



# Sensitivity Study of 1D/2D Power Synthesis Method for PWR Flexible Operation



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# Presentation Outline

## 01 Introduction

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- OPR-1000 Flexible Operation
- 3DPCM System Limitations
- 1D+2D PCM Objectives

## 02 Methods & Algorithm

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- PCM Formulation & Metrics
- Reference Operation Scenario
- Fixed PCF<sub>0</sub> & First-order M1

## 03 Results

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- Tin & Rod Position Studies
- Error Metric Validation (19 cases)

## 04 Discussion

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- 4-Parameter Driver Ranking
- Localised vs Distributed Error

## 05 Future Work & Conclusion

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- Higher-order PCF Exploration
- Deployment & Monitoring

# Background & Motivation

South Korea's energy transition imposes new demands on PWR operation

## Renewable Energy & Grid Flexibility

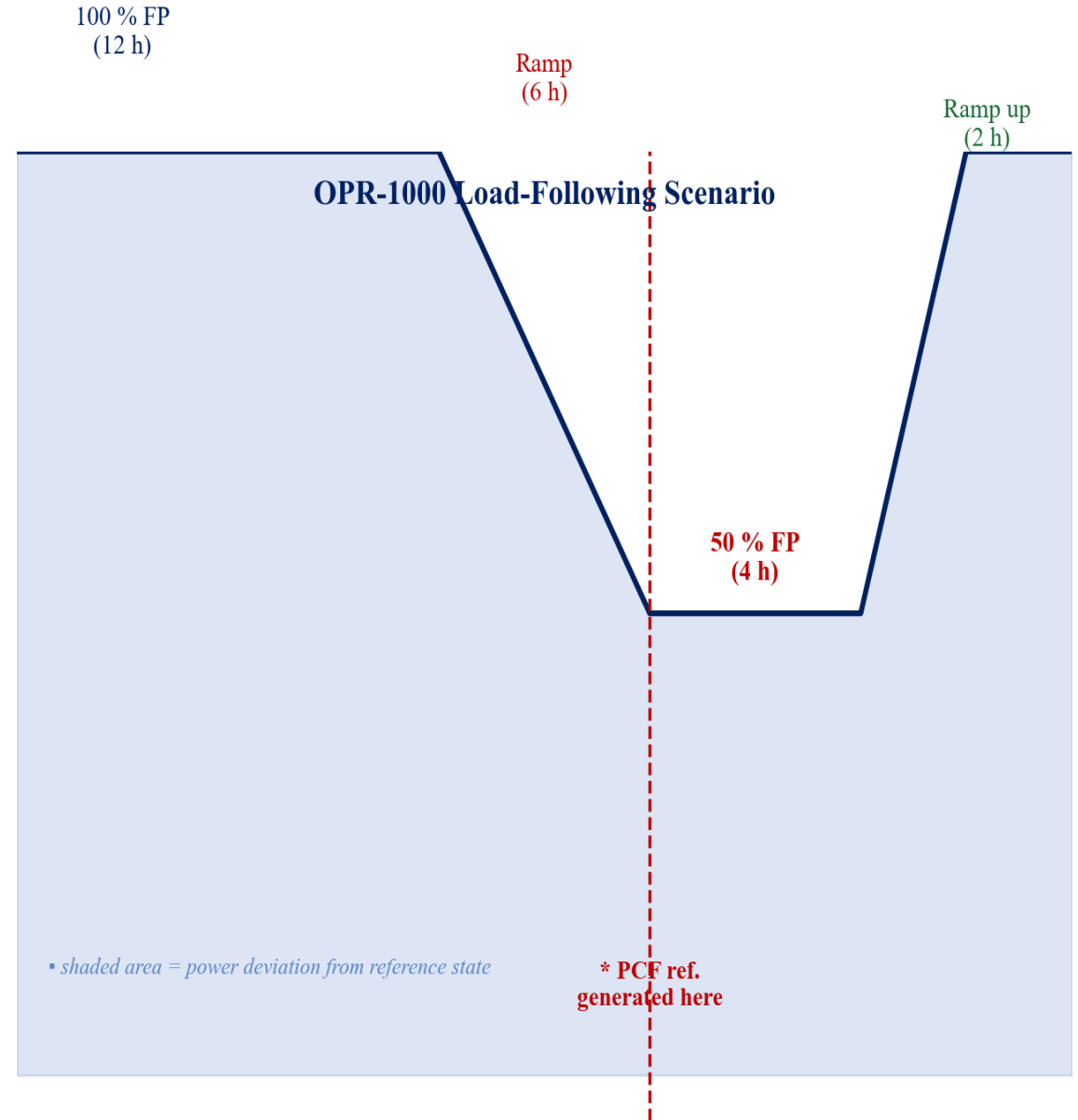
South Korea's rapid integration of solar and wind forces OPR-1000 PWRs away from baseload toward load-following — frequent power ramps and control rod movements to balance grid intermittency.

## Core Monitoring Challenge

Conventional systems (CECOR, OASIS/3DPCM) use pre-calculated PCF libraries valid only at design-basis conditions. Off-nominal operation introduces unquantified errors in 3D power reconstruction — a structural limitation that deepens under flexible operation.

## This Work

The 1D+2D PCM method resolves OASIS's structural flaws — decoupled axial/radial steps remove cross-assembly coupling and PSF dependency, making it inherently suited to flexible operation. Six OAT sensitivity studies quantify its robustness; a first-order  $\beta$ -correction model (M1) is validated:  $E_{3D} \leq 5\%$  and  $ERMS \leq 2\%$  thresholds.



# Problem Statement

Limitations of the existing 3D Power Connection Method (3DPCM)

## Definition – Power Sharing Factor (PSF)

The ratio of the calculated nodal power at node  $i$  to the total calculated power of detector  $d_k$  spanning. This is used by 3DPCM to apportion the measured detector integral among the axial nodes hence intra-detector flux shape matches the calculated distribution

$$PSF_i = \frac{P_i^c V_i}{\sum_{j \in d_k} P_j^c V_j} \quad \rightarrow \quad P_i^m = \frac{PSF_i \times P_{d_k}^m}{V_i} = \frac{P_{d_k}^m}{P_i^c} P_i^c$$

### PSF Inaccuracy (Issue 1)

1. PSF assumes intra-detector flux shape matches the calculated distribution.
2. Under flexible operation flux deviates, making the apportionment incorrect.

### 3D Cross-Assembly Coupling (Issue 2)

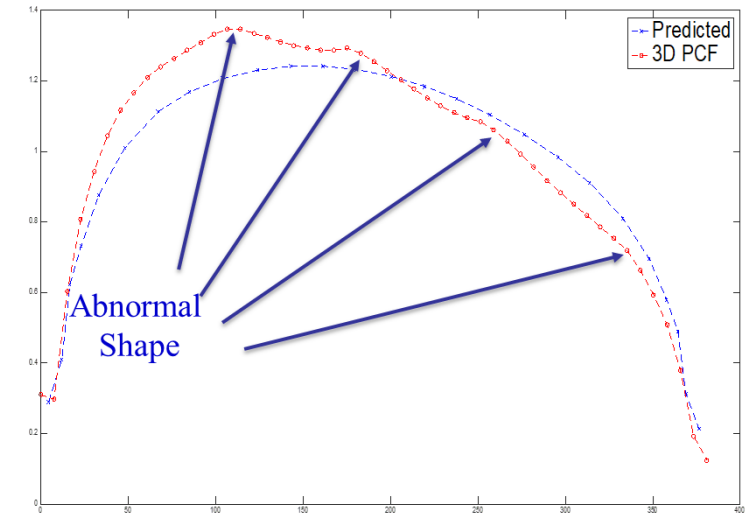
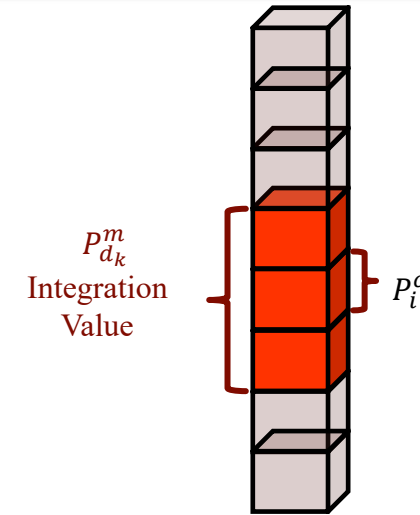
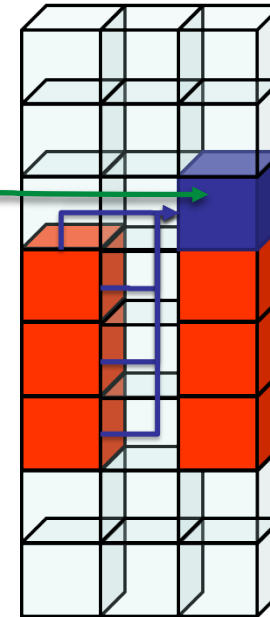
1. 3DPCM couples adjacent assemblies in 3D.
2. If predicted & measured power distributions are different, The node power are not consistent with the own assembly's axial power distribution.

Both issues worsen under flexible operation — frequent power ramps and rod movements push the core far from the design-basis assumptions of the CECOR/OASIS libraries.

### Solution

1D+2D PCM solves that because it:

1. Decouples axial and radial steps,
2. Eliminates cross-assembly coupling,
3. Suitable for parallel real-time computation.



Source: J. I. Yoon, H. S. Kim, H. S. Woo, and H. C. Lee, "Improvement of 3D Power Connection Method in the Online Core Monitoring System OASIS," in Proc. Korean Nuclear Society Autumn Meeting, Jeju, Korea, Oct. 2017.

# 1D+2D PCM — Mathematical Formulation

Step 1: axial reconstruction per assembly | Step 2: radial reconstruction for uninstrumented assemblies

## Step 1 - Axial Reconstruction (per assembly)

$$2 P_i^m \cdot PCF_i = P_{i-1}^m + P_{i+1}^m$$

$$2 PCF_i \cdot P_i^m = P_{i-1}^m + P_{i+1}^m + \alpha_{d_k} \cdot P_i^c$$

$$\sum_{j \in d_k} P_j^m = P_{d_k}^m$$

Where

$PCF_i$ : pre-generated power connection factor at node  $i$  (from calculated distribution).

$P_i^m$ : measured power at node  $i$  (unknown)

$P_i^c$ : calculated power at the node  $i$  (known)

$\alpha_{d_k}$ : intra-detector power redistribution factor for the  $k$ -th detector (unknown)

$d_k$ :  $k$ -th detector

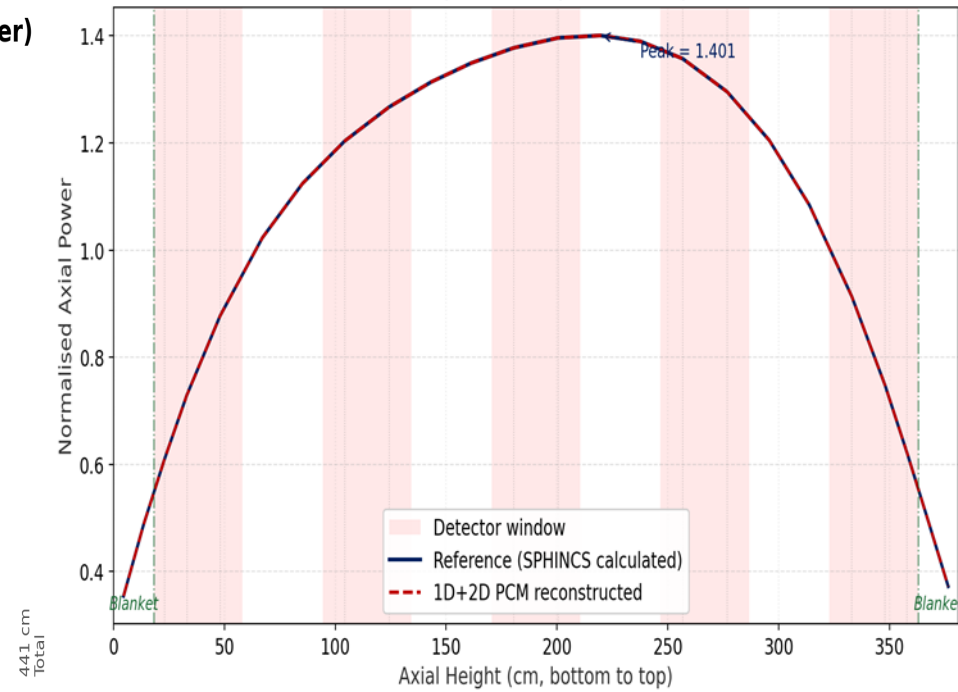
$N_{i,r}$ : the number of radially adjacent node

### YGN3 (OPR1000) - Axial Node Structure SPHINCS Cycle-1 BOC Calculation (100% Power)

Axial Node Structure  
24 nodes | Active = 381 cm | Reflectors = 2 x 30 cm



### Reference Flexible Operation State — Axial Power Shape OPR-1000 | 50 % FP | Rods out | BOC



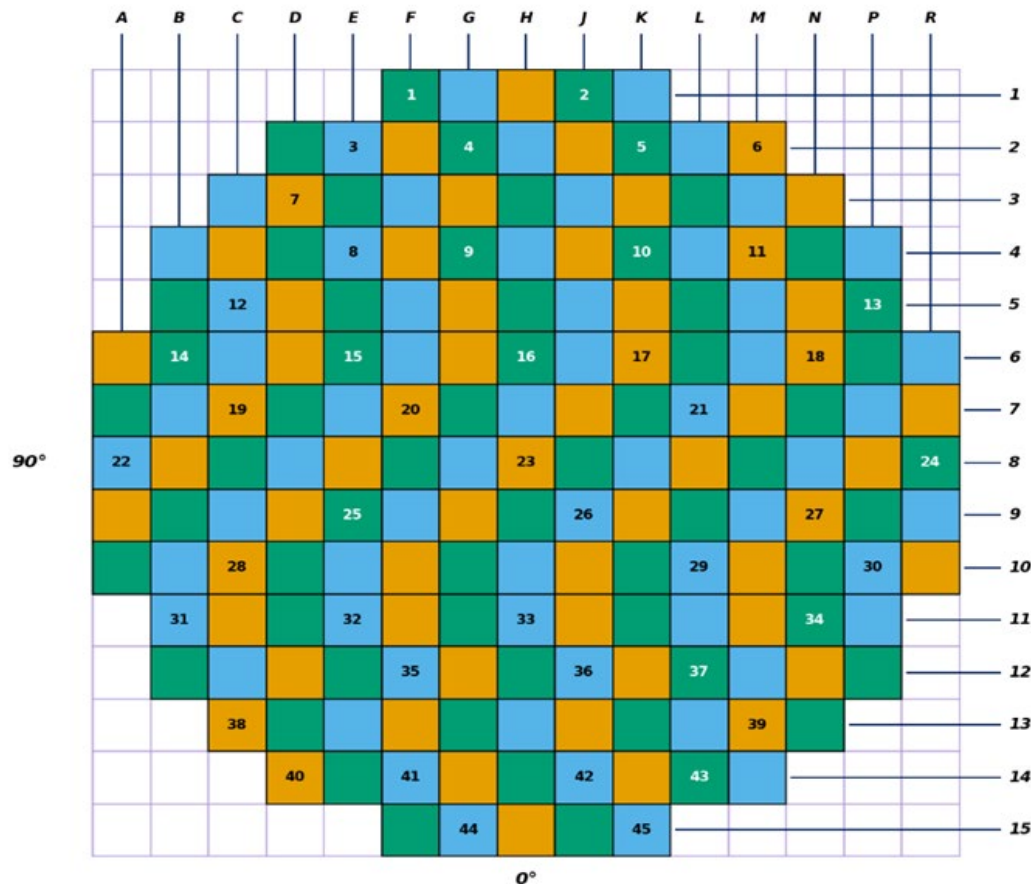
# 1D+2D PCM — Mathematical Formulation

Step 1: axial reconstruction per assembly | Step 2: radial reconstruction for uninstrumented assemblies

## Step 2 - Radial Reconstruction (per assembly)

$$PCF_i = \frac{\sum_{r=1}^{N_{i,r}} P_{i,r}^c}{P_i^c \cdot N_{i,r}}$$

$$PCF_i \cdot P_i^u \cdot N_{i,r} - \sum_{r=1}^{N_{i,r}} P_{i,r}^u = \sum_{r=1}^{N_{i,r}} P_{i,r}^m$$



Where

$PCF_i$ : pre-generated power connection factor at node i (from calculated distribution).

$N_{i,r}$ : the number of radially adjacent node

$P_i^u$ : unknown power of node i

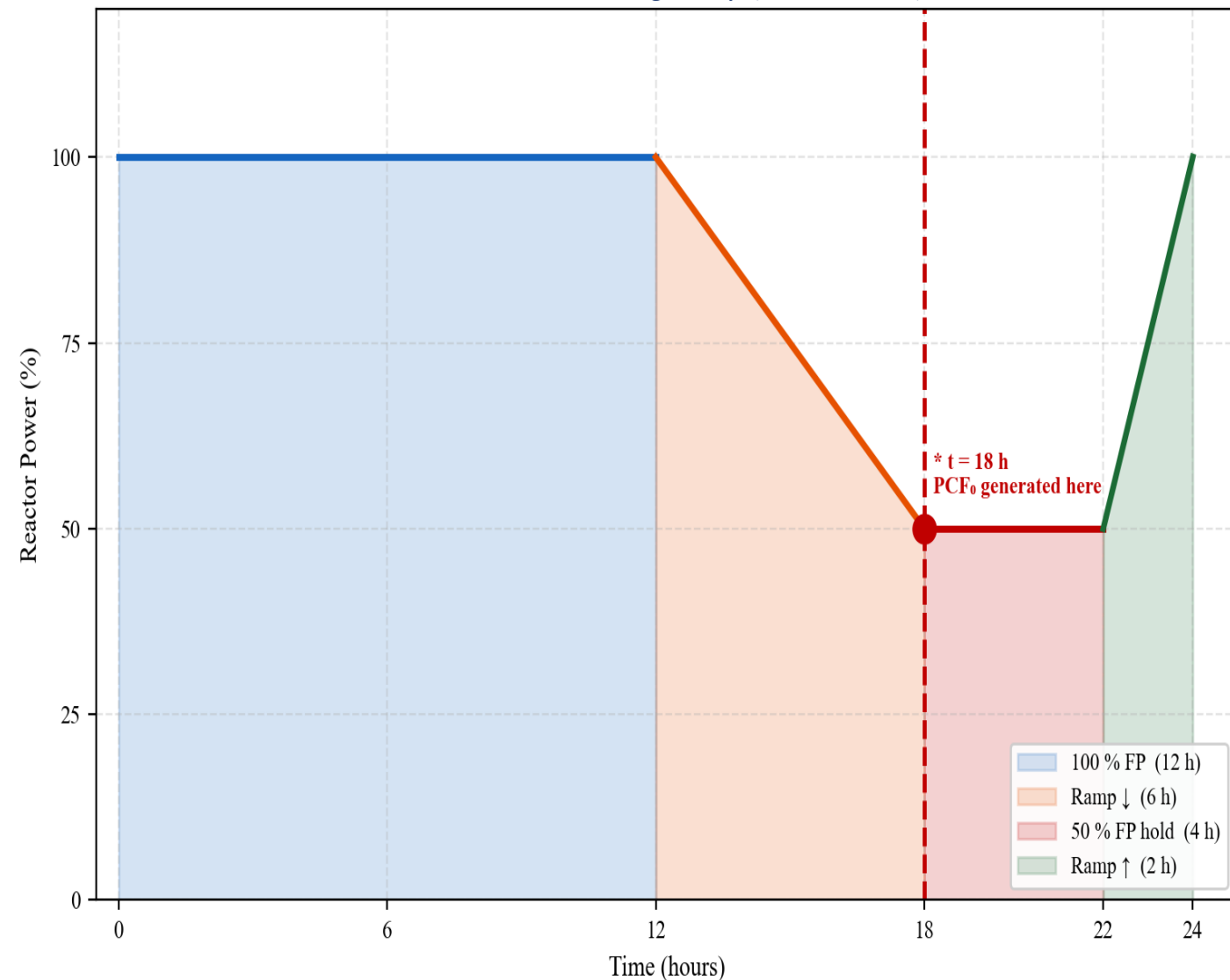
$P_{i,r}^u$ : unknown power of radially adjacent node

$P_{i,r}^m$ : measured power of neighboring instrumented assemblies

# Reference Flexible Operation & PCF Generation

PCF set generated at end of 50 % hold — any deviation from this state introduces synthesis error

Reference Load-Following History (OPR-1000, BOC)



Reference State Parameters

Parameter	Reference Value
Time point	t = 18 h
Burnup	25.70 MWD/MTU
Reactor power	50 % FP
Boron concentration	Nominal ( $\Delta b = 0$ ppm)
Inlet temperature	Nominal ( $\Delta T = 0$ °C)
Control rod position	100 % (all rods out)
PCF type	Axial PCF + Radial PCF

*Any deviation of actual plant state from this reference introduces error in the synthesised 3D power distribution.*

# Acceptance Thresholds

Based on NRC Reg. Guide 1.126 / EPRI NP-2245 / IAEA TECDOC-1183

Metric	Threshold	Physical meaning	Basis
E3D — Max Abs Error (%)	$\leq 5.0$	No single node exceeds 5 % error	NRC Reg. Guide 1.126
ERMS — RMS Error (%)	$\leq 2.0$	Root-mean-square error over all 4,248 nodes	EPRI NP-2245
E2D — 2D Max Abs (%)	$\leq 5.0$	Worst radial assembly error	EPRI NP-2245
MAE (%)	$\leq 1.5$	Mean absolute error across core	IAEA TECDOC-1183
Mean Bias  (%)	$\leq 0.5$	Systematic offset — must be near zero	NRC / EPRI
95/95 Tolerance (%)	$\leq 5.0$	95 % of nodes within limit at 95 % conf.	NRC statistical criterion

*Primary criteria used in this study:  $E3D \leq 5\%$  and  $ERMS \leq 2\%$ . These are the most stringent and widely cited limits for online 3D power reconstruction. All other metrics serve as secondary diagnostics.*

# PCM Method & Implementation

1D+2D Predicted Core Monitor flux reconstruction

## HOW 1D+2D PCM WORKS

### STEP 1 — 1D Axial Reconstruction

Axial Fourier fitting maps 5 detector signals per assembly → 24-node axial power profile. PCF\_1D(z) captures axial shape changes.

### STEP 2 — 2D Radial Reconstruction

Radial PCM distributes measured signals across all 177 assemblies in the horizontal plane. PCF\_2D(x,y) captures radial flux shape.

### STEP 3 — 3D Power Synthesis

$$P_3D(x,y,z) = PCF\_1D(z) \times PCF\_2D(x,y) \times P\_measured(detector)$$
  
→ ERMS, E2D, E3D vs NRC/EPRI thresholds.

### KEY QUESTION

How robust is 1D+2D PCM reconstruction when operating conditions deviate from the PCF reference (training) state?

## OAT SENSITIVITY PARAMETERS

**$\Delta P$**  Power level 11 levels  
30 – 60 % FP

**$\Delta b$**  Boron concentration 8 levels  
±25 / 50 / 75 / 100 %

**$\Delta T$**  Tin inlet temp. 10 levels  
±2 / 4 / 6 / 8 / 10 %

**$\Delta R$**  Rod withdrawal 10 levels  
91 – 99 % withdrawn

*One-At-a-Time (OAT) — ref: 50 % FP, rods out*

## SIMULATION SETUP

**Code:** SPHINCS

**Core:** OPR-1000 | YGN3 Cycle-1

**State:** BOC | Bu = 25.70 MWD/MTU

**Nodes:** 177 asm. × 24 axial = 4,248

**Ref.:** 50 % FP, rods out

## ACCEPTANCE THRESHOLDS

**ERMS** ≤ 2 %  
NRC Reg. Guide 1.126

**E2D** —  
Radial sum error

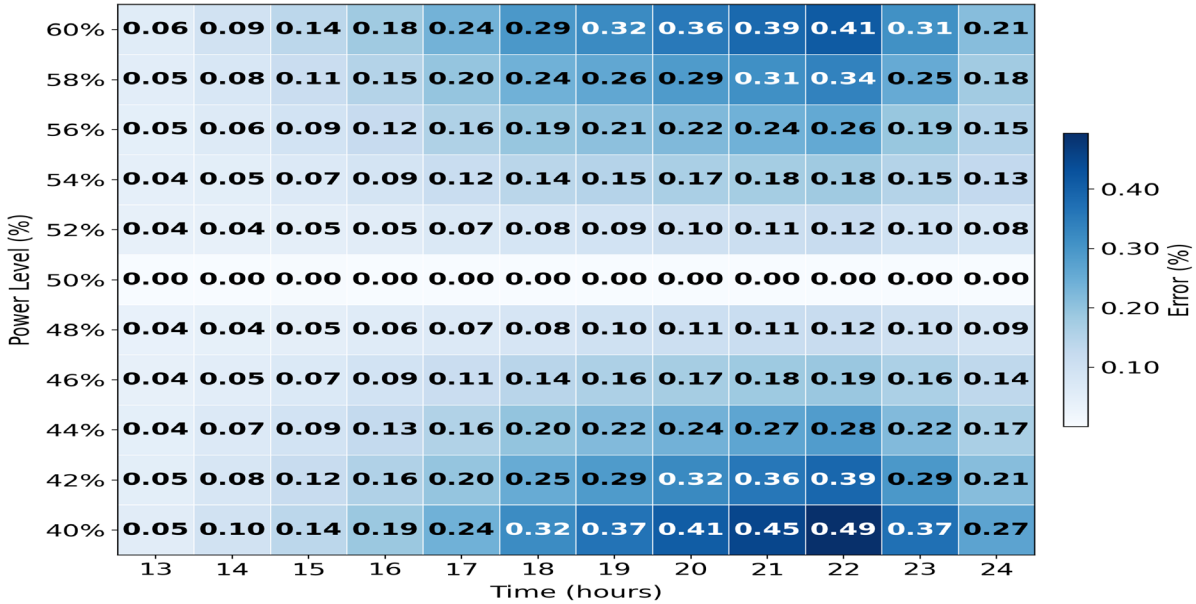
**E3D** ≤ 5 %  
EPRI NP-2245 / IAEA

# Part A — Fixed $PCF_0$ Baseline & OAT Diagnosis

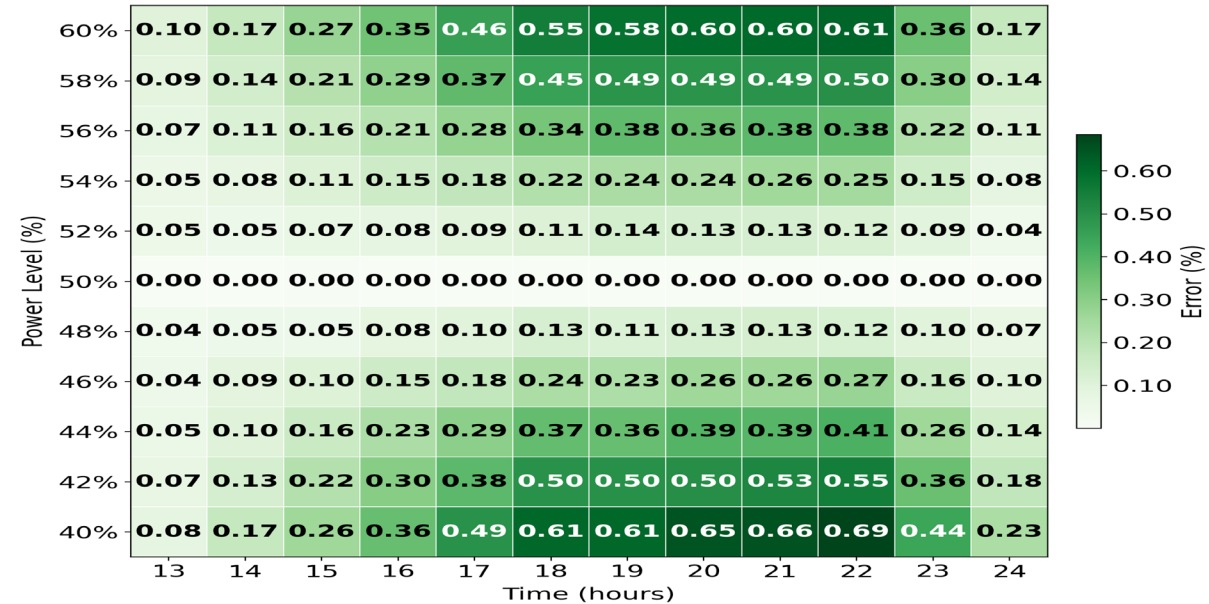
*Studies use frozen  $PCF_0$  only | establish where the baseline is robust and where it fails*

# Synthesis Power Distribution At Various Power Level

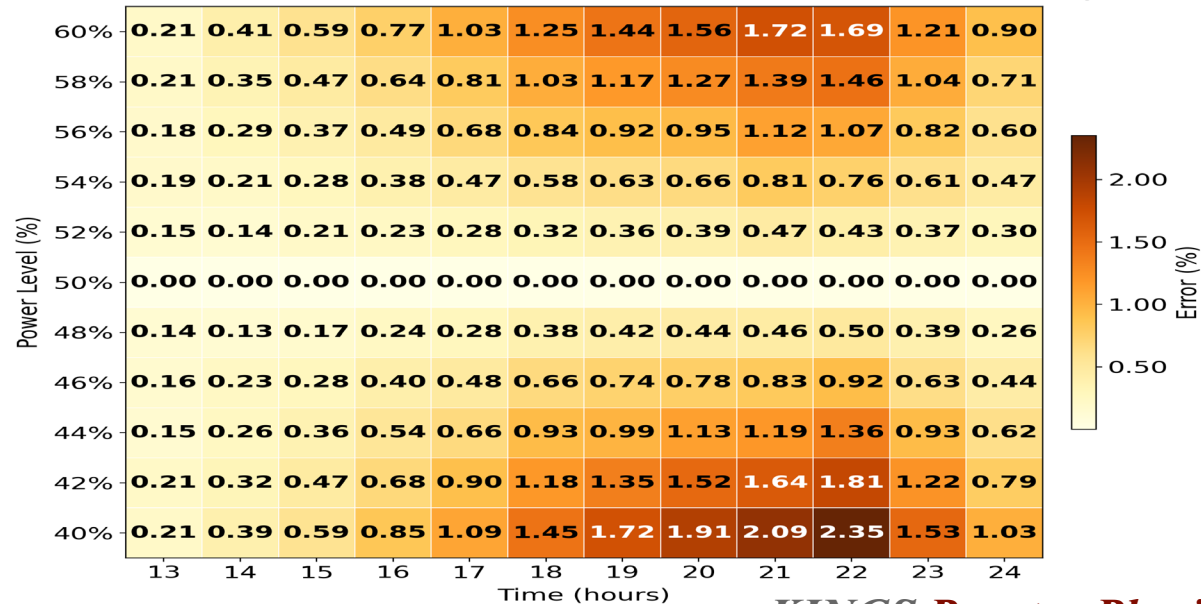
RMS Error — Time vs Power Level (vs Measured) [Power Level Sensitivity]



2D Max Error — Time vs Power Level (vs Measured) [Power Level Sensitivity]

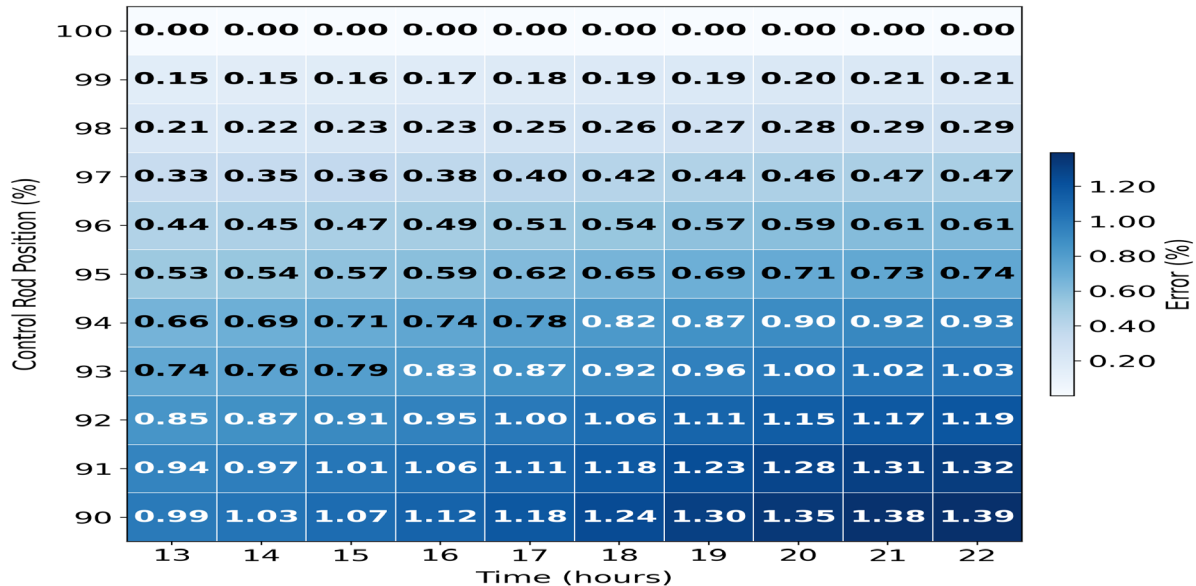


3D Max Error — Time vs Power Level (vs Measured) [Power Level Sensitivity]

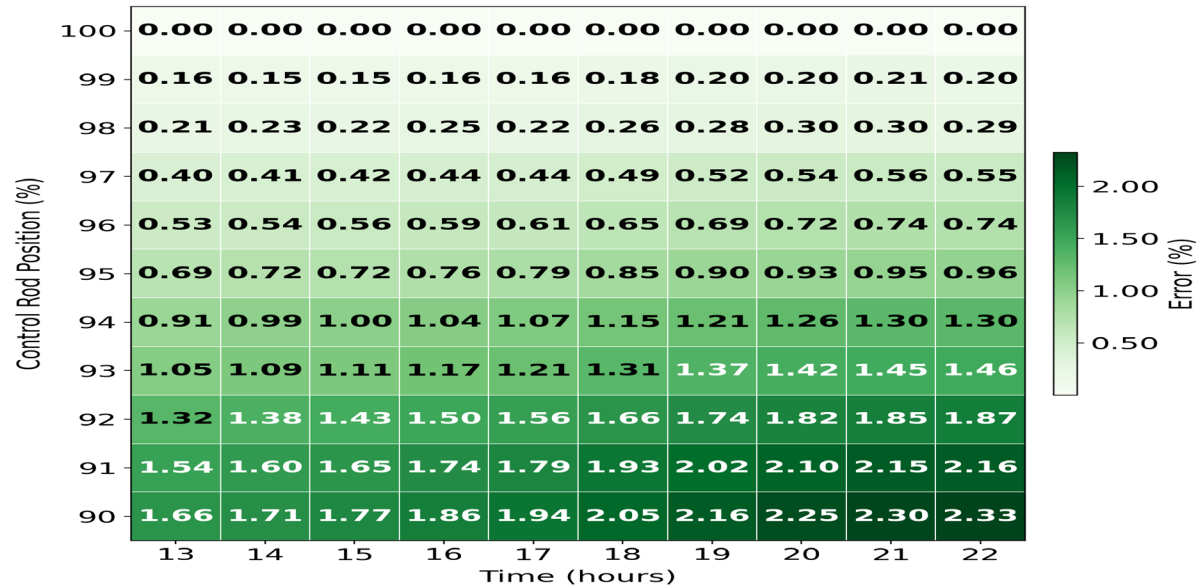


# Synthesis Power Distribution At Various Rod Positions

RMS Error — Time vs Rod Position (vs Measured) [50% Power]



2D Max Error — Time vs Rod Position (vs Measured) [50% Power]

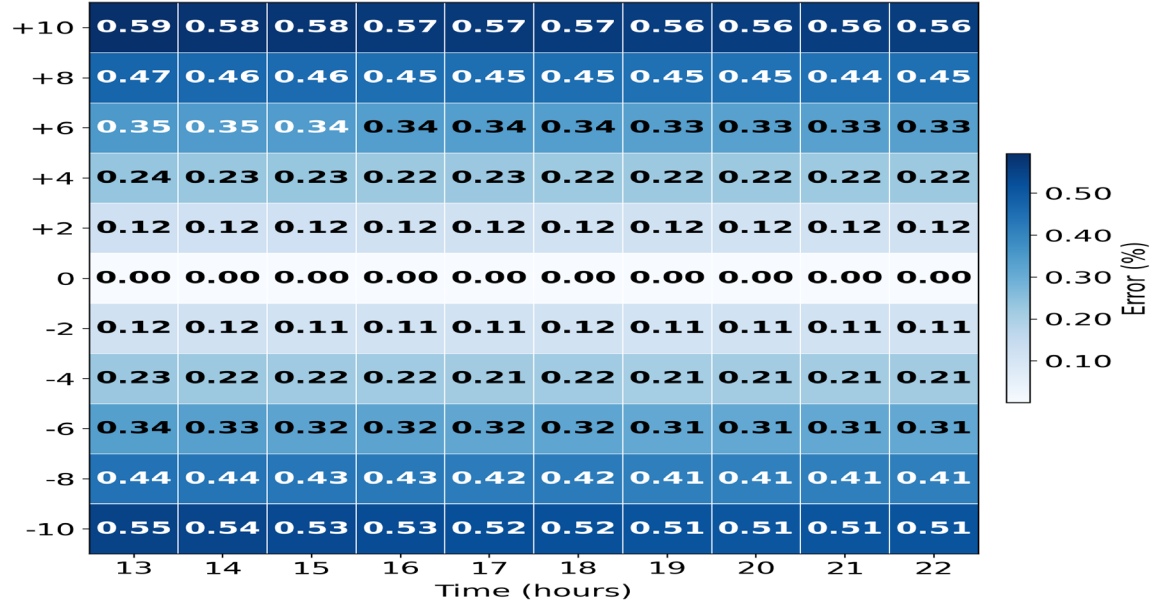


3D Max Error — Time vs Rod Position (vs Measured) [50% Power]

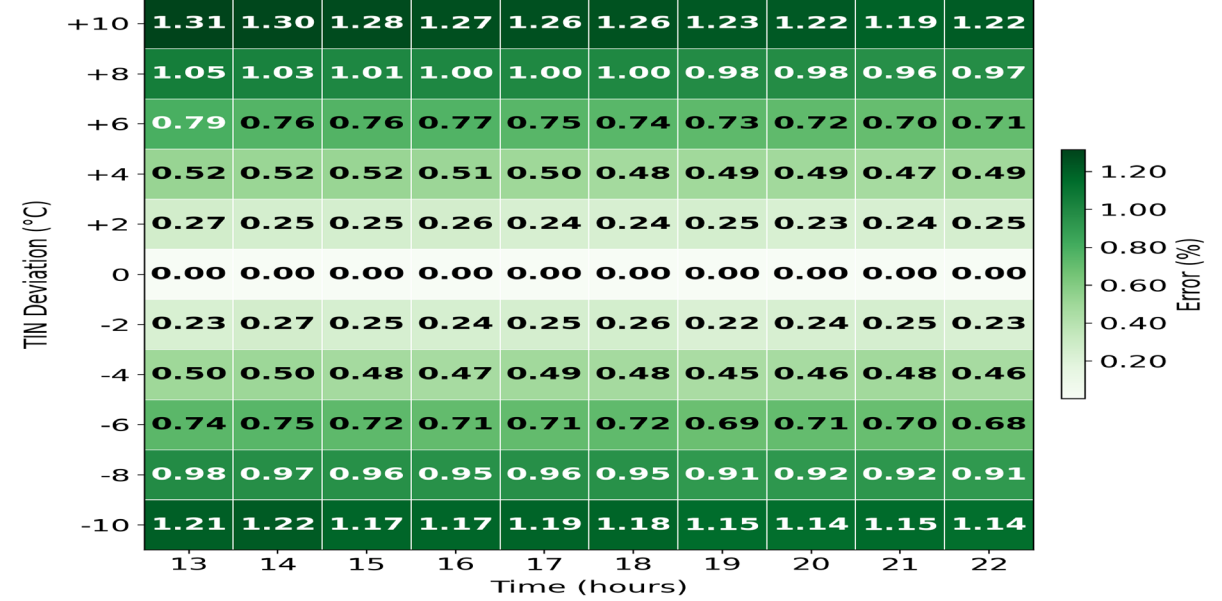


# Inlet Temperature Sensitivity Study

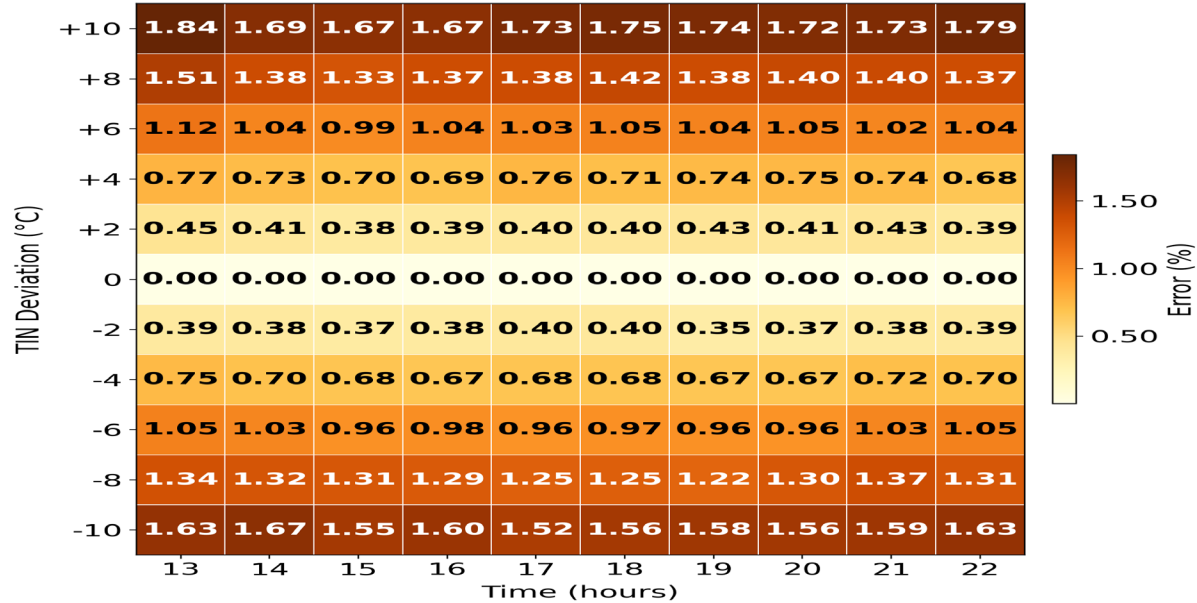
RMS Error — Time vs TIN Deviation (vs Measured) [50% Power]



2D Max Error — Time vs TIN Deviation (vs Measured) [50% Power]

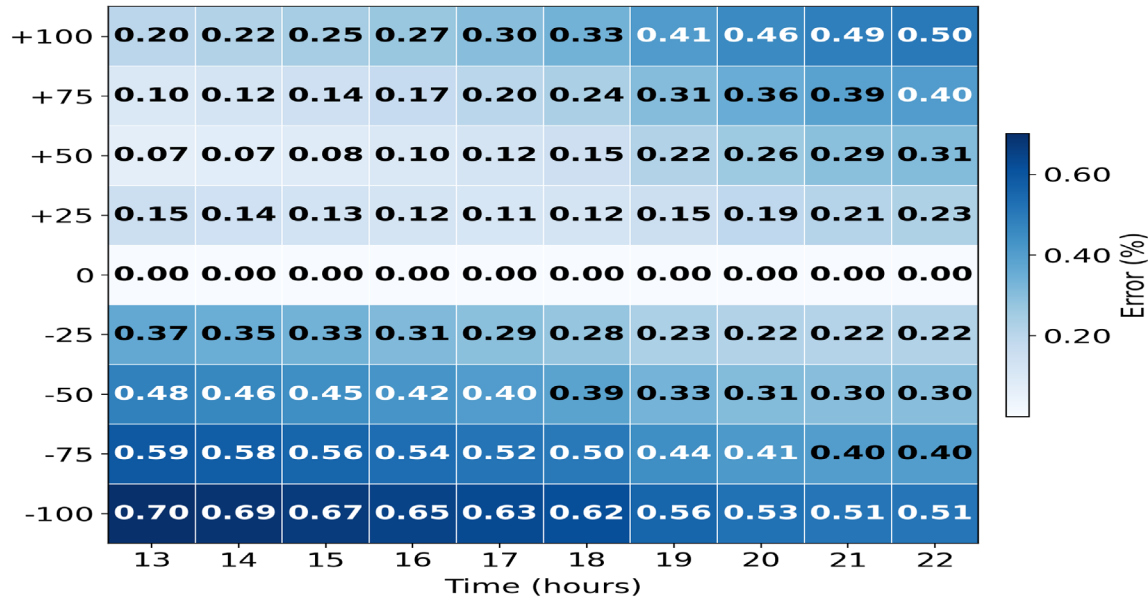


3D Max Error — Time vs TIN Deviation (vs Measured) [50% Power]

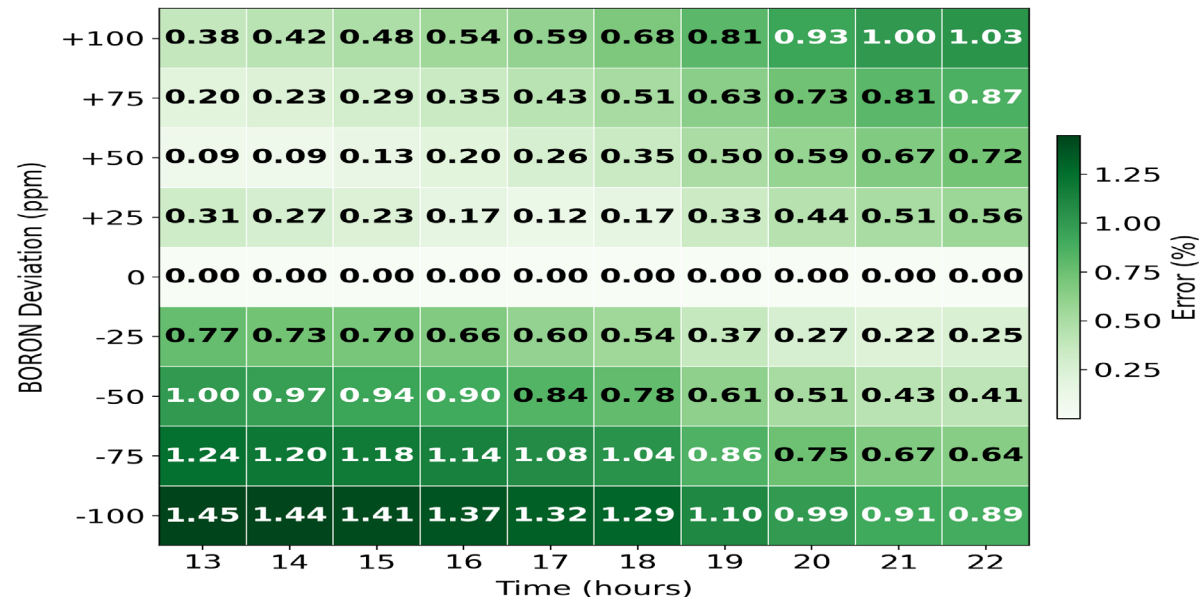


# Boron Sensitivity Study

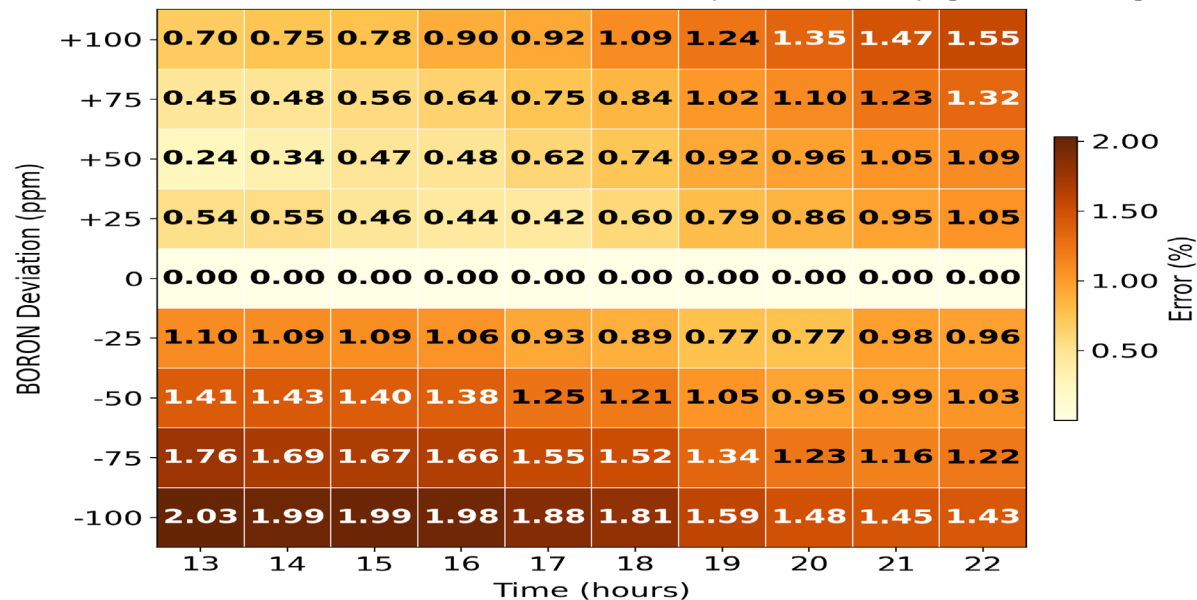
RMS Error — Time vs BORON Deviation (vs Measured) [50% Power]



2D Max Error — Time vs BORON Deviation (vs Measured) [50% Power]



3D Max Error — Time vs BORON Deviation (vs Measured) [50% Power]



# All OAT Sensitivity Studies

Power Level | Boron | Tin Inlet Temperature | Rod Position

## Study A — Power Level Mismatch

**Verdict: PASS** 40–60 % FP cases pass; Max E3D = 1.09 %.

**Error trend** Symmetric about 50 % FP; best accuracy at the reference point.

**Physics** Flux scales nearly uniformly, so PCF-shape change stays modest.

**Implication** Fixed PCF<sub>0</sub> is robust from 40–60 % FP; no power-specific update.

## Study B — Boron Concentration Mismatch

**Verdict: PASS** All  $\Delta b$  cases pass; Max ERMS = 1.1 % (< 2 %).

**Error trend** ERMS rises with  $|\Delta b|$  then saturates; 40 % FP is slightly worse.

**Physics** Boron perturbs the spectrum uniformly, keeping PCF changes smooth.

**Implication** Fixed PCF<sub>0</sub> tolerates  $\pm 100$  % boron;  $\Delta b$  is a tertiary driver.

## Study C — Tin Inlet Temperature Mismatch

**Verdict: PASS** All  $\Delta T$  cases pass; Max ERMS = 0.85 %, 3D Max  $\leq 3.70$  %.

**Error trend** Matches the boron pattern: symmetric, monotonic, no threshold.

**Physics** Feedback shifts stay mild and global, so flux-shape change is limited.

**Implication** Tin is the weakest driver; Fixed PCF<sub>0</sub> is robust across  $\pm 10$  %.

## Study D — Rod Position Mismatch [CRITICAL]

**Verdict: CONDITIONAL FAIL** 95–100 % pass; 90–94 % fail; Peak E3D = 17.66 %.

**Localised error** High E3D,max with low ERMS indicates a localized tip error.

**Physics** Partial insertion creates local depression and tilt the reference PCF misses;

**Implication** Rod withdrawal is the critical OAT failure;  $\beta_4 \cdot \Delta R$  in M1 is essential.

# Part B — First-order M1 Validation & Recommendation

*Introduced after the Fixed PCF<sub>0</sub> OAT diagnosis | Study F compares M1 vs Fixed PCF<sub>0</sub> on 19 combined cases*

# PCF Model Complexity — First-order M1 ( $\theta = 5$ ) — Recommended

$\theta$  = number of coefficients in the PCF prediction formula

## First-order M1 ( $\theta = 5$ ) — Recommended

$\theta = 5$

$$PCF(x, y, z; \Delta b, \Delta P, \Delta T, \Delta R) \approx \beta_0(x, y, z) + \beta_1(x, y, z)\Delta b + \beta_2(x, y, z)\Delta P + \beta_3(x, y, z)\Delta T + \beta_4(x, y, z)\Delta R$$

$\beta_0$

Intercept  
(= PCF<sub>0</sub>)

$\beta_1$

Boron  
sensitivity

$\beta_2$

Power  
sensitivity

$\beta_3$

Inlet Temp.  
sensitivity

$\beta_4$

Rod  
sensitivity

$$\beta_0 = PCF_0$$

$$\frac{\partial PCF}{\partial \Delta b} = \beta_1, \quad \frac{\partial PCF}{\partial \Delta P} = \beta_2$$

$$\frac{\partial PCF}{\partial \Delta T} = \beta_3, \quad \frac{\partial PCF}{\partial \Delta R} = \beta_4$$

**RECOMMENDED** — all cases within limits

*Notation:  $x, y$  = in-plane core-node coordinates;  $z$  = axial node index.*

$\theta$  counts coefficients, not multiplied terms. M1 uses intercept  $\beta_0$  plus four sensitivity coefficients  $\beta_1 \dots \beta_4$ .

# Matrix Form of the OLS System: $Y = X \beta$

5 OAT states at  $t = 18$  h | 4 parameters | Solved simultaneously for all 4,248 nodes

<b>Y</b> ( $5 \times 4,248$ )	<b>X</b> ( $5 \times 5$ )					<b><math>\beta</math></b> ( $5 \times 4,248$ nodes)
	intercept <b>1</b>	ppm <b><math>\Delta b</math></b>	% <b><math>\Delta P</math></b>	$^{\circ}\text{C}$ <b><math>\Delta T</math></b>	% <b><math>\Delta R</math></b>	
PCF (nominal) $n=1$ (nominal)	1	0	0	0	0	<b><math>\beta_0 = PCF_0</math></b> +9.945e-01
PCF ( $\Delta\text{boron}$ ) $n=2$ ( $\Delta\text{boron}$ )	1	+25	0	0	0	<b><math>\beta_1</math> (<math>\Delta\text{boron}</math>)</b> -6.970e-07
PCF ( $\Delta\text{Power}$ ) $n=3$ ( $\Delta\text{Power}$ )	1	0	-8.0	0	0	<b><math>\beta_2</math> (<math>\Delta\text{Power}</math>)</b> -1.643e-05
PCF ( $\Delta\text{Tin}$ ) $n=4$ ( $\Delta\text{Tin}$ )	1	0	0	+2	0	<b><math>\beta_3</math> (<math>\Delta\text{Tin}</math>)</b> -9.272e-06
PCF ( $\Delta\text{rod}$ ) $n=5$ ( $\Delta\text{rod}$ )	1	0	0	0	-6	<b><math>\beta_4</math> (<math>\Delta\text{rod}</math>)</b> +2.421e-05

**Intercept column** — added by construction, not a measured quantity.  
 $PCF = \beta_0 \cdot 1 + \beta_1 \Delta b + \beta_2 \Delta P + \beta_3 \Delta T + \beta_4 \Delta R$   
 At nominal state ( $\Delta = 0$ ):  $X\beta = \beta_0 \times 1 = PCF_0$   
 $\beta_0$  therefore stores the reference PCF captured at  $t = 18$  h

Values shown for centre node (axial node  $z=12$ , row 7, col 7).  
 Training uses 5 OAT states at  $t = 18$  h. Each of the 4,248 active nodes has its own  $\beta$  vector solved by lstsq.

# E3D Worst-Case Grid: Three-Model Comparison

Slice:  $\Delta P = +10\%$ ,  $\Delta R = -8\%$  | Rows:  $\Delta b$  (ppm) | Cols:  $\Delta T$  ( $^{\circ}\text{C}$ )

## Fixed PCF<sub>0</sub> ( $\theta=1$ )

$\Delta b \setminus \Delta T$	-2	+0	+2
-25 ppm	19.89	19.85	19.81
+0 ppm	19.10	18.98	18.97
+25 ppm	19.71	19.64	19.52

## First-order M1 ( $\theta=5$ ) — Recommended

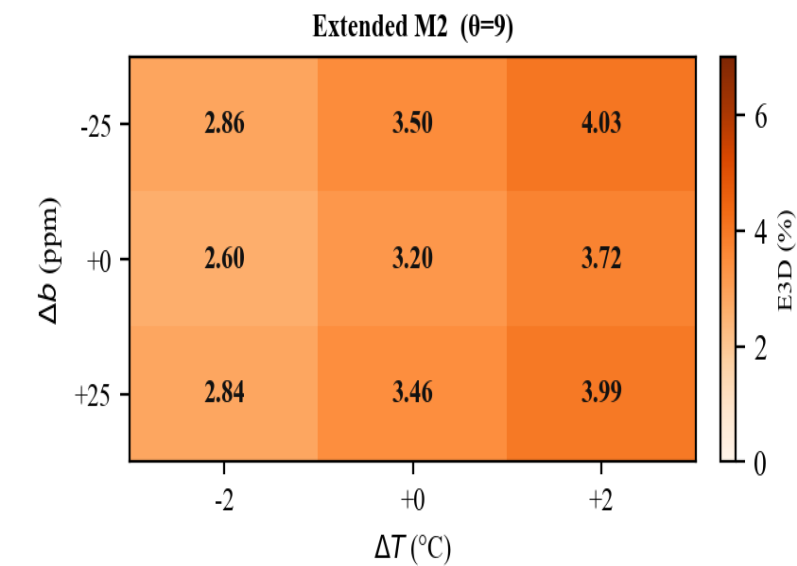
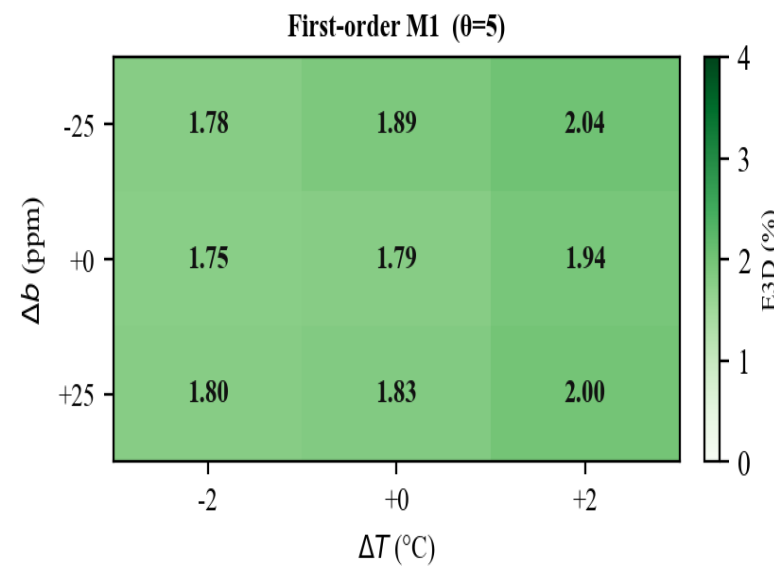
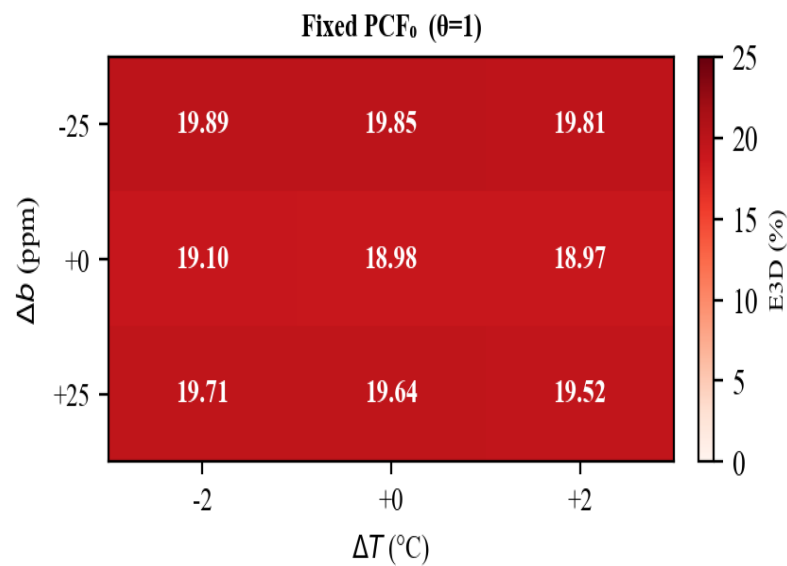
$\Delta b \setminus \Delta T$	-2	+0	+2
-25 ppm	1.78	1.89	2.04
+0 ppm	1.75	1.79	1.94
+25 ppm	1.80	1.83	2.00

## Extended M2 ( $\theta=9$ ) — Overfit

$\Delta b \setminus \Delta T$	-2	+0	+2
-25 ppm	2.86	3.50	4.03
+0 ppm	2.60	3.20	3.72
+25 ppm	2.84	3.46	3.99

**Limit: 5 %** | Fixed PCF<sub>0</sub>: up to 19.89 % — **FAIL**. M1: 1.75-2.04 % on this slice — **PASS**. Extended M2: 2.60-4.03 % here and 7.98 % at the nominal reference — **overfitting**.

Peak Assembly Error E3D (%) — Stage VIII worst-case slice:  $\Delta P = +10\%$ ,  $\Delta R = -8\%$



◆ *SECTION*

# Conclusions

*Summary of Findings*

# Validation Summary

For case combined validation metrics for Fixed PCF<sub>0</sub> vs First-order M1 — Current validation snapshot

## OBJECTIVE

Quantify OPR-1000 1D/2D PCM error under off-nominal flexible-operation states.

## CORE MODEL

SPHINCS | YGN3 Cycle-1 BOC  
24 axial nodes | 177 assemblies  
4,248 active nodes | Ref: 50 % FP, rods out  
Bu = 25.70 MWD/MTU

## OAT INPUT RANGES

$\Delta P$	Power level 40-60 % FP	11 lvls
$\Delta b$	Boron 0, +/-25/50/75/100 %	9 lvls
$\Delta T$	Tin inlet 0, +/-2/4/6/8/10 %	11 lvls
$\Delta R$	Rod position 90-100 % withdrawn	11 lvls

## Fixed PCF<sub>0</sub> ( $\theta = 1$ )

**19.89 %**

Peak E3D

**0.69 %**

Mean ERMS

**FAIL: E3D > 5 % limit**

10x lower peak E3D | 54 % lower mean ERMS

## First-order M1 ( $\theta = 5$ )

**2.04 %**

Peak E3D

**0.32 %**

Mean ERMS

**PASS: current validation snapshot (19 cases)**

Thresholds:  $E3D \leq 5\%$  |  $ERMS \leq 2\%$  (NRC / EPRI / IAEA)

## VALIDATION BASIS

### Fixed PCF<sub>0</sub> ( $\theta = 1$ )

Frozen at reference; fails when rods move off nominal.

### First-order M1 ( $\theta = 5$ )

$\beta_0 + \beta_1 \Delta b + \beta_2 \Delta P + \beta_3 \Delta T + \beta_4 \Delta R$

OLS fit |  $E3D \leq 2.04\%$

## VALIDATION VERDICT

### Deployable model: First-order M1

Validated on 19 cases; max E3D = 2.04 %, mean ERMS = 0.32 %.

#### LOCAL-SENSITIVITY RANKING



## NEXT STEPS

- Peaking factor uncertainty:  $F_Q$  and  $F_{\Delta H}$  propagation
- Burnup evolution: re-fit  $\beta$  from BOC to EOC
- Xenon transient and detector robustness studies

# Conclusions

OAT findings (power, boron, tin, rod @ 50 % FP) with combined-case M1 validation reminder

## OAT FINDINGS (FIXED PCF<sub>0</sub>)

### Power-level mismatch

Across the 40-60 % FP subset, power-level mismatch produces a gradual and near-symmetric error increase away from 50 % FP.

### Rod-position mismatch

At 50 % FP, deep R5 insertion is the limiting condition because it creates a localized peak-error tail during partial rod insertion.

### OAT DRIVER RANKING

Worst-case OAT 3D max error across the sensitivity studies.

<b>Rod @ 50 % FP</b>	
<b>Boron</b>	
<b>Inlet temp</b>	
<b>Power level</b>	

### Metric scope

Power card uses the 40-60 % FP heatmap subset. Rod card uses the R5 50 % FP subset. Presentation extends this with boron, inlet temperature, and M1 validation.

### Power OAT (40-60 % FP subset)

Peak 3D max	Peak RMS
<b>2.35 %</b>	<b>0.49 %</b>

PASS: below 5 % E3D across 40-60 % FP

### Rod OAT (50 % FP subset)

Peak 3D max	Peak RMS
<b>24.74 %</b>	<b>1.39 %</b>

LIMITING CASE: 90-99 % withdrawal at 50 % FP

### DATA SOURCES

Power OAT here = 40-60 % FP heatmap subset.  
Rod OAT here = 50 % FP subset.  
Presentation also adds boron, inlet temperature, and 19-case First-order M1 validation.

## POWER TAKEAWAY

- 1D+2D PCM is weakly sensitive to moderate operating-power mismatch.
- Across the 40-60 % FP heatmap subset, worst-case fixed-PCF power error stays at 2.35 % E3D and 0.49 % RMS.

## M1 VALIDATION REMINDER

- Boron and inlet-temperature studies remain moderate (worst-case E3D = 5.24 % and 3.70 %).
- In the combined -case validation, First-order M1 is recommended: mean ERMS = 0.32 %, max E3D = 2.04 %.

## FINAL TAKEAWAY

Fixed-PCF 1D+2D PCM is robust to power drift but limited by deep rod insertion whereby adaptive M1 extends robustness over broader operating variation and is the deployable model.

# Thank You

## Sensitivity Study of 1D/2D Power Synthesis Method for PWR Flexible Operation

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