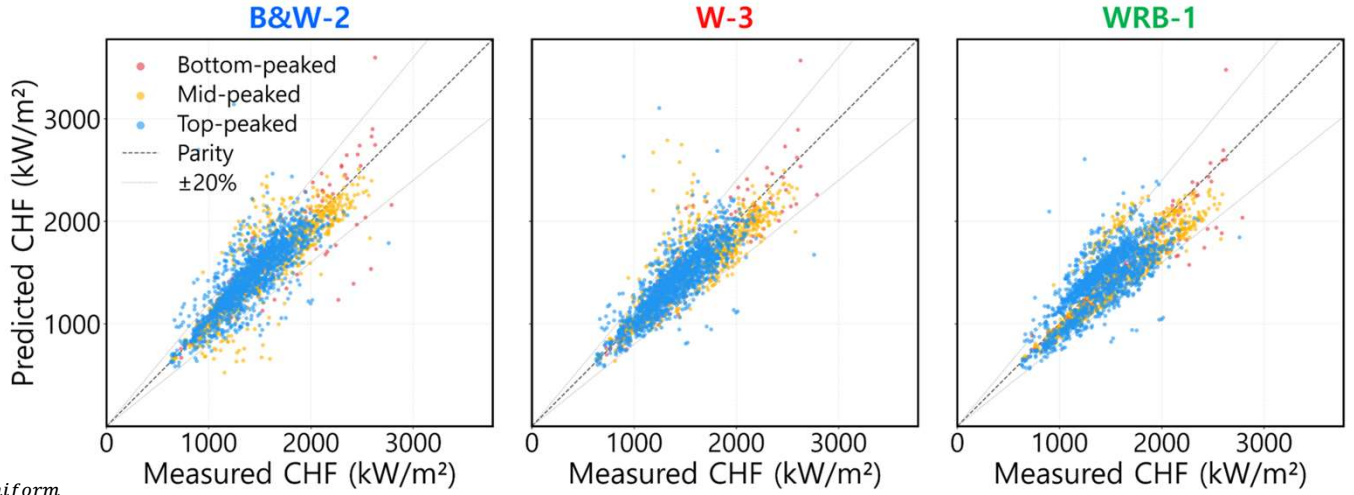
	B&W-2	W-3	WRB-1
mean P/M	1.020	1.082	1.001
σ(P/M)	0.193	0.290	0.188
RMSE	263 kW/m^2	329 kW/m^2	229 kW/m^2
MAPE	12.2%	15.2%	11.2%
R^2	0.655	0.462	0.739
$DNBR_{95/95}$	1.264	1.534	1.239

Result & Discussion

❑ Performance assessment: by axial power distribution

- 15 axial power distribution shapes in the EPRI database → bottom-, middle-, and top-peaked





$$q''_{Non-uniform} = \frac{q''_{W-3,Uniform}}{F}$$

$$F_{Tong,W-3} = \frac{C\int_0^{L_{DNB}} q''(z)e^{-C(L_{DNB}-z)}dz}{(q''(L_{DNB})[1-e^{-C\cdot L_{DNB}}])}$$

$$C = \frac{0.15(1-x_{DNB})^{4.31}}{(G/10^6)^{0.478}}\ [in^{-1}]$$

$$F_{B\&W-2} = \frac{K_D\cdot C_{BW}\cdot\int_0^{L_{DNB}} q''(z)\exp[-C_{BW}(L_{DNB}-z)]dz}{q''(L_{DNB})[1-\exp(-C_{BW}L_{DNB})]}$$

$$C_{BW} = \frac{0.24867(1-x)^{7.82293}}{(G/10^6)^{0.45758}}\left[\text{in}^{-1}\right]$$

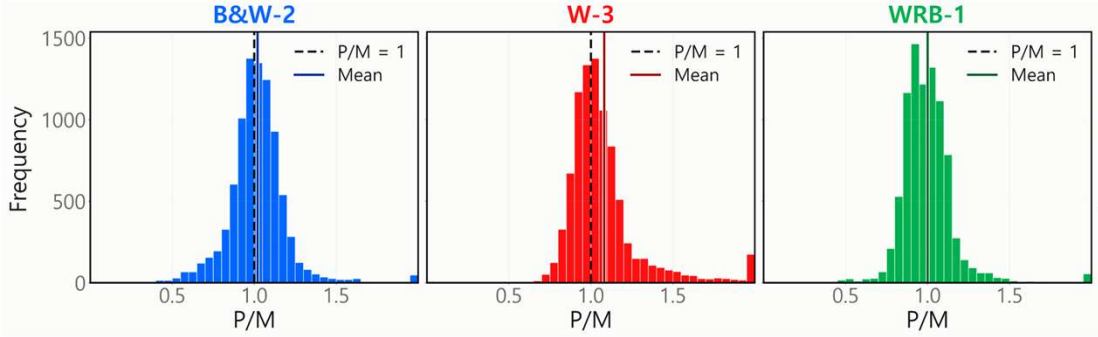
Peak	Top (n = 1,634)			Mid (n = 785)			Bottom (n = 147)		
correlations	B&W-2	W-3	WRB-1	B&W-2	W-3	WRB-1	B&W-2	W-3	WRB-1
mean P/M	1.035	1.012	1.012	1.000	0.966	0.948	1.024	0.996	0.951
σ(P/M)	0.140	0.131	0.147	0.146	0.151	0.120	0.122	0.111	0.084
RMSE	188 kW/m²	174 kW/m²	203 kW/m²	216 kW/m²	227 kW/m²	214 kW/m²	249 kW/m²	199 kW/m²	198 kW/m²
MAPE	9.5%	8.8%	11.7%	9.9%	10.1%	10.8%	9.3%	8.7%	7.0%
R^2	0.618	0.669	0.552	0.745	0.716	0.748	0.741	0.834	0.836
$DNBR_{95/95}$	1.299	1.230	1.270	1.326	1.319	1.267	1.232	1.358	1.089

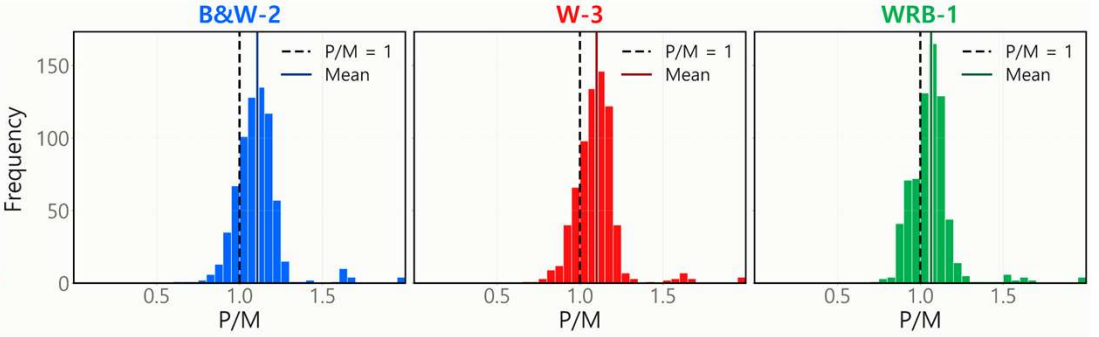
→ Effect of axial power distribution is minor, or effectively compensated by the F-factor correction

Result & Discussion

❑ Performance assessment: within the i-SMR design range

- Reduced scatter, but mean P/M increased by approximately **8.5%** for all correlations
- Existing correlations tend to **overpredict CHF within the i-SMR design range (non-conservative)**





All Data

	B&W-2	W-3	WRB-1
mean P/M	1.020	1.082	1.001
σ(P/M)	0.193	0.290	0.188
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1,200≤G≤1,650 kg/m^2·s & L =2.0~2.4 m

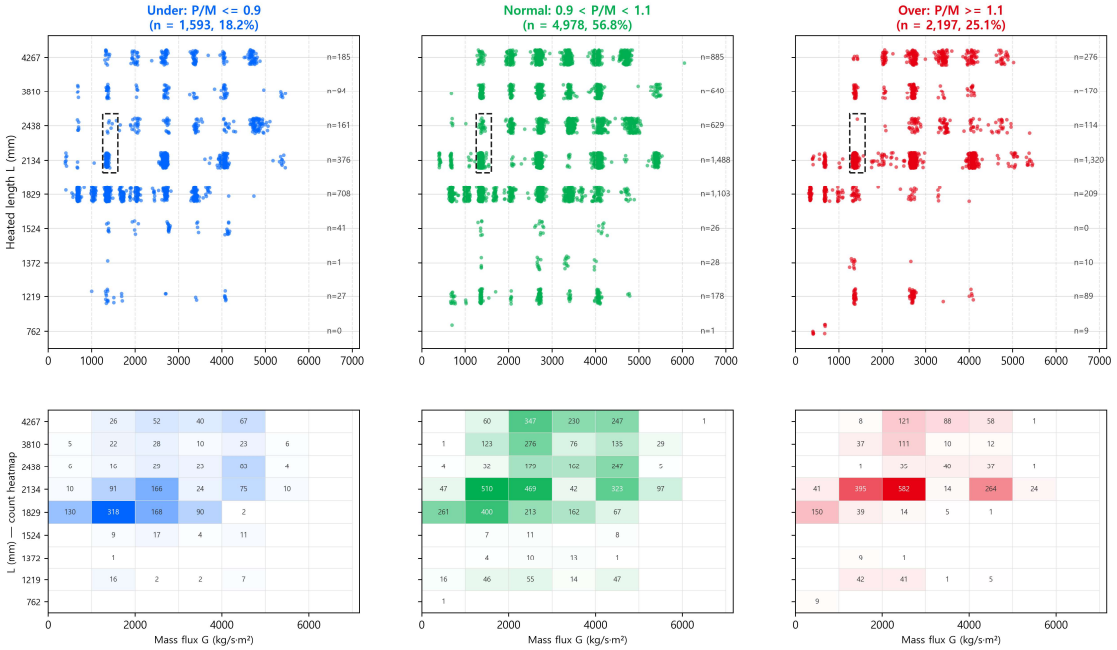
	B&W-2	W-3	WRB-1
mean P/M	1.107	1.101	1.065
σ(P/M)	0.169	0.164	0.158
RMSE	183 kW/m^2	175 kW/m^2	142 kW/m^2
MAPE	13.0%	12.6%	10.4%
R^2	0.428	0.480	0.657
$DNBR_{95/95}$	1.277	1.276	1.259

Result & Discussion

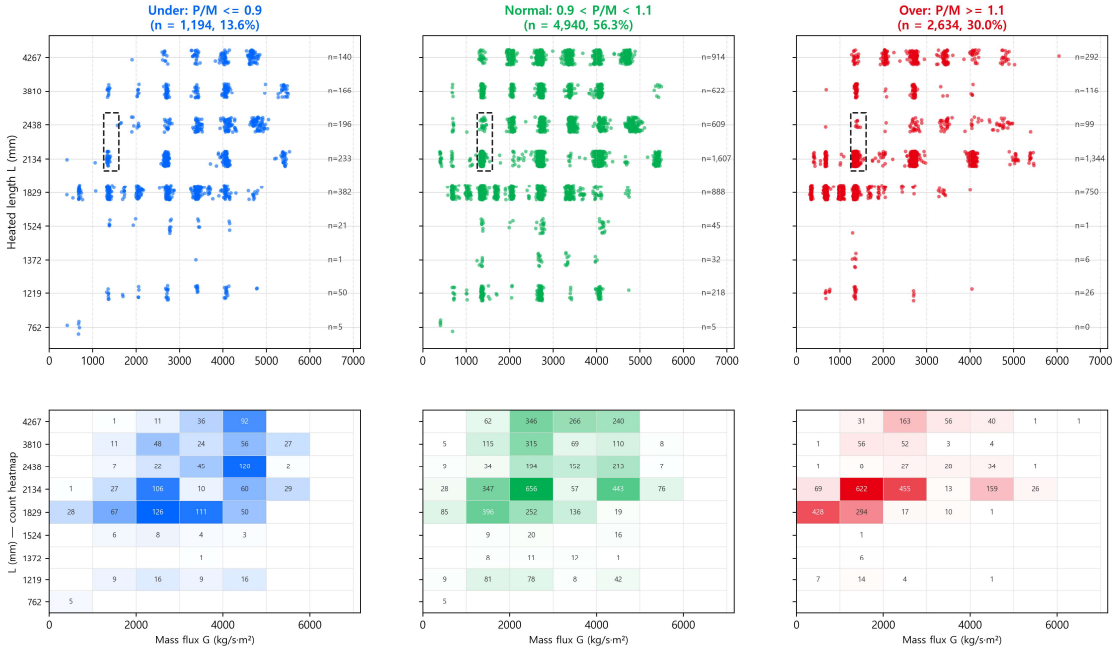
❑ Identify parameter dependence: G-L Plane

- Mean P/M: 8.5% overprediction → **possibly driven by a few large outliers?** → **No**
- Count comparison (P/M ≥ 1.1 vs. P/M ≤ 0.9)
  → **Overprediction is systematic, not outlier-driven**

B&W-2: n(P/M≥1.1) = 347 vs. n(P/M≤0.9) = 24



W-3: n(P/M≥1.1) = 338 vs. n(P/M≤0.9) = 26

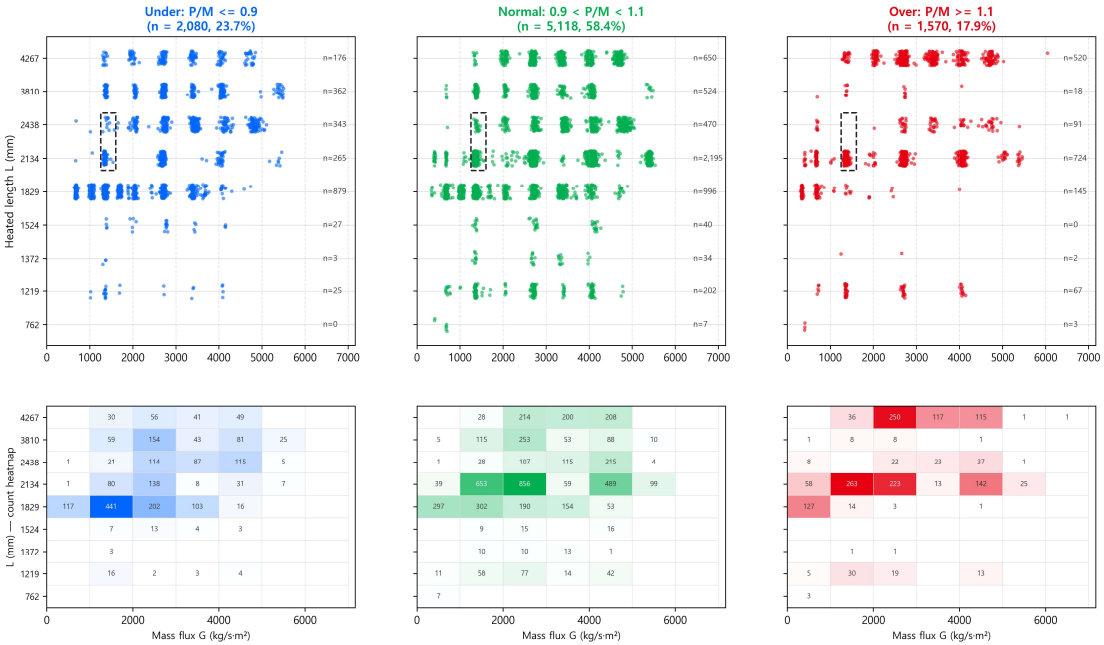


Result & Discussion

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WRB-1: (P/M≥1.1) = 214 vs. n(P/M≤0.9) = 49



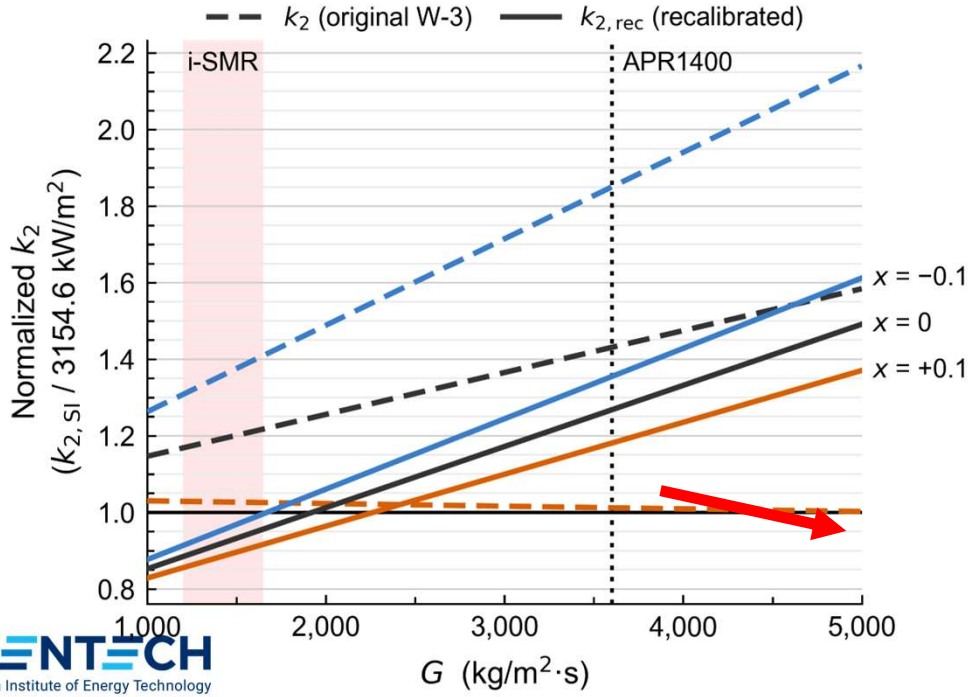
	B&W-2	W-3	WRB-1
Full (0.9<P/M<1.1)	4,978	4,940	5,118
Full (P/M≤0.9)	1,593	1,194	2,080
Full (P/M≥1.1)	2,197	2,634	1,570
i-SMR (0.9<P/M<1.1)	331	338	439
i-SMR (P/M≤0.9)	24	26	49
i-SMR (P/M≥1.1)	347	338	214

Non-conservative or 2.2 times

4.4~14.5 times

W-3 Correlation Recalibrated

- Applicability of correlations developed for large PWRs to i-SMR? → Limited (→ modification required)
- Overprediction at G ≤ 1,650 kg/m²·s is systematic → **G effect may not be adequately represented**
- In particular, at x ≥ 0.094, **CHF is adjusted downward** with increasing G: **presumed cause of the overprediction** → **Unphysical behavior: CHF in PWRs is mainly DNB-type (low quality)**
- → **Liquid supply enhancement to the near-wall region by turbulent mixing (CHF ↑) dominates over wall film stripping and droplet entrainment (CHF ↓)**
- → **CHF expected to increase with increasing G** → **Recalibration performed**



W−3 correlation

$$q''_{W-3,Uni} = k_1(P,x) \times k_2(x,G) \times k_3(x) \times k_4(D_e) \times k_5(\Delta h)$$

$$k_1 = (2.022 - 0.06238P) + (0.1722 - 0.01427P)e^{(18.177-0.5987P)x},$$
$$k_2 = 2.326 \times (0.1484 - 1.596x + 0.1729x|x|)G + 3271,$$
$$k_3 = 1.157 - 0.869x,$$
$$k_4 = 0.2664 + 0.8357e^{-124.1D_e},$$
$$k_5 = 0.8258 + 0.0003413(h_f - h_{in}).$$

$$k_2 = 2.326 \times (0.1484 - 1.596x + 0.1729x|x|)G + 3271$$

↓ EPRI uniform axial power data (n = 6,202)

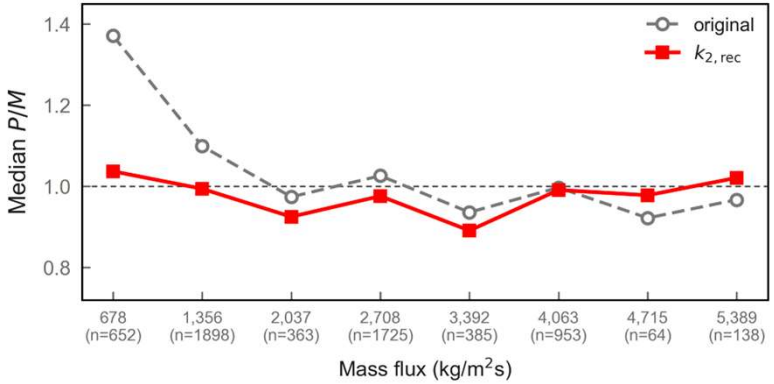
$$k_{2,rec} = 2.326 \times (0.2167 - 0.3828x + 0.5526x|x|)G + 2184.9$$

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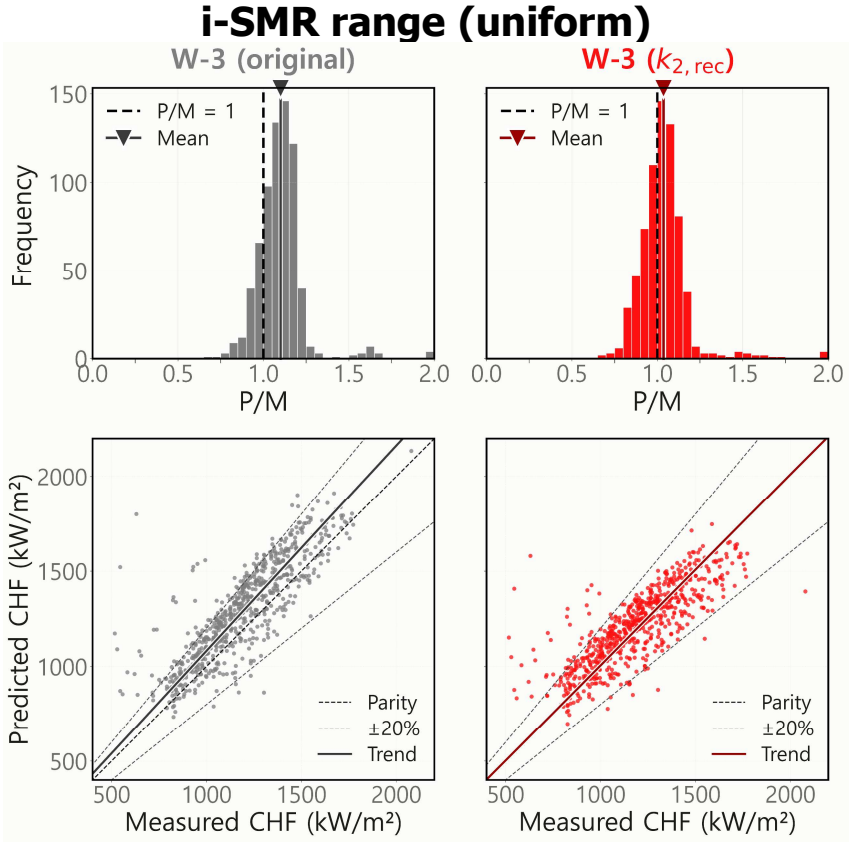
W-3 Correlation Recalibrated

- CHF increase with G properly represented → improved accuracy in the i-SMR region
  - Mean P/M decreased from 1.101 → **1.036**
  - Non-conservative fraction (P/M>1) reduced from 80.2% →**61.4%**

		Original W-3	Recalibrated W-3
Full (uniform)	**mean P/M**	1.113	1.031
	σ(P/M)	0.329	0.275
	Non-conservative fraction (P/M>1)	59.9%	46.5%
i-SMR (uniform)	**mean P/M**	1.101	1.036
	σ(P/M)	0.164	0.159
	Non-conservative fraction (P/M>1)	80.2%	61.4%



	Original W-3	Recalibrated W-3
i-SMR (0.9<P/M<1.1)	337	463
i-SMR (P/M≤0.9)	26	86
i-SMR (P/M≥1.1)	338	152
[P/M≥1.1] [P/M≤0.9]	**x 13.0**	**x 1.8**



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Conclusion

- **Large-PWR-based CHF correlations: applicability to i-SMR conditions not established**

  → Assess **prediction accuracy** of existing CHF correlations in the i-SMR region

  - Mean P/M within 1.00~1.08 for all correlations: measured CHF level generally reproduced
  - Full data: prediction accuracy WRB-1 > B&W-2 > W-3 (mean P/M 1.001 / 1.020 / 1.082)
  - i-SMR region: **overprediction** (P/M **+8.5%**) for all correlations (mean P/M: 1.065 / 1.107 / 1.101)

- **Identify regions and key parameters where prediction accuracy or conservatism may degrade under i-SMR conditions**

  → Examine the **effects** of Axial power distribution (APD), G, and L on prediction accuracy and conservatism with focus on the i-SMR region

  - Axial power distribution: prediction behavior insensitive to non-uniform APD
    → **shape factor (F-factor) correction effective within tested profiles**
  - **overprediction at i-SMR range ($G \leq 1{,}650$ kg/m²·s) & ($L = 2.0$~2.4 m)**

- **Recalibrating of W-3 mass flux term (k_2)**

  - Unphysical quality-dependent effect corrected
    → CHF variation with increasing G reflected, improving performance in the i-SMR region
  - i-SMR range (uniform): mean P/M 1.101 → 1.036; Non-conservative fraction 80.2% → 61.4%

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Thank you

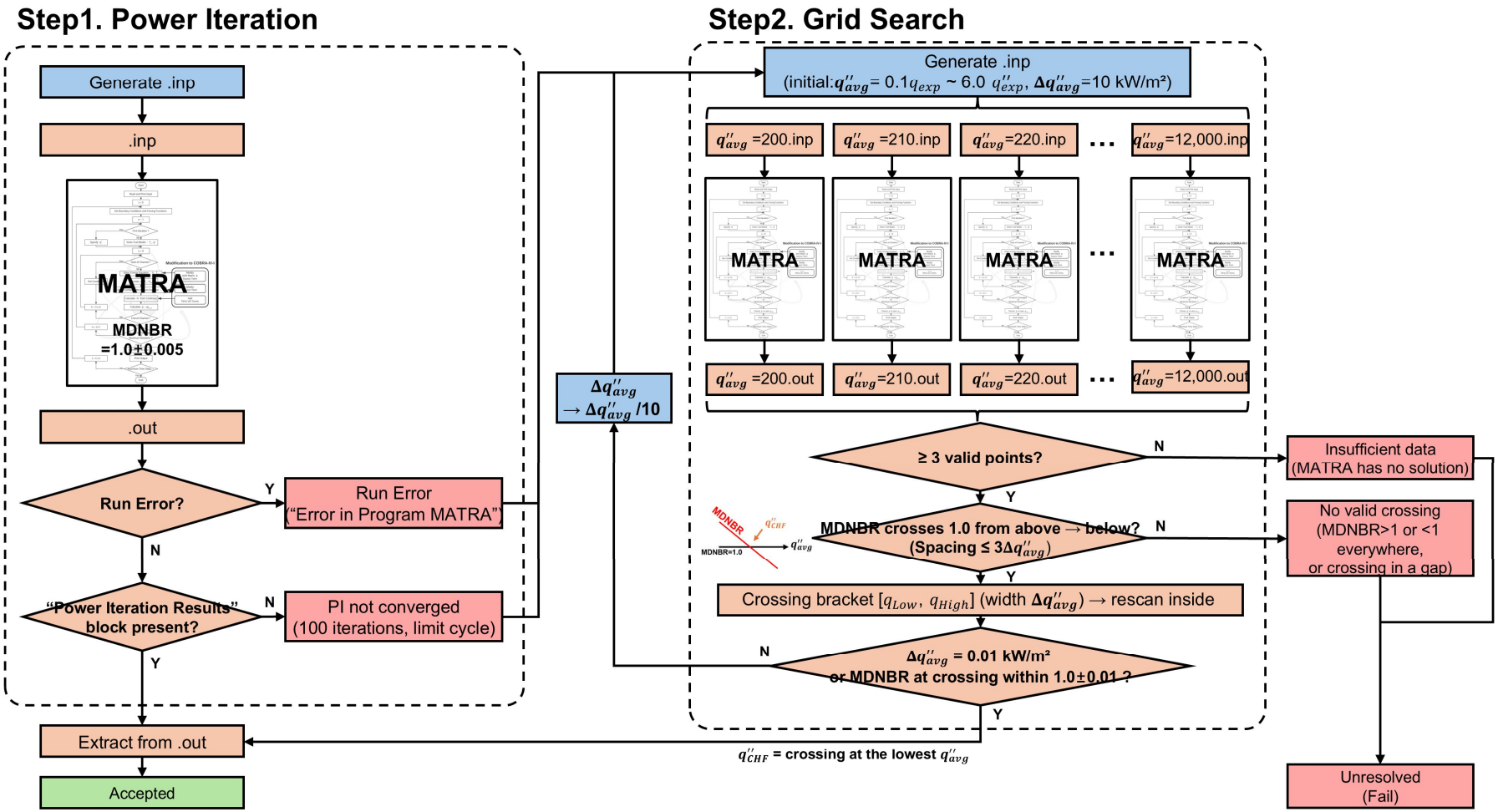
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KNS 26 Autumn meeting, Gyeongju, October 30, 2026

Appendix A

❑ Data Collection and Processing Procedure Using MATRA and EPRI CHF Database



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