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Burnup-Dependent Full-Core Sensitivity Analysis of PWR Fuel Performance to Fuel Properties and Design Parameters

Presenter: Donguk Kim

Supervisor: Prof. Youho Lee

kimdong1102@snu.ac.kr

leeyouho@snu.ac.kr *

Nuclear Fuel Materials and Safety Laboratory

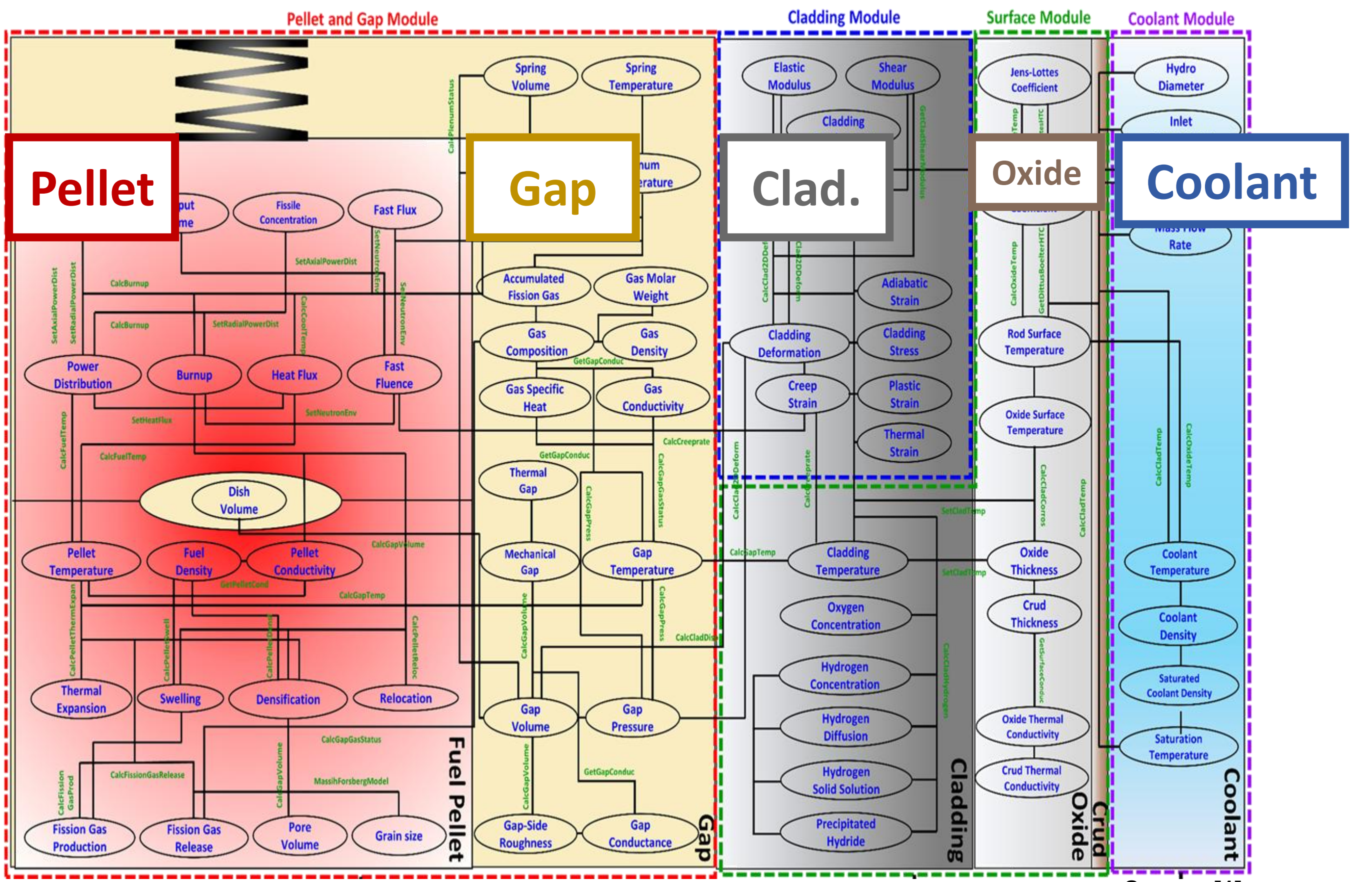
Department of Energy Systems Engineering, Seoul National University

Contents

Introduction

Complexity of Nuclear Fuel

<Complex behaviors and mechanisms of a nuclear fuel rod>



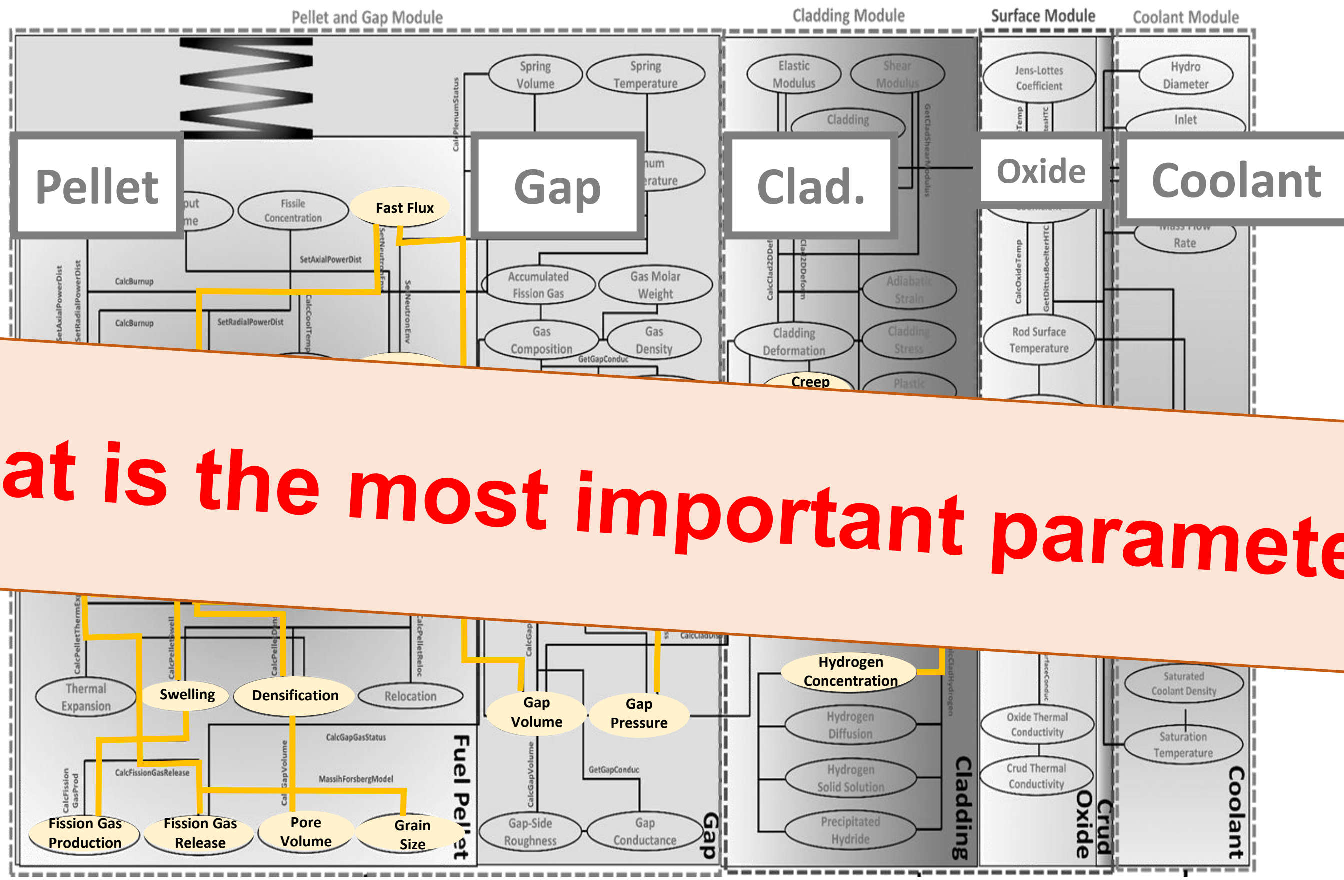
Source:[1]

Nuclear fuel is a complex system

[1] K. Shim et al., "GIFT-1.0: Advanced light water reactor fuel performance code," Nuclear Engineering and Technology, 2025.

Complexity of Nuclear Fuel

<Complex behaviors and mechanisms of a nuclear fuel rod>



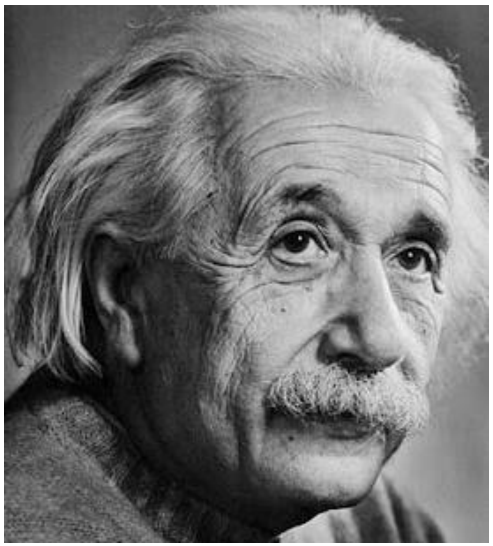
What is the most important parameter?

Nuclear fuel is a complex system

Toward simulation-based design

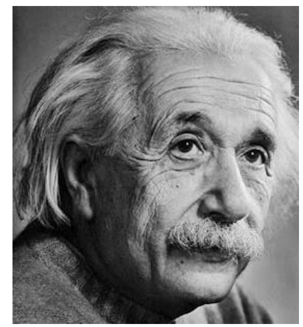
➢ **How to identify key parameters for design?**

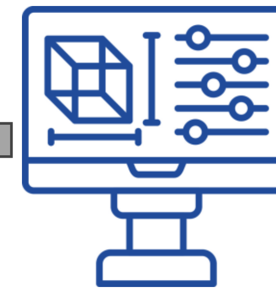
Until now



- **Decades of experience**
- **Expert intuition**

From now on





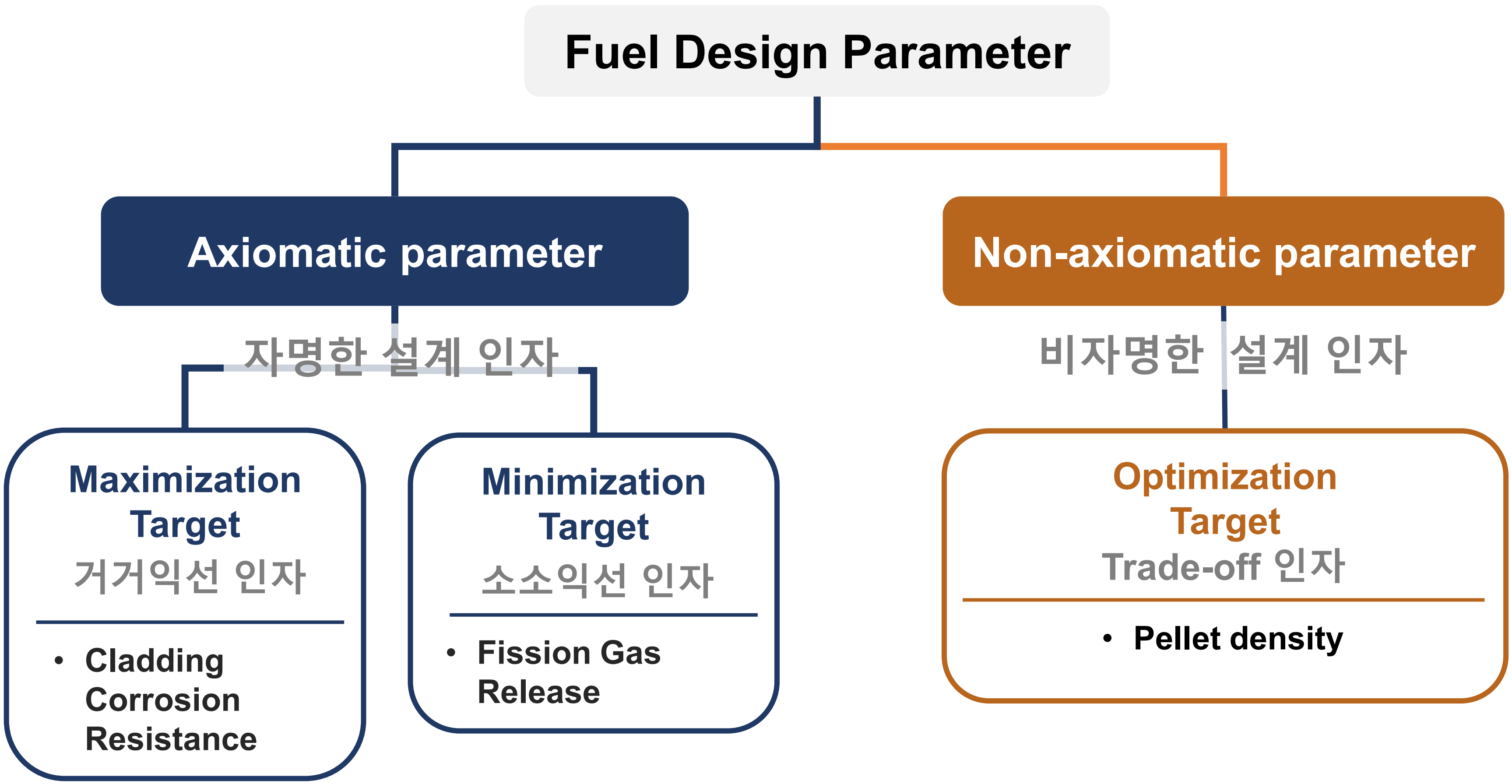
- **Decades of experience**
- **Expert intuition**

+ Systematic exploration
+ Quantitative evaluation

Simulation guides expert focus to key parameters

Simulation-based design

➢ **Axiomatic fuel design parameter** — *adapted from Suh's **Axiomatic Design** (2001)*[2]



→ **Uniform impact on fuel safety**

→ **Mixed impact on fuel safety**

[2] N. P. Suh, Axiomatic Design: Advances and Applications. New York, NY, USA: Oxford University Press, 2001.

Scope of axiomatic classification analysis

➢ 20 fuel design parameters

	Component / Region	Property
Material Parameter	Pellet	Fission Gas Release
		Thermal conductivity
		Swelling
		Thermal expansion
		Theoretical density
		Relocation
	Cladding	Friction coefficient
		Thermal conductivity
		Irradiation growth
		Corrosion resistance
		Thermal expansion
		Young's modulus
		Shear modulus
		Creep rate
		Yield strength
Geometry Parameter	Plenum	Length
	Gap	Initial pressure
		Initial gap size
	Spring	Diameter
		Number of turns

GIFT →

Nuclear fuel[1] simulation code

➢ 5 safety parameters

QoIs (Quantity of Interest)

- Cladding Hoop Stress
- Plenum Pressure
- Fuel Centerline Temperature
- Oxide Thickness
- Hydrogen Concentration

➢ Simulation scale

- ~118,000 GIFT runs
- Full-core analysis
- APR1400 18 / 24-month cycles

[1] K. Shim et al., "GIFT-1.0: Advanced light water reactor fuel performance code," Nuclear Engineering and Technology, 2025.

Axiomatic classification

Methodology: Axiomatic classification workflow

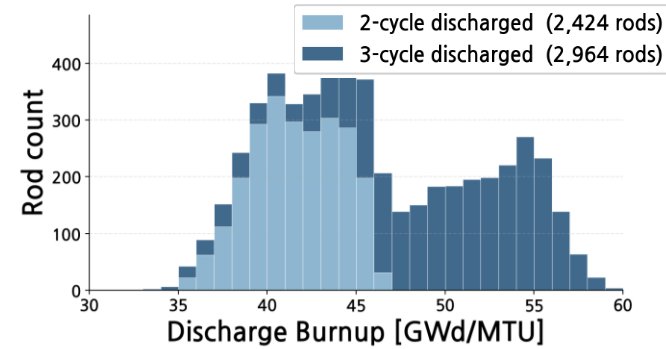
➢ **Full core rod selection**

18-month PWR full core

Row	A	B	C	D	E	F	G	H	J	K	L	M	N	P	R	S	T
1						H1	P11	D0	J5	D0	D11	K1					
2				N16	D0	R12	D0	R10	D2	C10	D0	C12	D0	E16			
3			M11	D1	M10	D3	L17	D3	N8	D3	G17	D3	F10	D1	G12		
4		S13	D1	K10	D3	N12	D2	P16	D3	D16	D2	E12	D3	H10	D1	B13	
5		D0	K12	D3	D9	D3	P13	D3	J16	R4	D13	D3	J4	D3	H12	D0	
6	A8	M15	D3	M13	D3	T12	B7	D3	K5	D3	S7	F17	D3	F13	D3	F15	T8
7	L14	D0	T11	D2	N14	G2	L9	M16	D2	F16	J11	L2	E14	D2	A12	D0	G14
8	D0	K15	D3	S14	C4	D3	S12	D1	M17	D1	B12	D3	P3	B14	D3	H15	D0
9	E9	D2	H5	D3	S9	E8	D2	T6	G6	A12	D2	N10	B9	D3	K13	D2	N9
10	D0	K3	D3	S4	C14	D3	S6	D1	F1	D1	B6	D3	R14	B4	D3	H3	D0
11	L4	D0	T6	D2	N4	G16	J7	M2	D2	F2	G9	L16	E4	D2	A7	D0	G4
12	A10	M3	D3	M5	D3	M1	B11	D3	H13	D3	S11	A6	D3	F5	D3	F3	T10
13		D0	K6	D3	J14	D3	P5	D15	J2	P15	D5	D3	P9	D3	H6	D0	
14		S5	D1	K8	D3	N6	D2	P2	D3	D2	D2	E6	D3	H8	D1	B5	
15			L6	D1	M8	D3	L1	D3	E10	D3	G1	D3	F8	D1	F7		
16				N2	D0	R9	D0	R8	D2	C8	D0	C6	D0	E2			
17						H17	P7	D0	J13	D0	D7	K17					

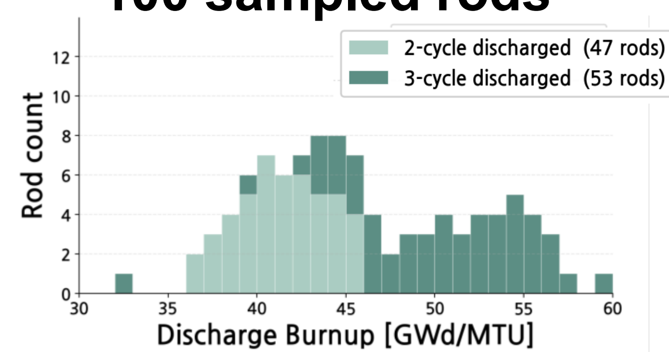
Discharge Burnup distribution

Full-core rods



Sampling

100 sampled rods

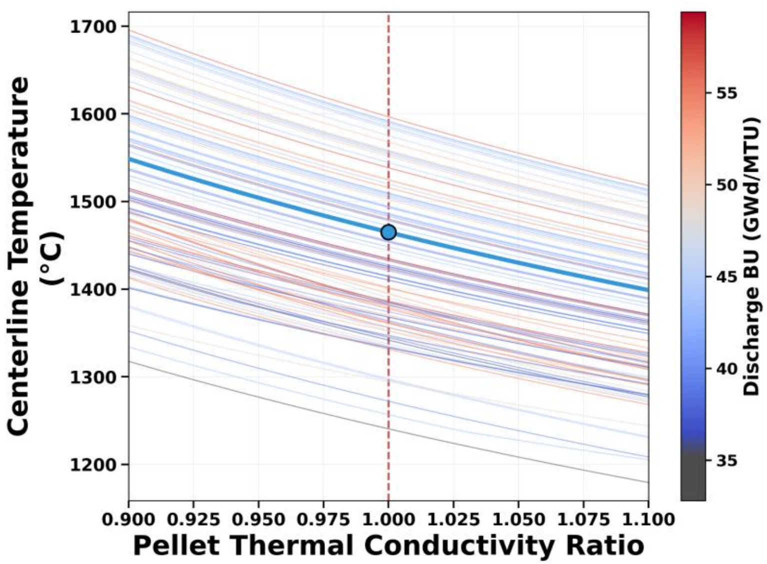


Methodology: Axiomatic classification workflow

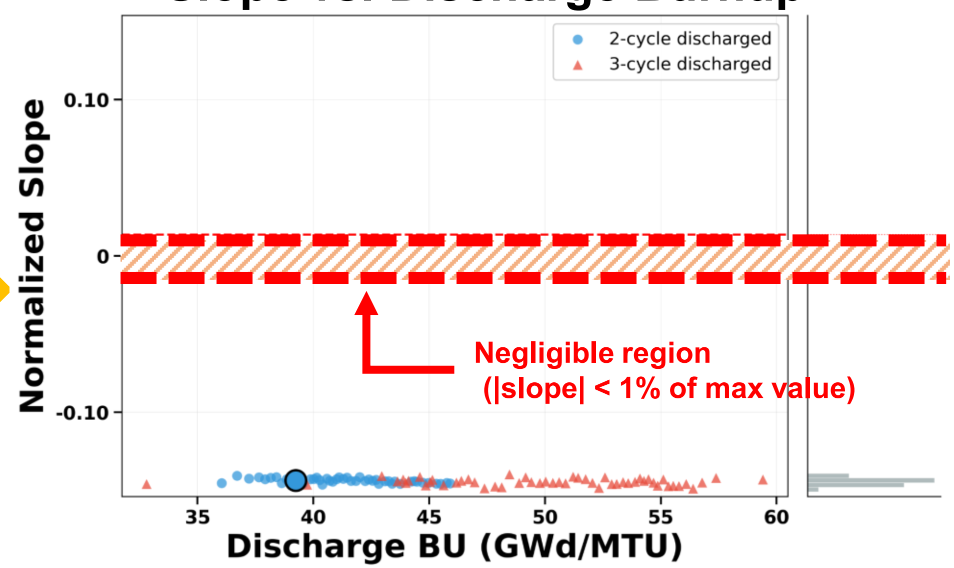
- **Define design – safety relationship**

  Case study) Pellet thermal conductivity – Fuel centerline temperature

Response curve at each rod



Slope vs. Discharge Burnup



Pellet Thermal Conducivity↑ → **Plenum Pressure ↓** → **Fuel Safety ↑**

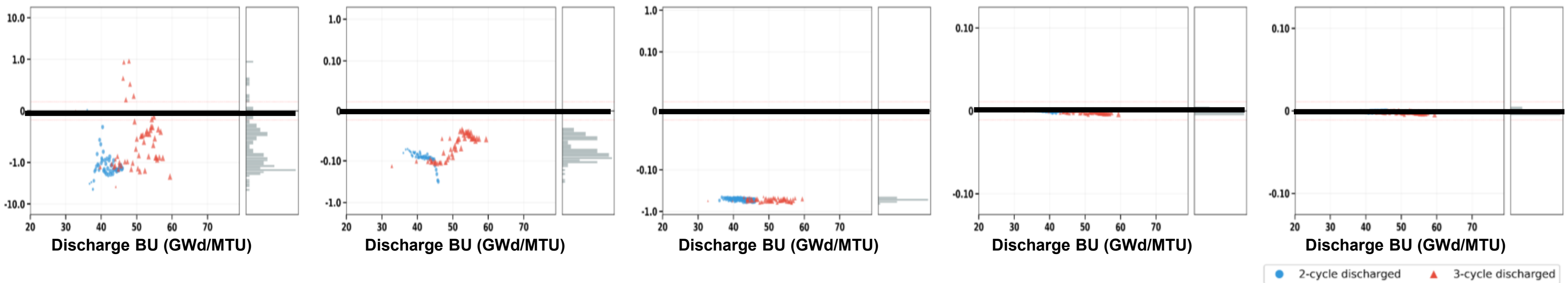
클수록 좋음

Methodology: Classification of axiomatic/non-axiomatic

➢ Axiomatic parameter

Pellet thermal conductivity

Cladding Hoop Stress	Plenum Pressure	Fuel Centerline Temperature	Oxide Thickness	Hydrogen Concentration



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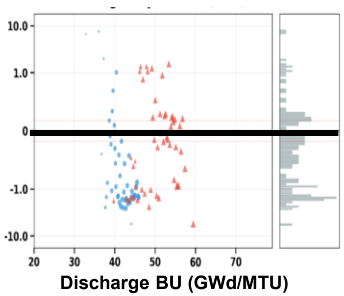
Axiomatic parameter
자명 인자 - 거거익선

Methodology: Classification of axiomatic/non-axiomatic

➢ Non-axiomatic parameter

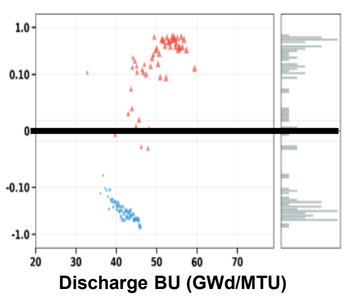
Pellet Theoretical Density

Cladding Hoop Stress



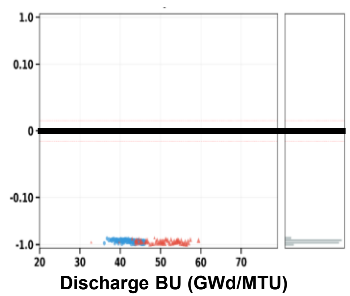
복합 영향

Plenum Pressure



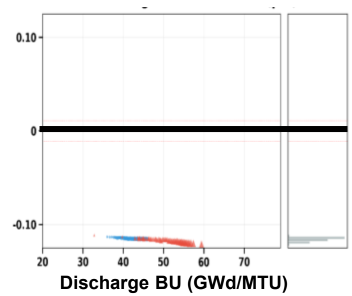
복합 영향

Fuel Centerline Temperature



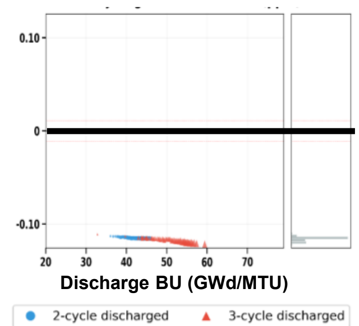
클수록 좋음

Oxide Thickness



클수록 좋음

Hydrogen Concentration

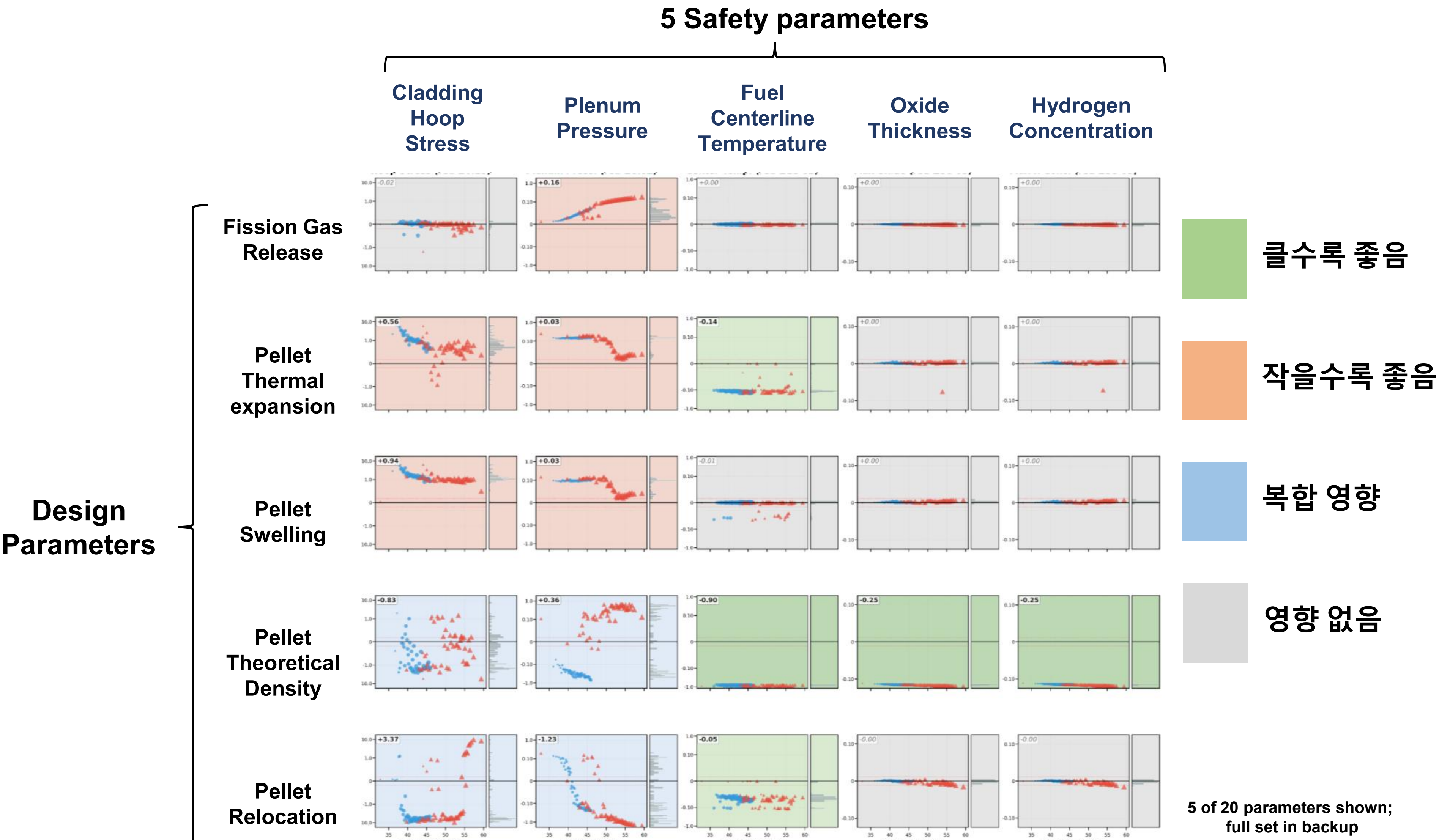


클수록 좋음

Non-axiomatic parameter
비자명 인자

Results: parameter classification matrix

➢ Parameter classification matrix for fuel safety



5 of 20 parameters shown;
full set in backup

Results: Classification of axiomatic/non-axiomatic parameter

➢ Axiomatic parameters for 18-month core

	Component / Region	Property	Hoop stress	Plenum Pressure	Center Temperature	Oxide thickness	Hydrogen concentration
Axiomatic 자명 인자 8	Pellet	Fission Gas Release					
		Swelling					
		Thermal conductivity					
	Cladding	Thermal conductivity					
		Irradiation growth					
		Corrosion resistance					
	Spring	Diameter					
		Number of turns					
Non-axiomatic 비자명 인자 11	Pellet	Thermal expansion					
		Theoretical density					
		Relocation					
		Friction coefficient					
	Cladding	Thermal expansion					
		Young's modulus					
		Shear modulus					
		Creep rate					
	Plenum	Length					
	Gap	Initial pressure					
		Initial gap size					
Negligible	Cladding	Yield strength					

클수록 좋음

작을수록 좋음

복합 영향

영향 없음

Result: Classification of axiomatic/non-axiomatic parameter

➢ Non-axiomatic parameters for 18-month core

- Optimization target

	Component / Region	Property	Hoop stress	Plenum Pressure	Center Temperature	Oxide thickness	Hydrogen concentration
Axiomatic 자명 인자 8	Pellet	Fission Gas Release					
		Swelling					
		Thermal conductivity					
	Cladding	Thermal conductivity					
		Irradiation growth					
		Corrosion resistance					
	Spring	Diameter					
		Number of turns					
Non-axiomatic 비자명 인자 11	Pellet	Thermal expansion					
		Theoretical density					
		Relocation					
	Cladding	Friction coefficient					
		Thermal expansion					
		Young's modulus					
		Shear modulus					
		Creep rate					
	Plenum	Length					
	Gap	Initial pressure					
		Initial gap size					
Negligible	Cladding	Yield strength					

- 클수록 좋음
- 작을수록 좋음
- 복합 영향
- 영향 없음

Result: Classification of axiomatic/non-axiomatic parameter

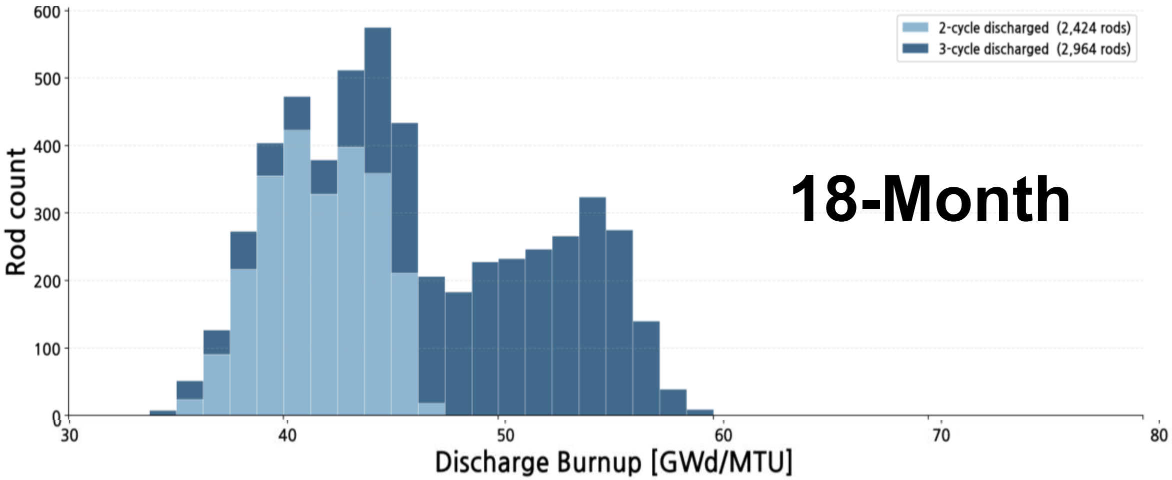
➢ Negligible parameter for 18-month core

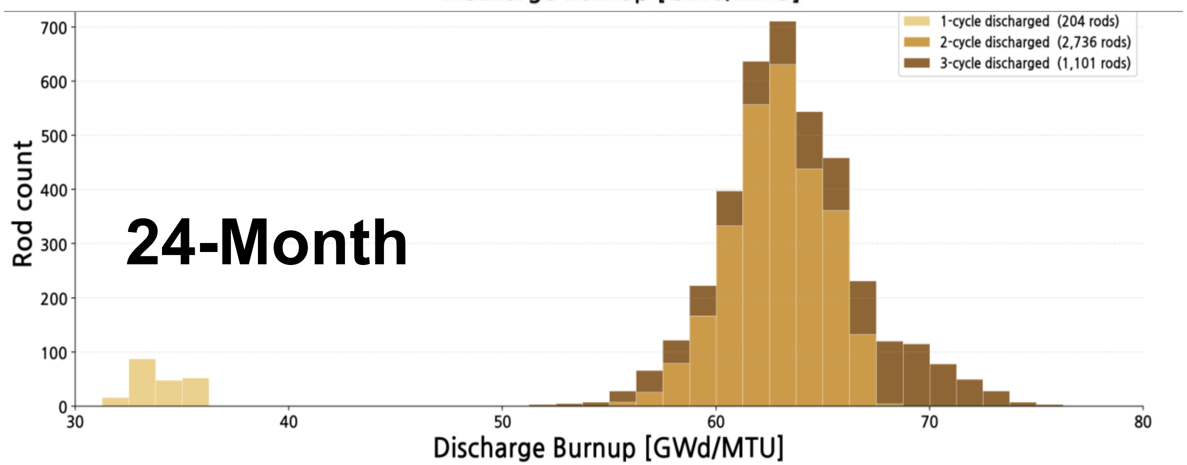
	Component / Region	Property	Hoop stress	Plenum Pressure	Center Temperature	Oxide thickness	Hydrogen concentration
Axiomatic 자명 인자 8	Pellet	Fission Gas Release					
		Swelling					
		Thermal conductivity					
	Cladding	Thermal conductivity					
		Irradiation growth					
		Corrosion resistance					
	Spring	Diameter					
		Number of turns					
Non-axiomatic 비자명 인자 11	Pellet	Thermal expansion					
		Theoretical density					
		Relocation					
	Cladding	Friction coefficient					
		Thermal expansion					
		Young's modulus					
		Shear modulus					
		Creep rate					
	Plenum	Length					
	Gap	Initial pressure					
		Initial gap size					
Negligible	Cladding	Yield strength					

- 클수록 좋음
- 작을수록 좋음
- 복합 영향
- 영향 없음

From 18-month to 24-month core: key changes

➢ **Key differences to consider**





BU distribution change

➢ Mean discharge BU:

45.9 → 60.1 GWd/MTU

Changes in fuel design

➢ Introduced higher enrichment

4.5% → 5.5, 6.0, 6.5%

➢ Longer Plenum length (+30%)

Gap closure duration

➢ Mean gap closed duration:

471.6 → 885.89 EFPD

18-month → 24-month: what shifts?

➢ Axiomatic parameters for 24-month core

- ★ marks change from 18-month

Category	Component / Region	Property	Hoop stress	Plenum Pressure	Center Temperature	Oxide thickness	Hydrogen concentration
Axiomatic 자명 인자 8	Pellet	Fission Gas Release					
		Swelling					
		Thermal conductivity					
	Cladding	Thermal conductivity		★			
		Irradiation growth					
		Corrosion resistance					
	Spring	Diameter					
		Number of turns					
Non-axiomatic 비자명 인자 11	Pellet	Thermal expansion	★	★			
		Theoretical density		★			
		Relocation		★			
	Cladding	Friction coefficient					
		Thermal expansion	★	★			
		Young's modulus	★				
		Shear modulus					
		Creep rate	★				
	Plenum	Length	★				
	Gap	Initial pressure	★				
		Initial gap size	★				
Negligible	Cladding	Yield strength					

- 클수록 좋음
- 작을수록 좋음
- 복합 영향
- 영향 없음

✓ **Axiomatic classification preserved**

✓ **But signs changed in 12 cells**

Axiomatic analysis: summary

	Component / Region	Property	Is axiomatic	Is controllable
Axiomatic 자명 인자 8	Pellet	Fission Gas Release	소소익선	
		Swelling	소소익선	
		Thermal conductivity	거거익선	
	Cladding	Thermal conductivity	거거익선	
		Irradiation growth	거거익선	
		Corrosion resistance	거거익선	
	Spring	Diameter	소소익선	O
		Number of turns	소소익선	O
Non-axiomatic 비자명 인자 11	Pellet	Theoretical density		O
		Thermal expansion		
		Relocation		
	Cladding	Friction coefficient		
		Thermal expansion		
		Young's modulus		
		Shear modulus		
		Creep rate		
	Plenum	Length		O
	Gap	Initial pressure		O
		Initial gap size		O
Negligible	Cladding	Yield strength		

클수록 좋음 | 복합 영향 | 작을수록 좋음 | 영향 없음

- **Axiomatic parameters: high R&D leverage**
- **Framework surfaces overlooked ones**

  (e.g. spring, irradiation growth)
- **Classification preserved across cycles**

  (18-month→24-month core)

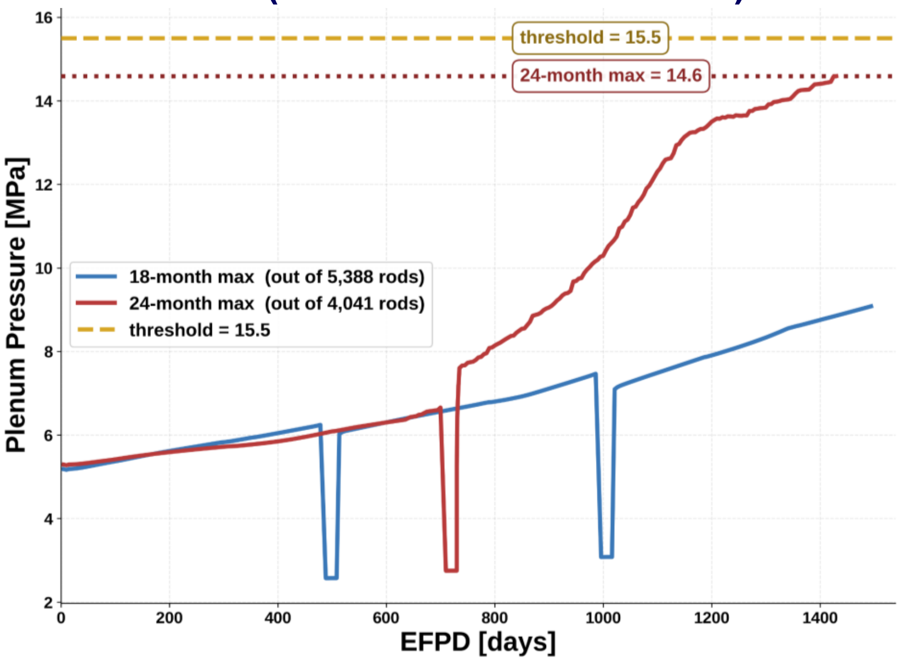
→ Next: optimizing **6 controllable parameters**

Fuel Design Optimization

Fuel Optimization: motivation and setup

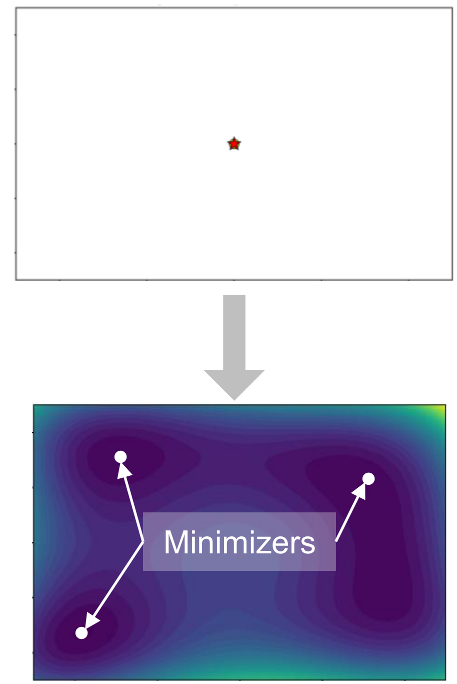
➢ Motivation

Plenum Pressure peak-rod trajectory (18-month vs 24-month)



Need to Optimize Plenum Pressure

➢ Optimization Setup



Bayesian Optimization

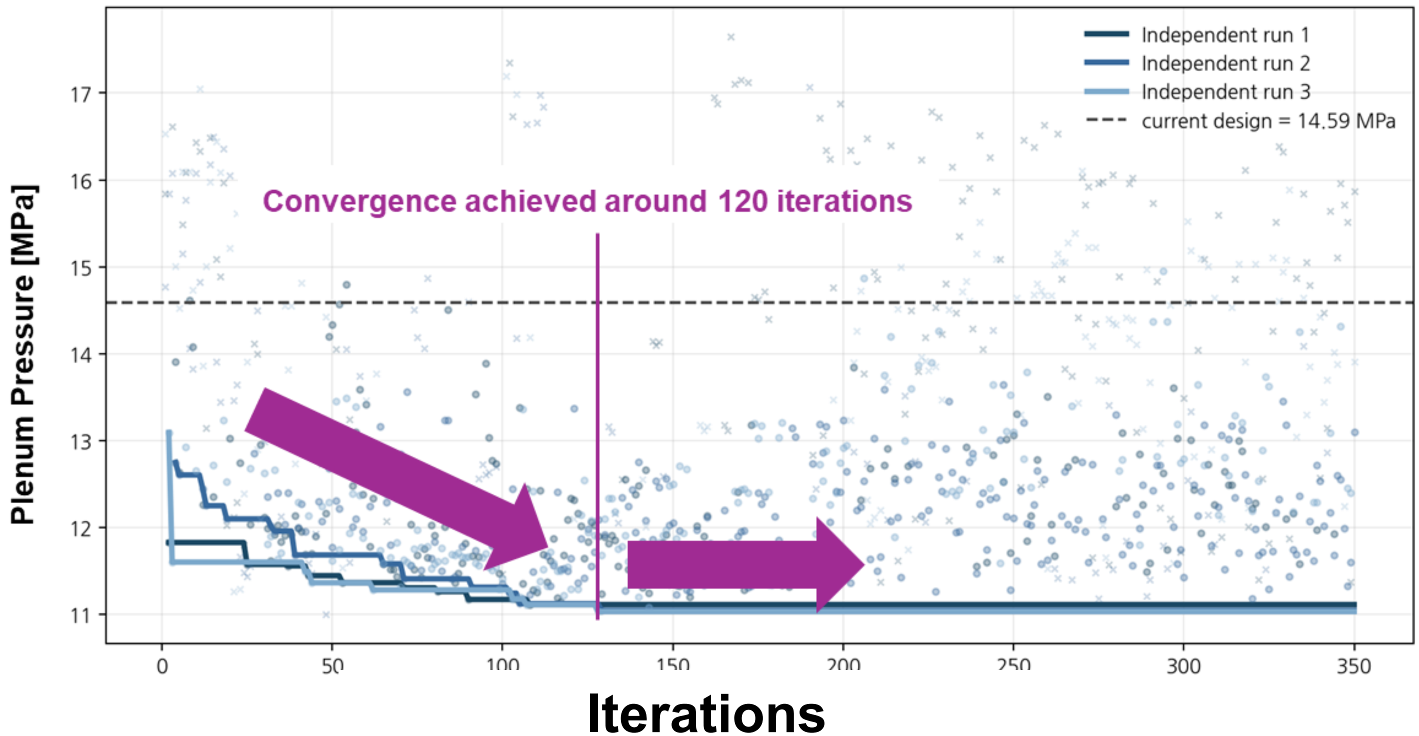
Ground Truth Map (GIFT)

- **6 Fuel Design Variables ($\pm 10\%$ limit)**
- **Minimize Plenum Pressure**
- **With no degradation in 6 safety parameters including hoop strain**

Convergence behavior of Bayesian Optimization

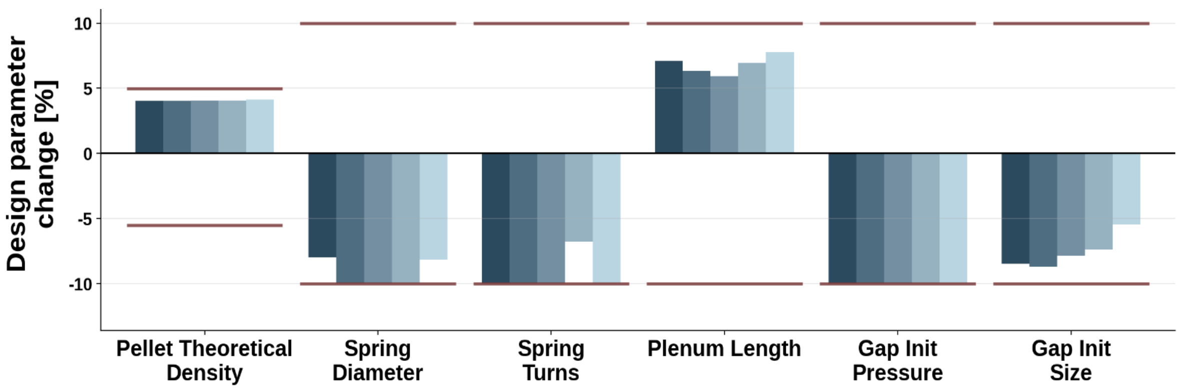
- **Optimization converged after 120 iterations**
  - Exhaustive grid: ~1.8M points → ~15,000× efficient

Plenum Pressure Reduction
across three independent optimization runs

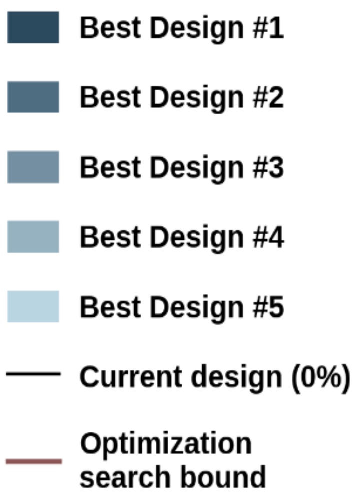


Optimization results: parameters and QoIs

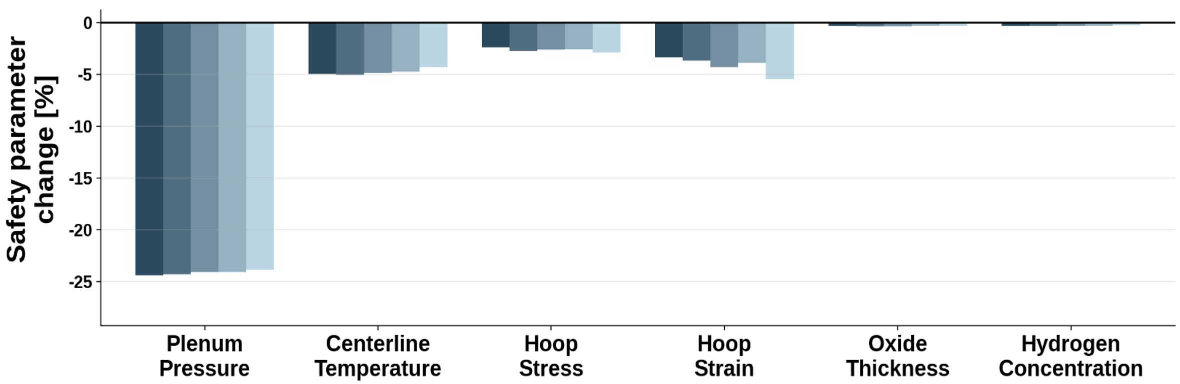
How Design parameter change
(top 5 best designs)



Optimized value: +4.1% -10.0% -10.0% +7.8% -10.0% -8.7%



Result in Safety parameter
(top 5 best designs)



Optimized value: -24.4% -5.0% -2.9% -5.4% -0.3% -0.3%

✓ **Plenum Pressure reduced: 14.6 → 11.0 MPa (−24%)**

✓ **All other QoIs: no degradation**

Optimization directions match axiomatic prediction

➢ **Axiomatic direction** (consistent across safety parameters)

Component / Region	Property	Plenum Pressure	Optimized value
Pellet	Theoretical density		**+4.1% (limit: ±5%)**
Spring	Diameter		**-10% (limit: ±10%)**
	Number of turns		**-10% (limit: ±10%)**
Plenum	Length		**+7.8% (limit: ±10%)**
Gap	Initial pressure		**-10% (limit: ±10%)**
	Initial size		**-8.7% (limit: ±10%)**

클수록 좋음

작을수록 좋음

복합 영향

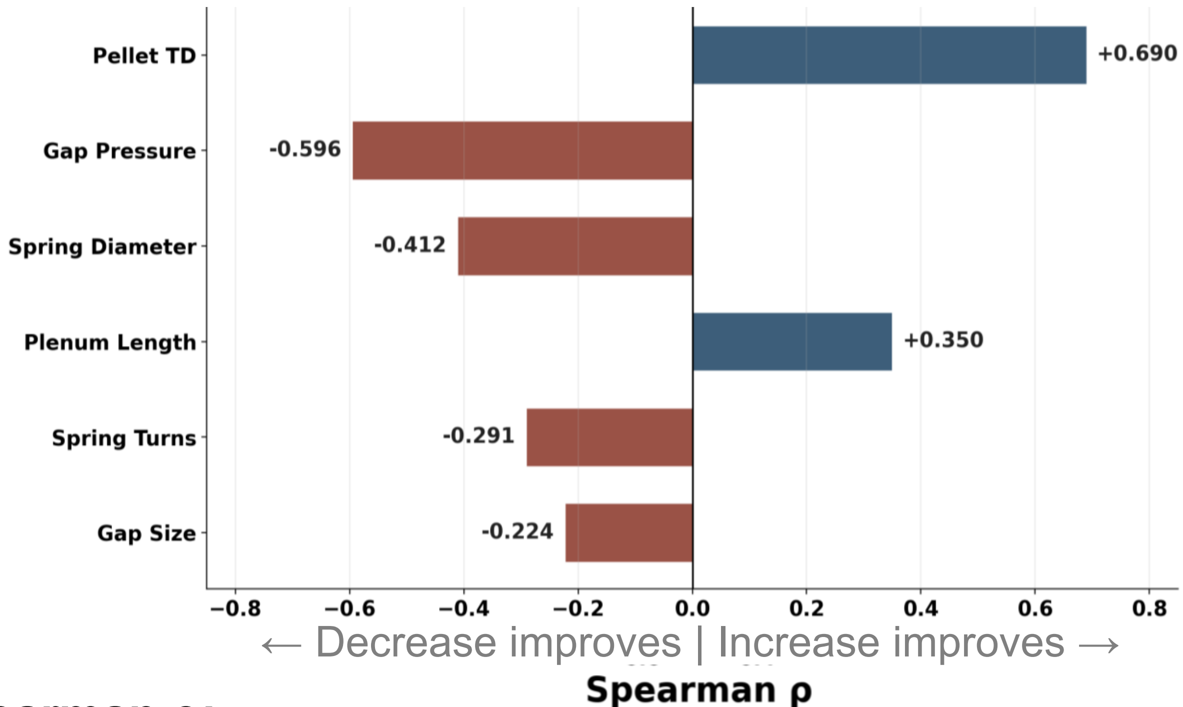
영향 없음

✓ Consistent with axiomatic classification

Fuel Optimization Contribution

- **Contribution ranking**

Variable contribution to optimization reward



Greater contribution

- **Spearman ρ:**
  Rank correlation between variable change and optimization reward

- **Dominant variables:**

1. Pellet Density
2. Gap Initial Pressure

Conclusion

- ✓ **Axiomatic classification framework built**
  - ➢ Design–safety map
  - ➢ New finding (e.g. spring, irradiation growth)

- ✓ **Preserved axiomatic classification: 18 → 24-month core**
  - ➢ But other reactors need re-verification

- ✓ **Optimization for non-axiomatic parameters**
  - ➢ **Plenum Pressure**: 14.6 → 11.0 MPa **(-25%)**
  - ➢ Key contributors:

    Pellet density, Gap Initial pressure

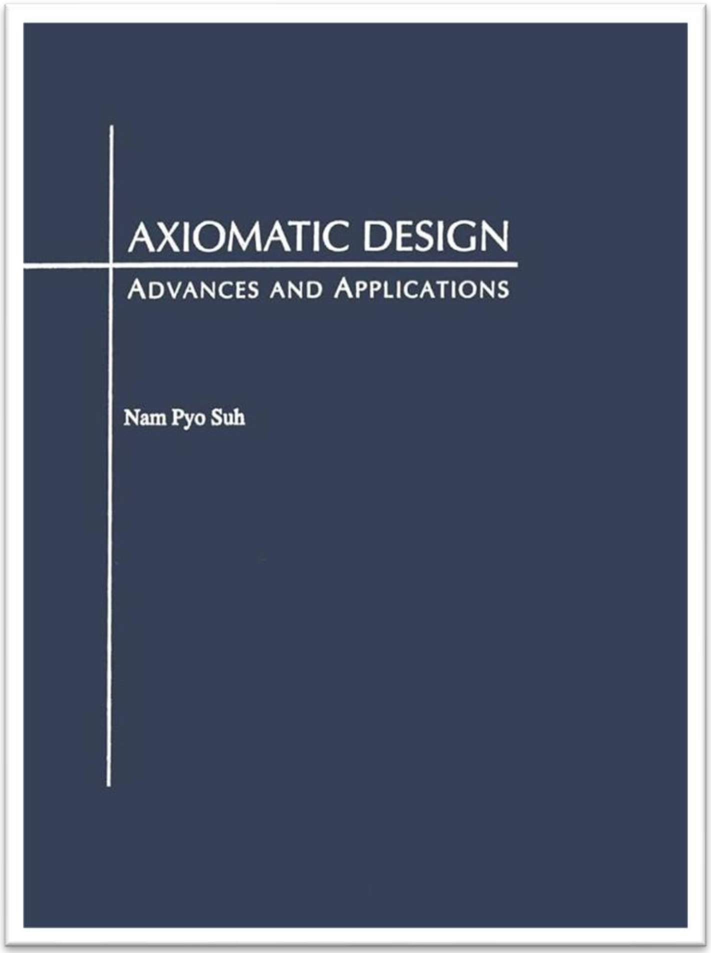
Future work

- **Sobol** global SA for non-axiomatic interactions
- **Reactor system code** coupling
- **Validation with other reactor** types (e.g., i-SMR)

Thank you

Toward simulation-based design

➢ **What is key design parameter?**



Axiomatic Design (Suh, 2001)[2]

- What is a **good design**?
  - ✓ With **clear cause-effect relations**
  - ✓ Where every influence is **visible**

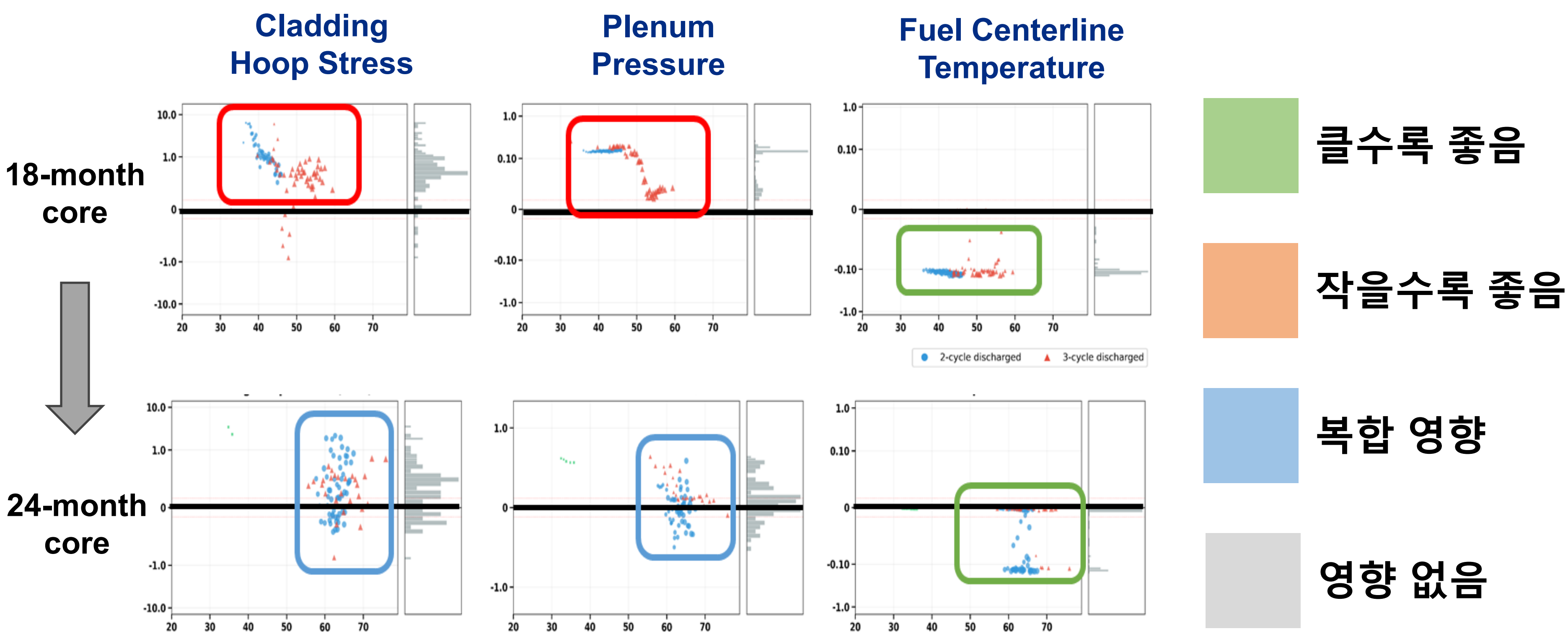
Adapted to nuclear fuel design

- What is **important design parameter**?
  - ✓ With **clear parameter-safety relations**
  - ✓ Where behavior is **visible**

[2] N. P. Suh, Axiomatic Design: Advances and Applications. New York, NY, USA: Oxford University Press, 2001.

Why this matters: implication of sign change

➢ **Pellet Thermal Expansion: same parameter, different behavior**



✓ **Sign change occurs — but direction is not predictable in advance**

➢ New reactors: cannot guess — need to re-evaluate using this framework

Appendix

어제 연료 워크샵에서 첫 세미나에서 김동주 박사님께서 차세대 경수로 핵연료 기술개발과 시험기술 인프라의 역할에 대해서 설명해주시면서 pellet thermal conductivity가 좋아지면 좋은 이유에 대해서 설명해주신 것이 인상깊었습니다.

제 연구에서도 그것을 코드레벨 알고리즘분석과 수치적 값으로 분석을 하게 되는데요.

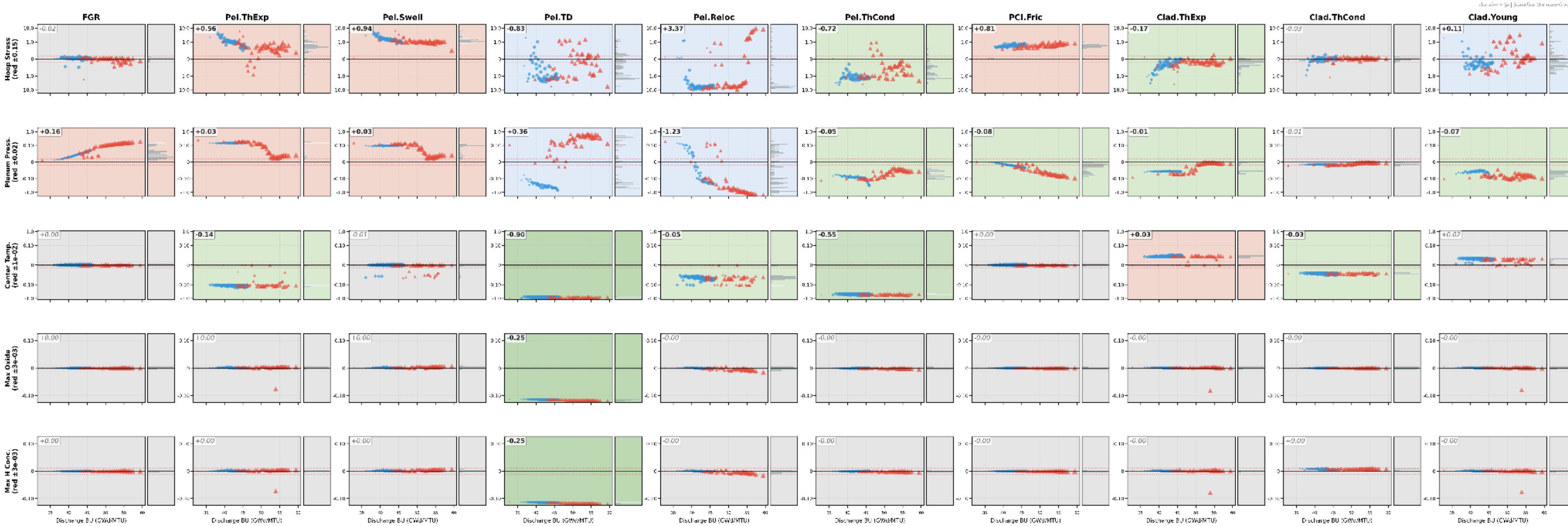
Pellet thermal conductivity 좋아지면

메커니즘:

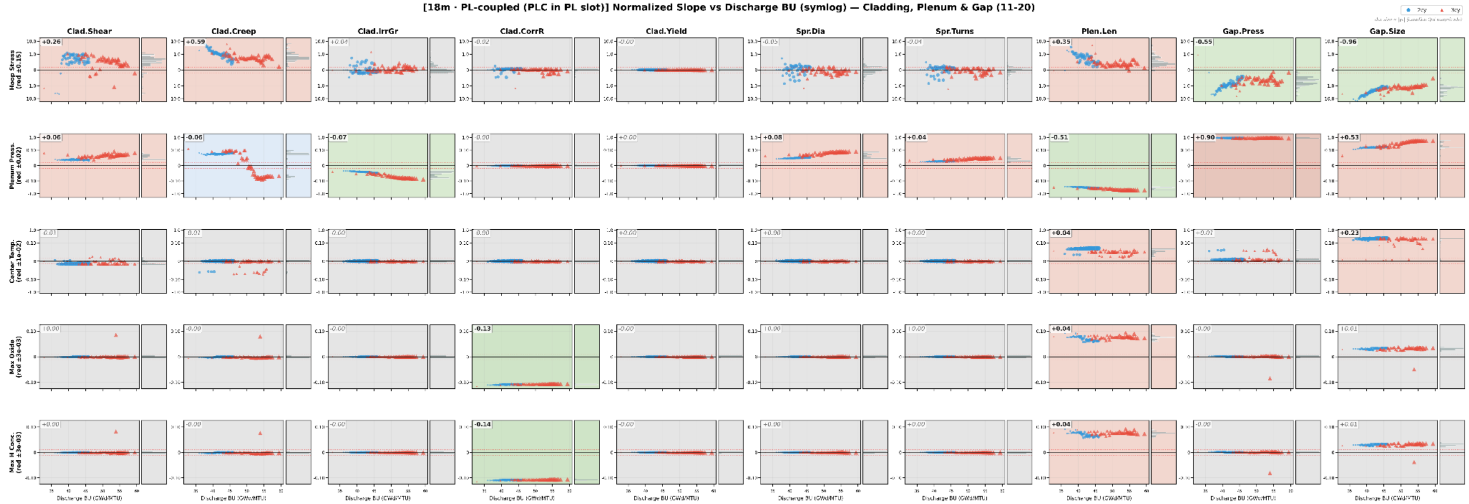
결과 수치:

References

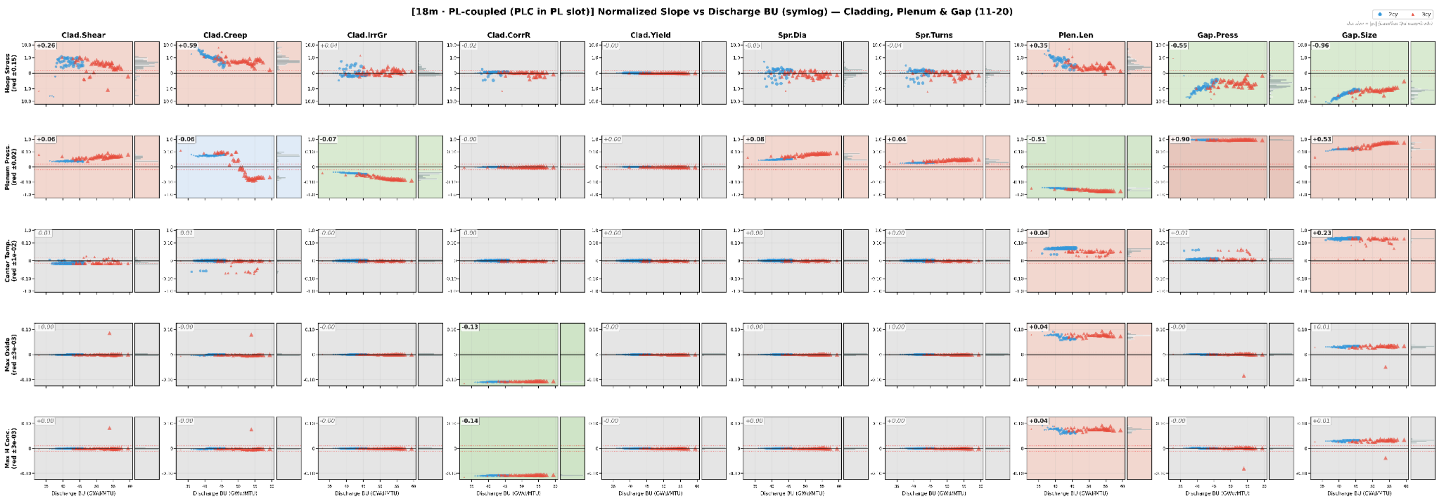
[18m · PL-coupled (PLC in PL slot)] Normalized Slope vs Discharge BU (symlog) — Pellet & PCI (1-10)



[18m · PL-coupled (PLC in PL slot)] Normalized Slope vs Discharge BU (symlog) — Cladding, Plenum & Gap (11-20)



References



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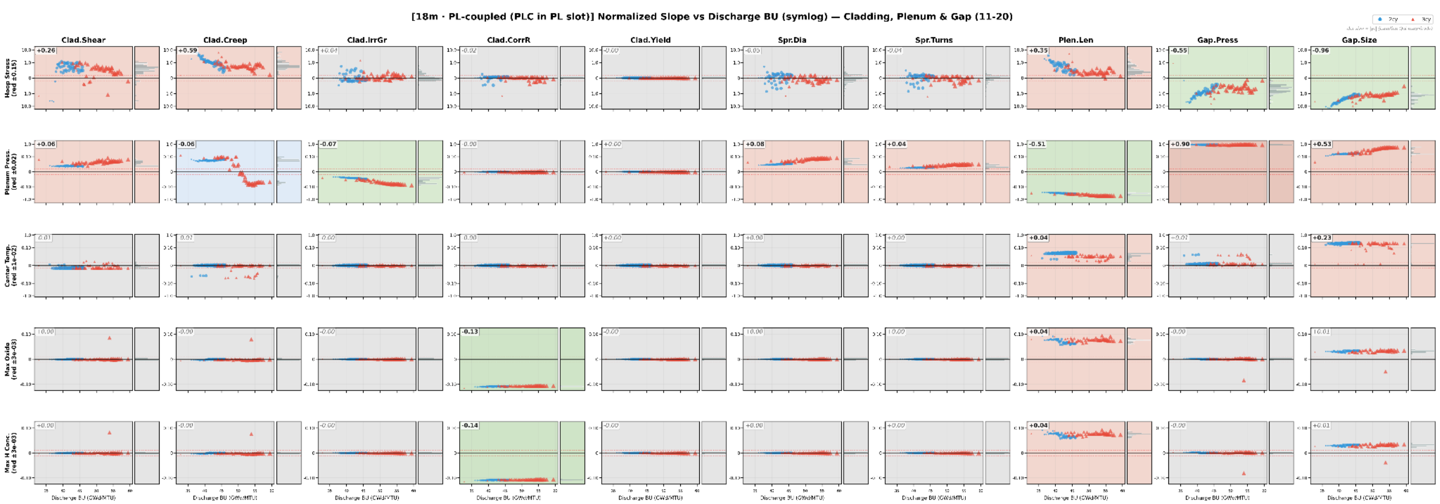

References

1 메커니즘

(a) 핵심 원인 사슬

펠릿 열전도도가 좋아지면 같은 선출력에서 **펠릿 중심 온도가 직접 낮아진다.** 1차원 정상상태 가정에서 중심선과 표면 온도차는

$$T_c - T_s = \int_{T_s}^{T_c} \kappa(T)\, dT \propto q'/\kappa,$$

이므로 κ 가 1.10배 증가하면 ΔT 가 약 10% 만큼 감소한다. 중심 온도가 낮아지면 다음과 같은 *2*차 효과들이 연쇄적으로 완화된다.

1. **Fission gas release ↓.** Speight, Booth, MATPRO-11 등 thermally-activated diffusion 모델은 $D \propto \exp(-Q/RT_c)$ 형태이므로 T_c 가 80 °C 낮아지면 D 는 한 배에 가깝게 줄어든다. GIFT의 step_5 (gas-release/plenum) 모듈도 동일한 Arrhenius 의존성을 가진다.
2. **Plenum pressure ↓.** 방출된 fission gas mole 수가 줄어들고, plenum gas 평균 온도도 함께 낮아지므로 $PV = nRT$ 양쪽에서 압력이 낮아진다.
3. **Cladding hoop stress / strain ↓.** 낮은 펠릿 온도 → 펠릿 열팽창 감소 → PCMI/gap closure 시점이 늦춰지고, gap-closed 이후의 push-out 으로 인한 hoop strain/stress 증가율이 완만해진다.
4. **펠릿 결함진행 (cracking, restructuring) 완화.** central void 형성 임계 온도(약 1700–1800 °C)에 도달 하기까지 여유가 커지고, columnar/equiaxed grain restructuring threshold도 늦춰진다.
5. **LOCA / RIA 안전여유 확대.** stored thermal energy ($\propto T_c^2$ 까지 비례)가 줄어들어 transient peak fuel temperature 가 낮아지고, NUREG-0800/RG-1.236 에서 정한 acceptance criteria 대비 더 큰 margin 을 확보한다.

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References

Table 1: Pellet Thermal Conductivity Ratio sweep — per-cycle elasticity summary (1_8 ranking_summary, top-10 rod 평균 normalized slope). 음수는 *ratio* 증가 시 *QoI* 감소를 의미하며, |value| 가 클수록 민감도가 크다.

QoI	18m elast. (rank)	24m elast. (rank)	효과 방향
Centerline Temperature	−0.55 (#2)	−0.70 (#2)	직접 감소
Plenum Pressure	−0.05 (#13)	−2.20 (#2)	24m에서 매우 큰 감소
Cladding Hoop Stress	−0.72 (#6)	−0.45 (#5)	감소
Cladding Hoop Strain	(n.s.)	(n.s.)	부수적
Maximum Cladding Oxide	(n.s.)	(n.s.)	직접 영향 미미
Maximum Hydrogen Conc.	(n.s.)	(n.s.)	직접 영향 미미

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대표 봉 (median 18m PWR rod) 정량 변환. median 봉의 baseline 중심온도가 ~1465 °C 일 때, 정의상 normalized slope $s = (\Delta y/y_0)/(\Delta x/x_0)$ 이므로 $\Delta x/x_0 = +0.10$ (즉 κ 10 % 증가) 인 경우의 QoI 변화량은 다음과 같다.

Table 2: 대표 (median) 봉에 대한 PelTC +10 % 시나리오의 QoI 변화량 (18m PWR baseline).

QoI	baseline y_0	slope s	$\Delta y = s\, y_0\, (\Delta x/x_0)$	단위
Centerline Temperature	1465	−0.55	−80.6	°C
Cladding Hoop Stress	~ 150	−0.72	−10.8	MPa
Plenum Pressure (18m)	~ 8.5	−0.05	−0.04	MPa
Plenum Pressure (24m)†	~ 10	−2.20	−2.2	MPa

† 24m 의 경우 베이스라인 값은 median 봉이 아닌 typical 값을 사용; 비교 용도.

References

Table 3: 1_8 ranking_summary — 18m PWR, signed normalized slope (top-10 rod mean) and magnitude rank within each QoI.

Param	Hoop Str.	Plenum P.	Center T.	Max Ox.	Max H
Pel.Reloc	3.37 (#1)	−1.23 (#1)	−0.05 (#5)	—	—
Gap.Size	−0.96 (#2)	0.53 (#3)	0.23 (#3)	—	—
Pel.TD	−0.83 (#3)	0.36 (#5)	−0.90 (#1)	−0.25 (#1)	−0.25 (#1)
Pel.Swell	0.94 (#4)	0.03 (#16)	—	—	—
PCI.Fric	0.81 (#5)	−0.08 (#8)	—	—	—
Pel.ThCond	−0.72 **(#6)**	−0.05 **(#13)**	−0.55 **(#2)**	—	—
Clad.Creep	0.59 (#7)	−0.06 (#12)	—	—	—
Pel.ThExp	0.56 (#8)	0.03 (#15)	−0.14 (#4)	—	—
Gap.Press	−0.55 (#9)	0.90 (#2)	—	—	—
Plen.Len	0.35 (#10)	−0.51 (#4)	0.04 (#6)	0.04 (#3)	0.04 (#3)
Clad.Shear	0.26 (#11)	0.06 (#11)	—	—	—
Clad.ThExp	−0.17 (#12)	−0.01 (#17)	0.03 (#7)	—	—
Clad.Young	0.11 (#13)	−0.07 (#9)	—	—	—
FGR	—	0.16 (#6)	—	—	—
Spr.Dia	—	0.08 (#7)	—	—	—
Clad.IrrGr	—	−0.07 (#10)	—	—	—
Spr.Turns	—	0.04 (#14)	—	—	—
Clad.ThCond	—	—	−0.03 (#8)	—	—
Clad.CorrR	—	—	—	−0.13 (#2)	−0.14 (#2)

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References

Table 4: 1_8 ranking_summary — 24m PWR (extended), signed normalized slope (top-10 rod mean) and magnitude rank within each QoI.

Param	Hoop Str.	Plenum P.	Center T.	Max Ox.	Max H
Pel.Reloc	−1.55 (#1)	−1.09 (#3)	−0.02 (#7)	—	—
Pel.TD	−0.18 (#2)	−3.06 (#1)	−1.12 (#1)	−0.11 (#1)	−0.10 (#1)
Clad.Young	0.68 (#3)	−0.08 (#11)	—	—	—
PCI.Fric	0.58 (#4)	−0.04 (#16)	—	—	—
Pel.ThCond	**−0.45 (#5)**	**−2.20 (#2)**	**−0.70 (#2)**	—	—
Gap.Size	−0.04 (#6)	0.28 (#6)	0.09 (#3)	—	—
Pel.Swell	0.39 (#7)	0.05 (#13)	—	—	—
Clad.Shear	−0.30 (#8)	0.05 (#15)	—	—	—
Pel.ThExp	0.12 (#9)	−0.00 (#14)	−0.06 (#4)	—	—
Clad.Creep	0.11 (#10)	−0.02 (#17)	—	—	—
Gap.Press	−0.06 (#11)	0.35 (#4)	—	—	—
Plen.Len	0.06 (#12)	−0.23 (#7)	0.06 (#5)	0.02 (#3)	0.02 (#3)
Clad.ThExp	−0.01 (#13)	—	0.01 (#8)	—	—
FGR	—	0.35 (#5)	—	—	—
Spr.Dia	—	0.15 (#8)	—	—	—
Clad.ThCond	—	−0.12 (#9)	−0.03 (#6)	—	—
Spr.Turns	—	0.08 (#10)	—	—	—
Clad.IrrGr	—	−0.07 (#12)	—	—	—
Clad.CorrR	—	—	—	−0.04 (#2)	−0.04 (#2)

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