A Study on Daily Load-follow Operation in the APR1400 Reactor using Manganese-Based Partial Strength Control Element Assembly

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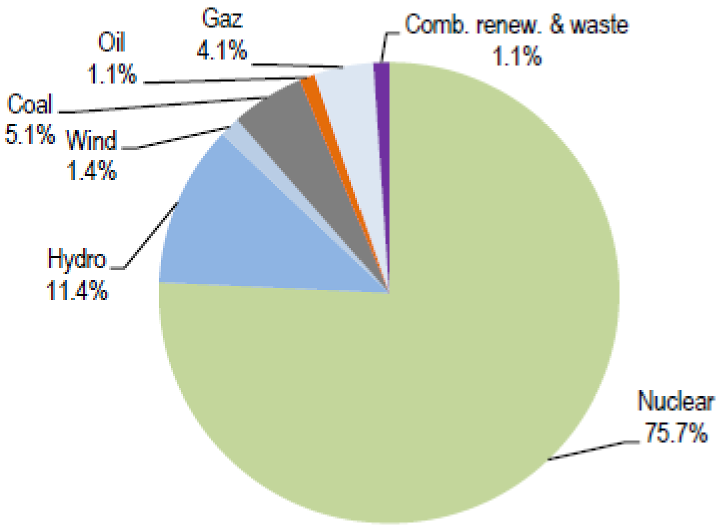
Content

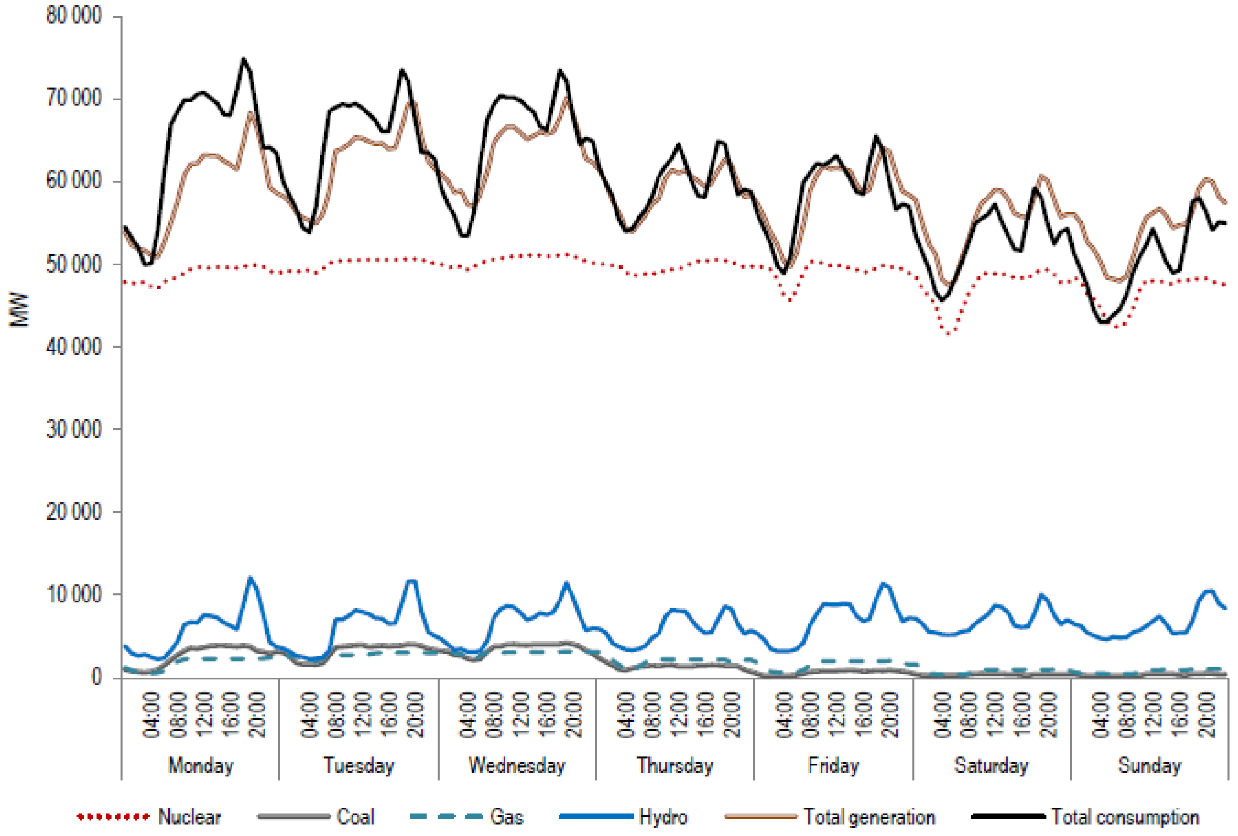
I. Introduction

Importance of daily Load-Follow-Operation (LFO) in NPP:

- ✓ If the nuclear energy share of electricity mix, LFO is important to match the daily or seasonal power demand changes.
- ✓ With a large contribution of intermittent renewable energy (wind, solar.. etc), NPP shall be able to cover the difference between the demand and the supply depending on the status of the power production.



Electricity generation by source in France year 2019 [1]

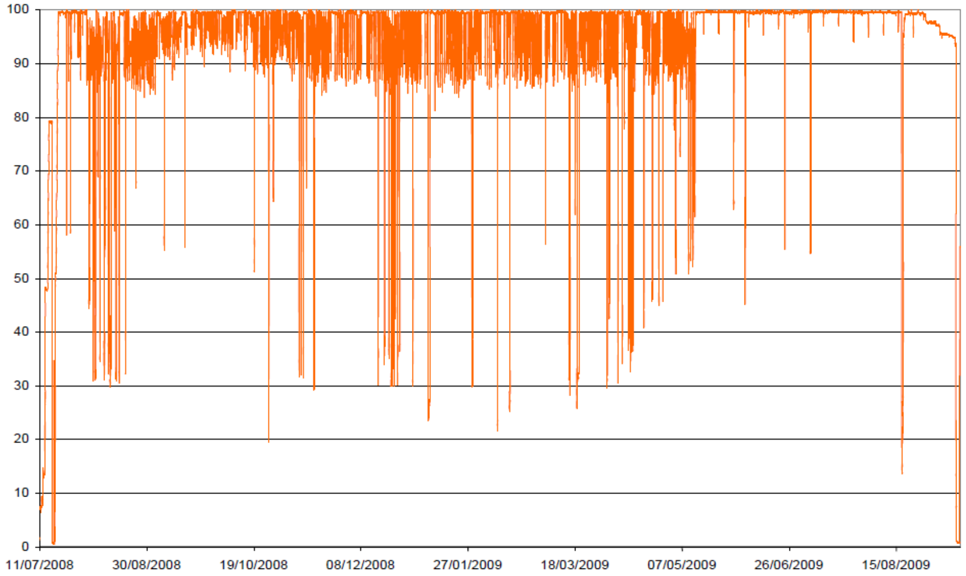


Example of energy generation in France in Nov. 2010 [1]

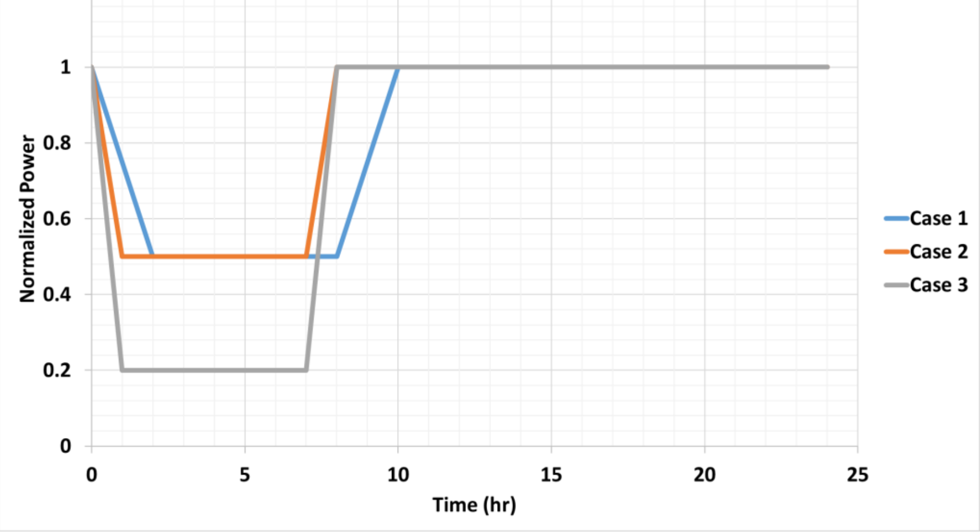
Introduction (2/3)

Operation mood and requirements:

- Base load operation:
  - ✓ Constant power generation over long period of time.
- Primary and secondary frequency control:
  - ✓ To resolve the uncertainty in the power demand.
  - ✓ European standards requires frequency control of ±5% of rated power.
- **Load-Follow-Operation (LFO)**
  - ✓ Daily variation of the reactor power.
  - ✓ Usually 100-50-100 % of the full power variation within 24-hr is adopted.
  - ✓ Some extreme cases shall be considered as well (ie. 100-20-100 % scheme, rapid power increase.. etc).



Power history in an EDF reactor. [1]

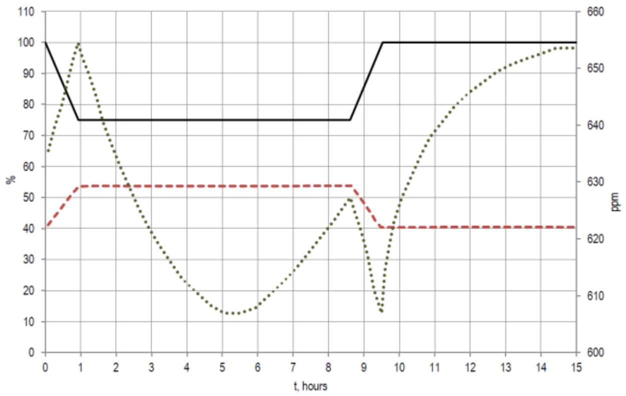


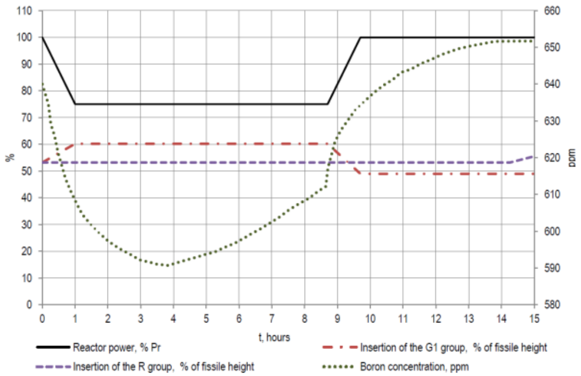
Possible daily LFO scenarios.

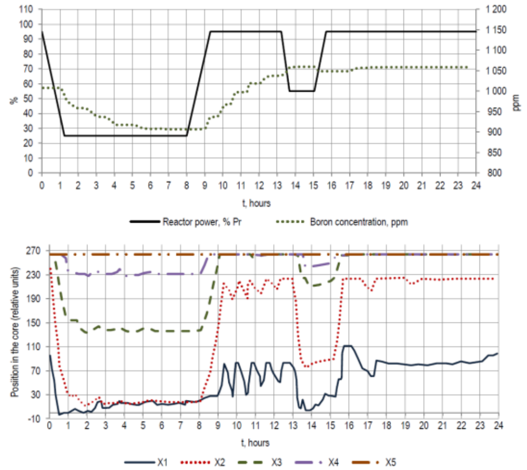
Introduction (3/3)

Example of France LFO modes:

	Mode A	Mode G	Mode X
Primary frequency control	$\pm 2\%P_r$	$\pm 2\%P_r$	$\pm 3\%P_r$
Secondary control	$\pm 3\%P_r$	$\pm 5\%P_r$	$\geq \pm 5\%P_r$
LFO ramp speed	$2\%P_r$/min till 80% cycle length $0.2\%P_r$/min after 80% cycle length	$5\%P_r$/min till 80% cycle length $2\%P_r$/min after 80% cycle length	$5\%P_r$/min





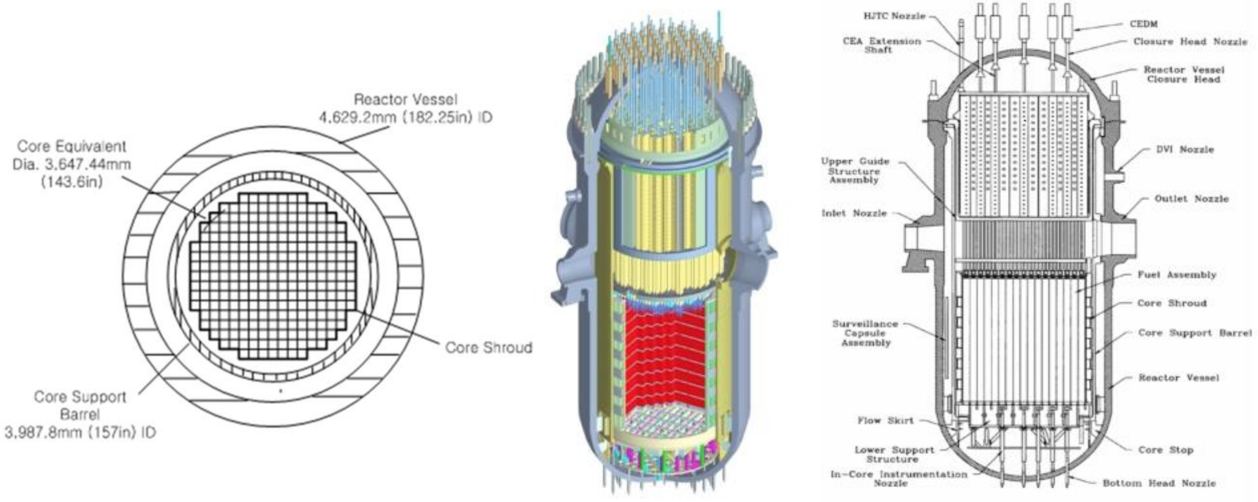


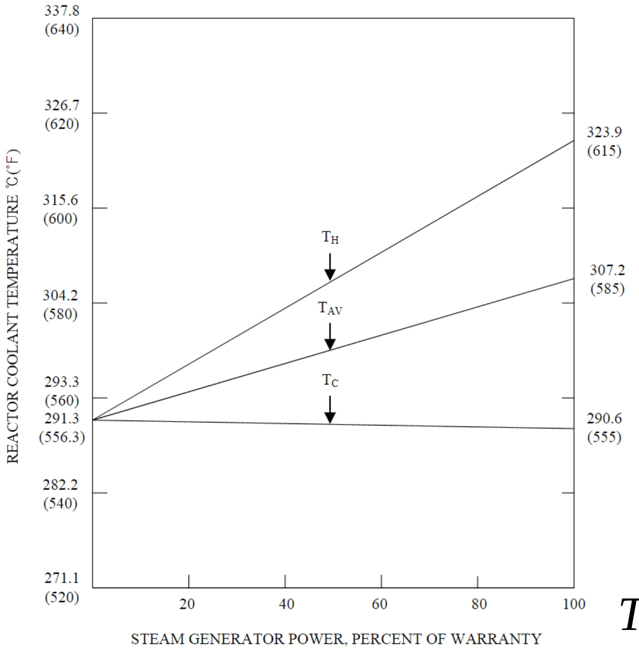
Reactor Description

Reactor Description(1/3) [2]

Parameter [2]	Value
Reactor power (MWth)	3983
Number of fuel assemblies	241
Lattice design	16X16
Active core height (cm)	381
Burnable absorber	Gd_2O_3-UO_2
Soluble neutron absorber	Boron
Inlet coolant temperature (̊c)	290.6
Primary coolant flow rate (Kg/s)	20900
Steam generator operation strategy	Constant inlet coolant temperature
Core configuration	Initial core

Reactor core layout





Temperature control strategy

Reactor Description(2/3) [2]

A0	A0	C3	A0	B1	A0	B3	C2	B0
A0	B3	A0	B3	A0	B1	A0	B3	C0
C3	A0	C2	A0	C3	A0	C3	B1	B0
A0	B3	A0	B3	A0	B3	A0	B2	C0
B1	A0	C3	A0	C2	A0	B1	C0	
A0	B1	A0	B3	A0	B3	C1	C0	
B3	A0	C3	A0	B1	C1	C0		
C2	B3	B1	B2	C0	C0			
B0	C0	B0	C0					

Initial core APR1400 configuration

Assembly	# FA	Enrichment (w/o)	Rods/FA	# Gd_2O_3 rods/FA	Gd_2O_3 (w/o)
A0	77	1.71	236	-	-
B0	12	3.14	236	-	-
B1	28	3.14/2.64	172/52	12	8
B2	8	3.14/2.64	124/100	12	8
B3	40	3.14/2.64	168/52	16	8
C0	36	3.64/3.14	184/52	-	-
C1	8	3.64/3.14	172/52	12	8
C2	12	3.64/3.14	168/52	16	8
C3	20	3.64/3.14	120/100	16	8

Reactor Description(3/3) [2]

	1	2	3	4	5	6	7	8	9
A	R5				R3		R5		R3
B		R2		S		R1		S	
C			R3				P2		
D		S		P1		S		S	
E	R3				R4		R2		
F		R1		S		S			
G	R5		P3		R2		R4		
H		S		S					
I	R3								

CEA loading pattern

P = PSCEA, R = Regulating bank, and S = Shutdown bank).

Full Strength Control Element Assembly	
CEA in core	81*
Clad material	Inconel625
Burnable absorber	B_4C
Clad OD (cm)	2.073
Partial Strength CEA	
CEA in core	12
Clad material	Inconel625
Burnable absorber	Inconel625
Clad OD (cm)	2.073

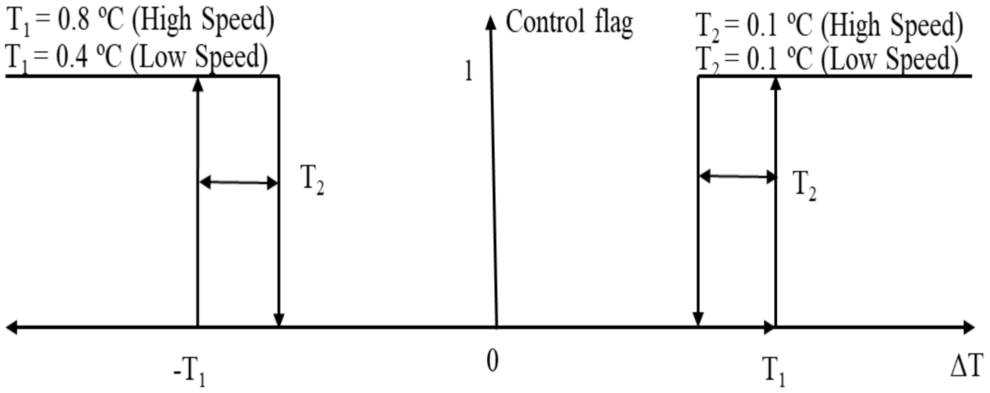
* 45 regulating banks and 36 shutdown banks

Control Logic

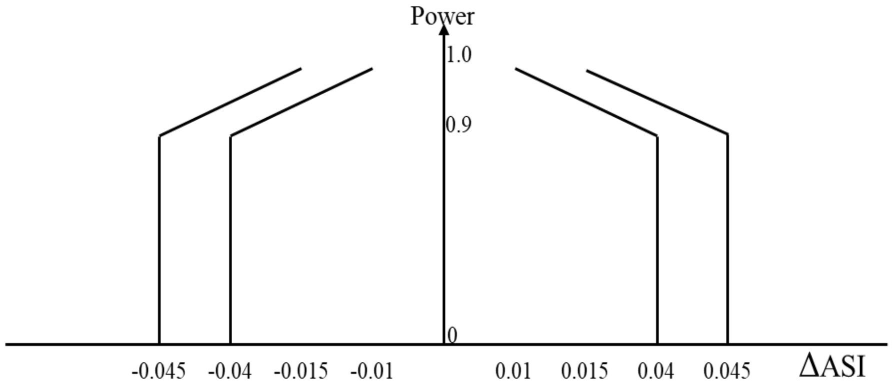
Control Logic(1/3)[3]

Mode-K+ control logic was adopted:

- **Soluble Boron scenario is pre-determined by the operator.**
- **The Temperature mismatch (ΔT) is defined as $T_{target} - T_{avg}$.**
  - Control Element Assembly (CEA) movement speed is determined by the ΔT value.
  - If ΔT is smaller than T_2, no control action is taken.
  - The high speed is 1.27 cm/s, and low speed is 0.127 cm/s.
- **In large scale PWRs, Axial Shape Index (ASI) shall also be controlled:**
  - ASI = P_B-P_T/ P_B+P_T
  - ΔASI is defined as ($ASI_{current}$ - ASI_{target}).
  - Based on ΔASI value the decision and direction of CEA movement is determined



Temperature mismatch control set points



ΔASI control setpoints

Control Logic(2/3)

Mode-K+ control logic:

– ASI control physics

- CEA insertion in the upper half of the core will result in reduction of P_T, then bottom skewed power profile (+ASI).
- CEA withdrawal from the top half will result in increase P_T, so more top skewed power profile compared to initial status.
- CEA insertion in the lower half of the core will result in reduction of P_B, then ASI will decrease.
- Similarly, CEA withdrawal from the bottom half will result in increase P_B, so power profile shift to bottom.

– The order of CEA insertion is (P3→P2 →P1 →R5 →R4 →R3) and the opposite in withdrawal.

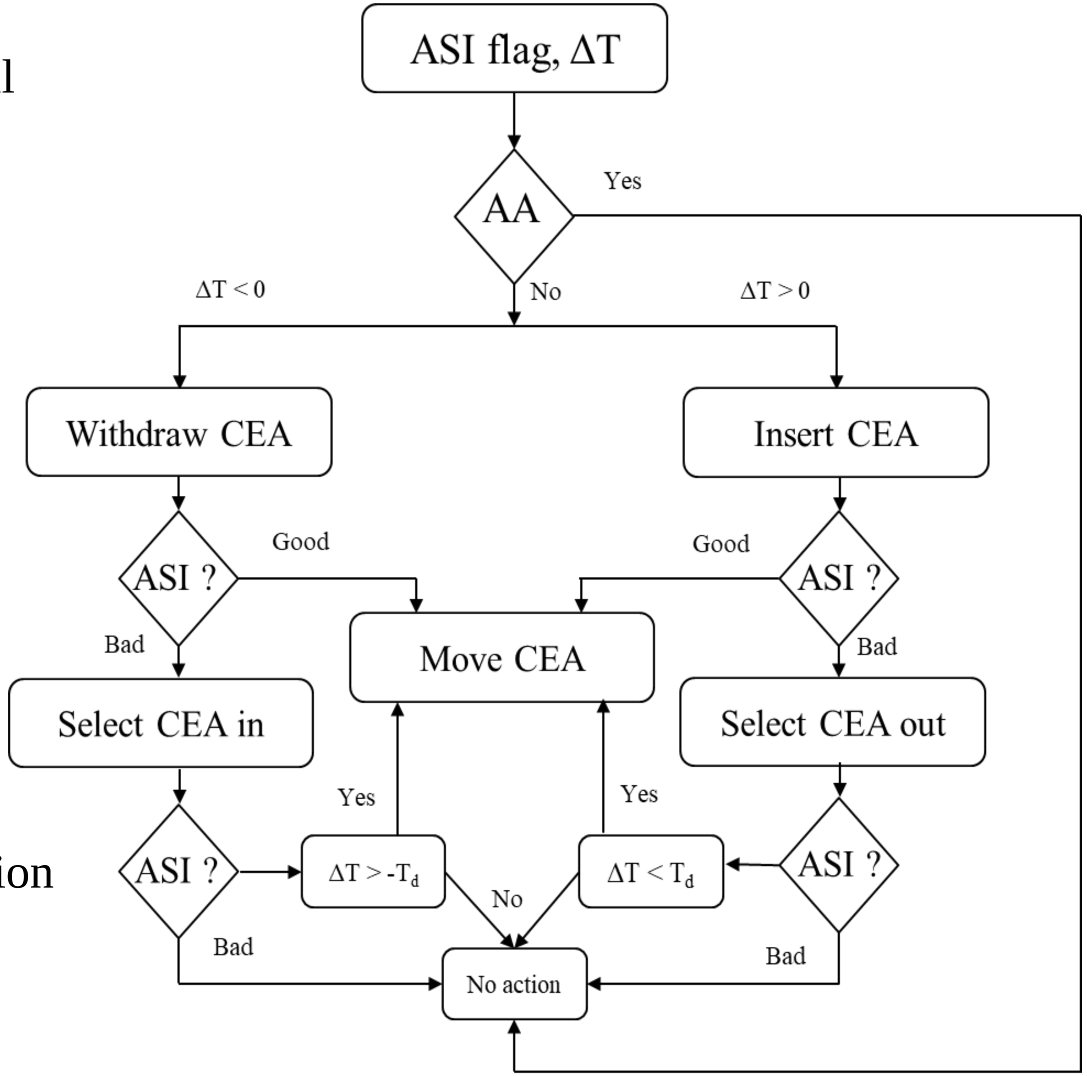
– No CEA can be inserted more than P3.

– 55% overlap between RBs is considered.

Condition			Selected CEA
Stage flag	**CEA direction**	**CEA Position**	
ΔASI+	Insertion	$W_{P3} > B$, $W_{P3} <= H/2$	**P3**
		$W_{P3} = B$,$W_{P2} > B$, $W_{P2} <= H/2$	**P2**
		$W_{P3} = B$,$W_{P2} = B$, $W_{P1} > B$, $W_{P1} <= H/2$	**P1**
		$W_{P3} = B$,$W_{P2} = B$, $W_{P1} = B$, $W_{R5+} > B$, $W_{R5+} <= H/2$	**R5+**
	Withdrawal	$W_{R5} < T$, $W_{R5} >= H/2$	**R5+**
		($W_{R5} = T$ or $W_{R5} <= H/2$), $W_{P1} < T$, $W_{P1} >= H/2$	**P1**
		($W_{R5} = T$ or $W_{R5} <= H/2$), ($W_{P1} = T$ or $W_{p1} <= H/2$), $W_{P2} >= H/2$	**P2**
		($W_{R5} = T$ or $W_{R5} <= H/2$),($W_{P1} = T$ or $W_{p1} <= H/2$), ($W_{P2} = T$ or $W_{p2} <= H/2$),$W_{P3} >= H/2$	**P3**
ΔASI-	Insertion	$W_{P3} > H/2$	**P3**
		$W_{P3} <= H/2$, $W_{P2} > H/2$	**P2**
		$W_{P2} <= H/2$, $W_{P3} <= H/2$, $W_{P1} > H/2$	**P1**
		$W_{P2} <= H/2$, $W_{P3} <= H/2$, $W_{P1} <= H/2$, $W_{R5} > H/2$	**R5+**
	Withdrawal	$W_{R5} > B$, $W_{R5} < H/2$	**R5+**
		($W_{R5} = T$ or $W_{R5} >= H/2$), $W_{P1} < H/2$	**P1**
		($W_{R5} = T$ or $W_{R5} >= H/2$), ($W_{p1} = T$ or $W_{p1} >= H/2$), $W_{P2} < H/2$	**P2**
		($W_{R5} = T$ or $W_{R5} >= H/2$), ($W_{p1} = T$ or $W_{p1} >= H/2$), ($W_{p2} = T$ or $W_{p2} >= H/2$), $W_{P3} < H/2$	**P3**

Mode-K+ control logic:

- If the temperature is within the deadband, ASI control might still be needed.
- $+\Delta T$, indicated CEA insertion , while $-\Delta T$ means withdrawal is needed:
  - This action shall only be taking place if an ASI favorable movement is found, other wise the movement in the other direction will be considered.
  - On one condition, that ΔT is not exceeding pre setpoint T_d, which is smaller than T_2, to prevent negative effects on temperature.
  - If search for ASI-favorable CEA movement in opposite direction fails again, no action is taken.

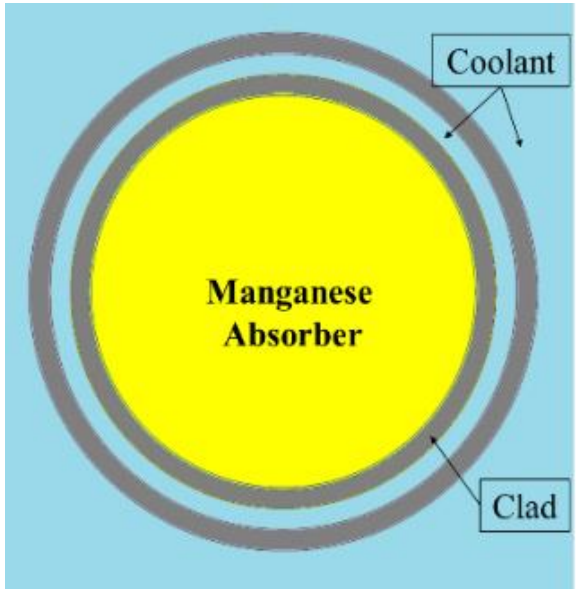


Results

Results(1/8)

Modified Partial Strength Control Element Assembly (PSCEA):

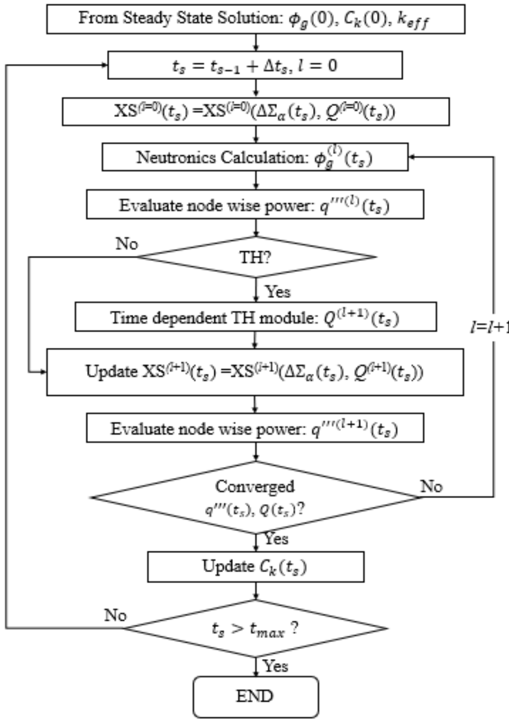
- To enhance the PSCEA worth, a different burnable absorber material is introduced.
  - Manganese is replacing the weak Inconel625 absorber in the original PSECA design.
  - *Replacing the 12 Inconel-PSCEAs with Mn-PSCEA increases the total worth from 194 pcm to 344 pcm.*
  - The main motivation for that is to reduce/eliminate the insertion of the Full-Strength Control Element Assemblies (FSCEA), which would enhance the axial and radial BU distribution due to smaller perturbation of flux.
  - Also, regulating CEA bank insertion limits reservation.
- The same scenario has been considered for the two cases for comparison.
- Inconel cladding layer is considered to prevent the corrosion or interaction with coolant.
- **The simulation were done at BOC fresh core condition.**



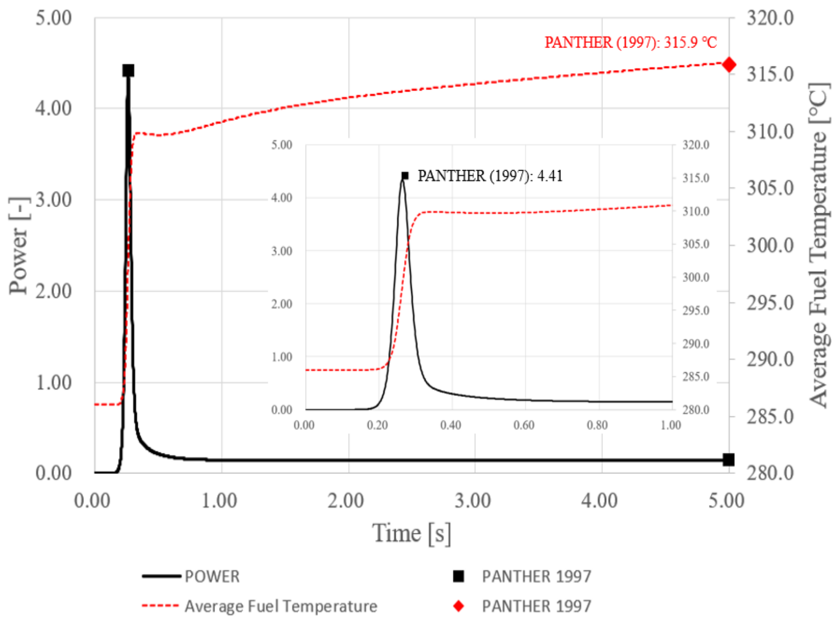
Modified PSCEA

Simulation tool: KANT

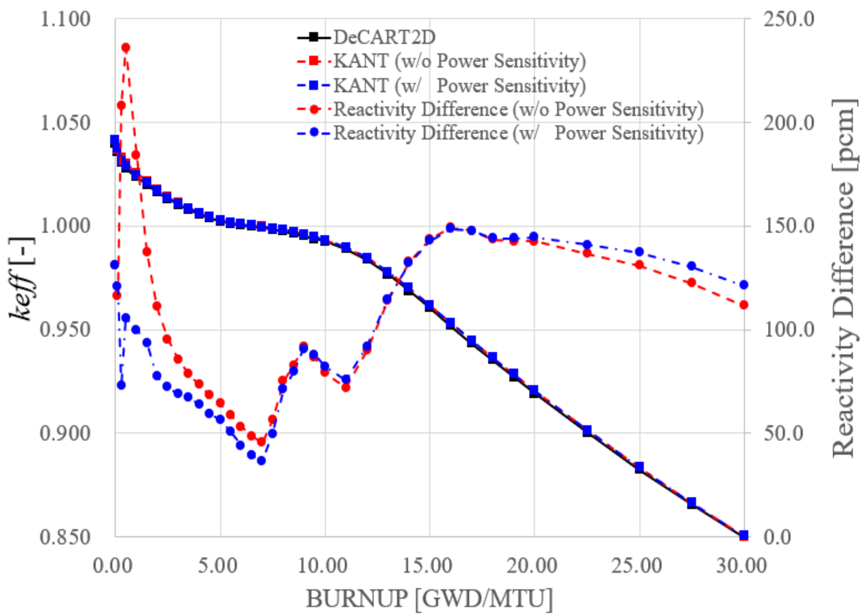
- Multi-physics nodal code developed at KAIST.
  - KANT (KAIST Advanced Nodal Tachygraphy) / V&V performed!
  - Based on NEM-CMFD, supports TH feedback, Soluble boron consideration, Xenon effect, **Load-follow**,…
  - Cross-sections are generated using SERPENT2 MC.



Transient Calculation Flowchart of KANT

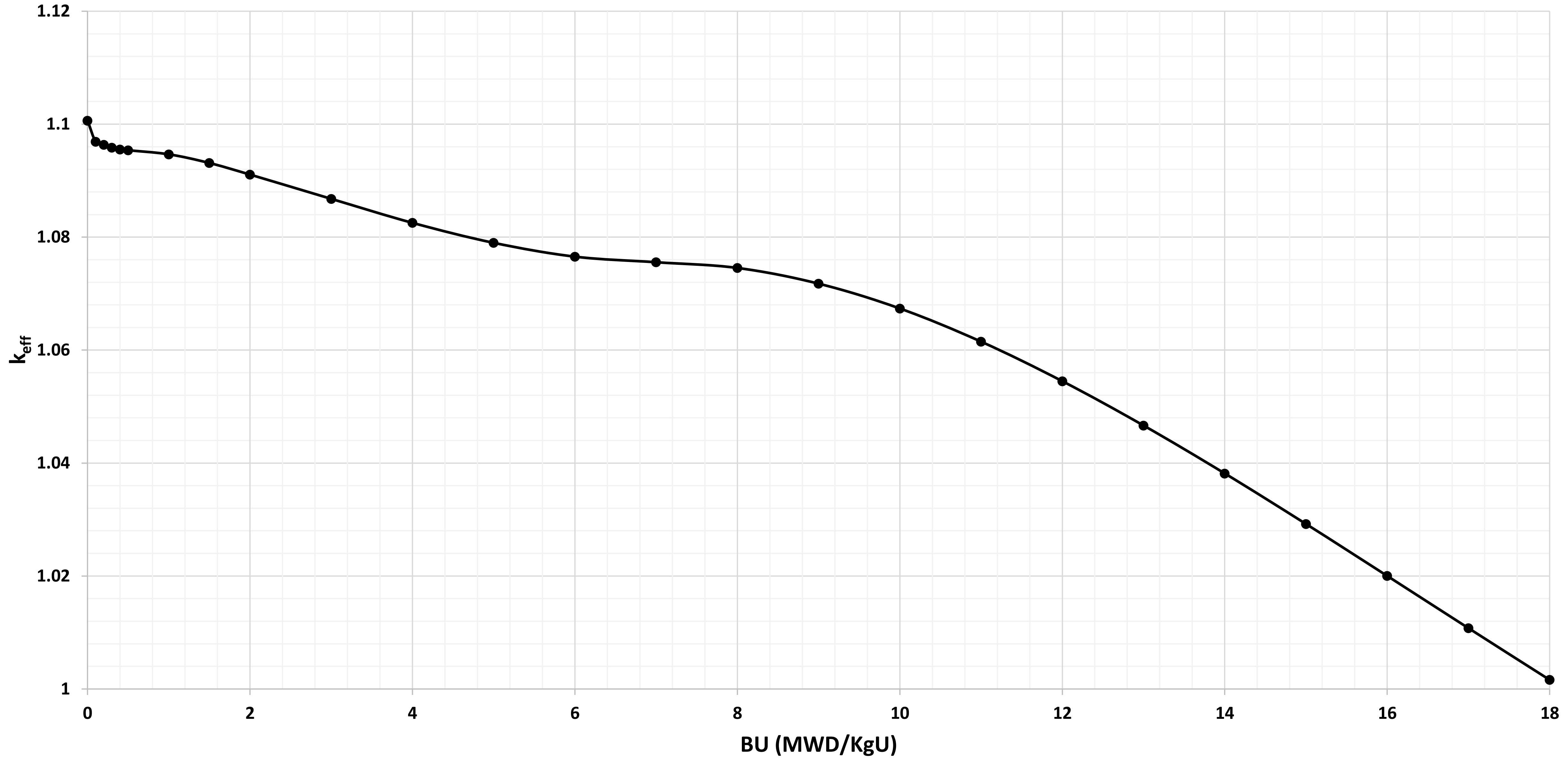


NEACRP Benchmark Result (TH feedback, Transient)

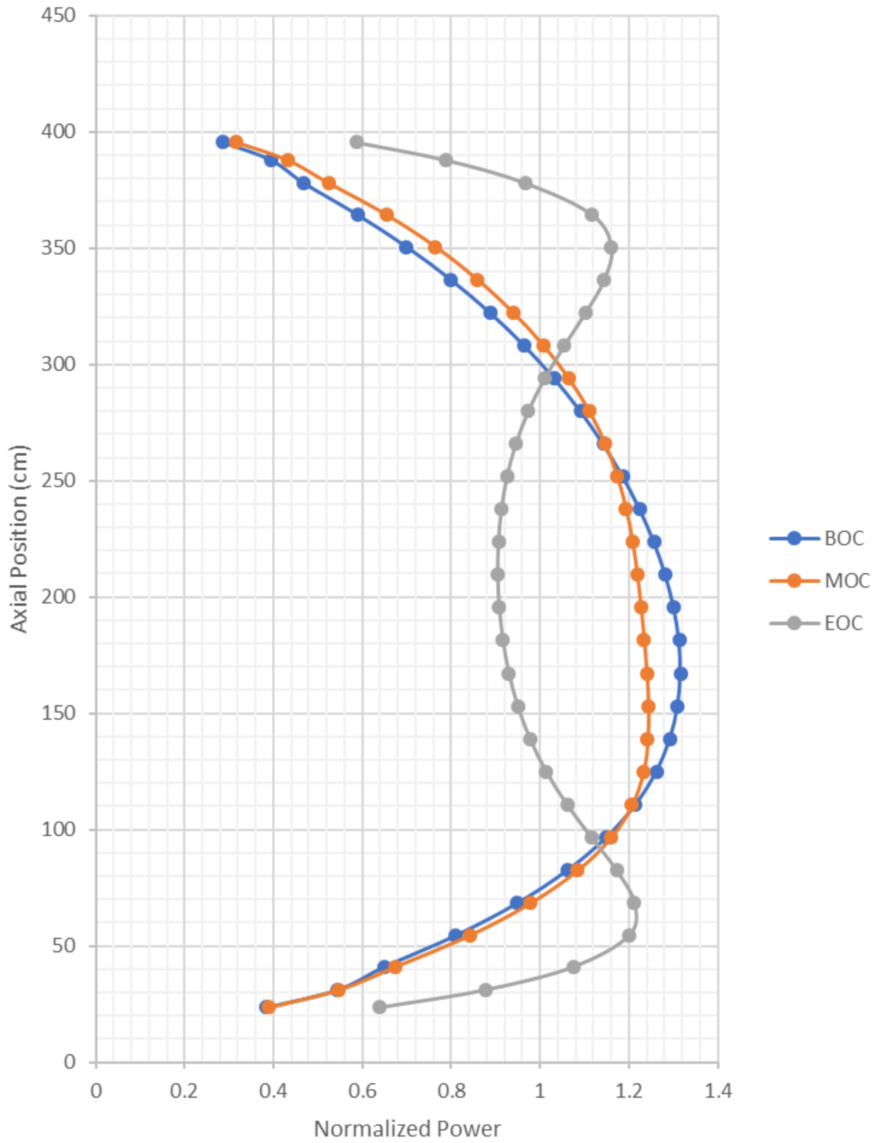


KAIST SMR Benchmark Result (Depletion)

Results(3/8)



Results(4/8)



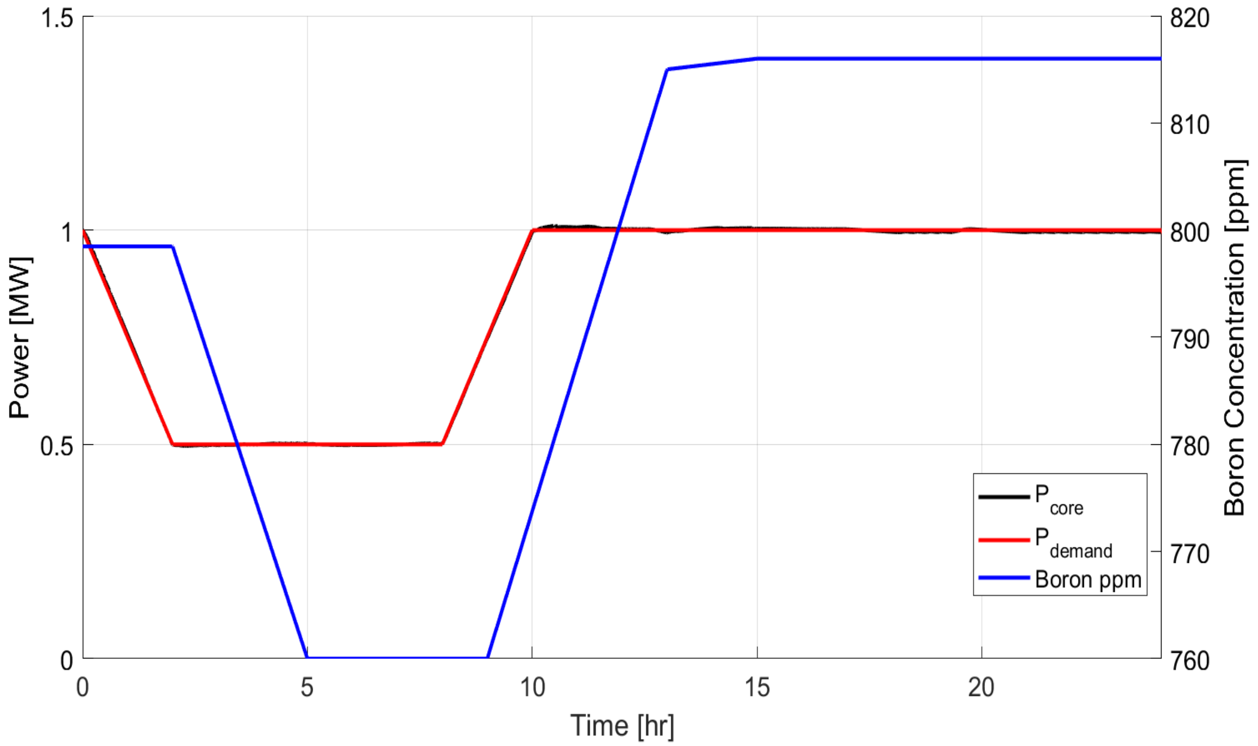
Initial cycle simulated axial power profile.

0.92	0.89	1.06	0.91	1.13	0.97	1.05	1.11	1.04
0.87	0.89	1.21	0.95	1.19	0.96	1.20	1.21	0.85
0.89	0.91	1.21	0.93	1.13	0.92	1.17	1.20	0.82
0.89	0.98	0.89	1.01	0.95	1.15	0.96	1.04	1.08
0.89	1.13	0.94	1.18	0.95	1.20	0.96	1.13	0.87
0.91	1.15	0.94	1.16	0.93	1.14	0.95	1.12	0.85
1.06	0.89	1.09	0.91	1.11	0.95	1.12	1.07	0.96
1.21	0.94	1.25	0.96	1.24	0.95	1.21	1.08	0.77
1.21	0.94	1.24	0.94	1.21	0.94	1.21	1.09	0.76
0.91	1.01	0.91	1.02	0.93	1.04	0.95	0.99	0.76
0.95	1.18	0.96	1.19	0.95	1.16	0.90	0.95	0.62
0.93	1.16	0.94	1.17	0.95	1.16	0.92	0.98	0.64
1.13	0.95	1.11	0.93	1.13	0.94	1.11	1.09	
1.19	0.95	1.24	0.95	1.23	0.92	1.07	0.87	
1.13	0.93	1.21	0.95	1.24	0.94	1.10	0.88	
0.97	1.15	0.95	1.04	0.94	1.01	1.07	0.80	
0.96	1.20	0.95	1.16	0.92	1.09	1.00	0.63	
0.92	1.14	0.94	1.16	0.94	1.15	1.07	0.66	
1.05	0.96	1.12	0.95	1.11	1.07	0.83		
1.20	0.96	1.21	0.90	1.07	1.00	0.70		
1.17	0.95	1.21	0.92	1.10	1.07	0.74		
1.11	1.04	1.07	0.99	1.09	0.80		BOC	
1.21	1.13	1.08	0.95	0.87	0.63		MOC	
1.20	1.12	1.09	0.98	0.88	0.66		EOC	
1.04	1.08	0.96	0.76					
0.85	0.87	0.77	0.62					
0.82	0.85	0.76	0.64					

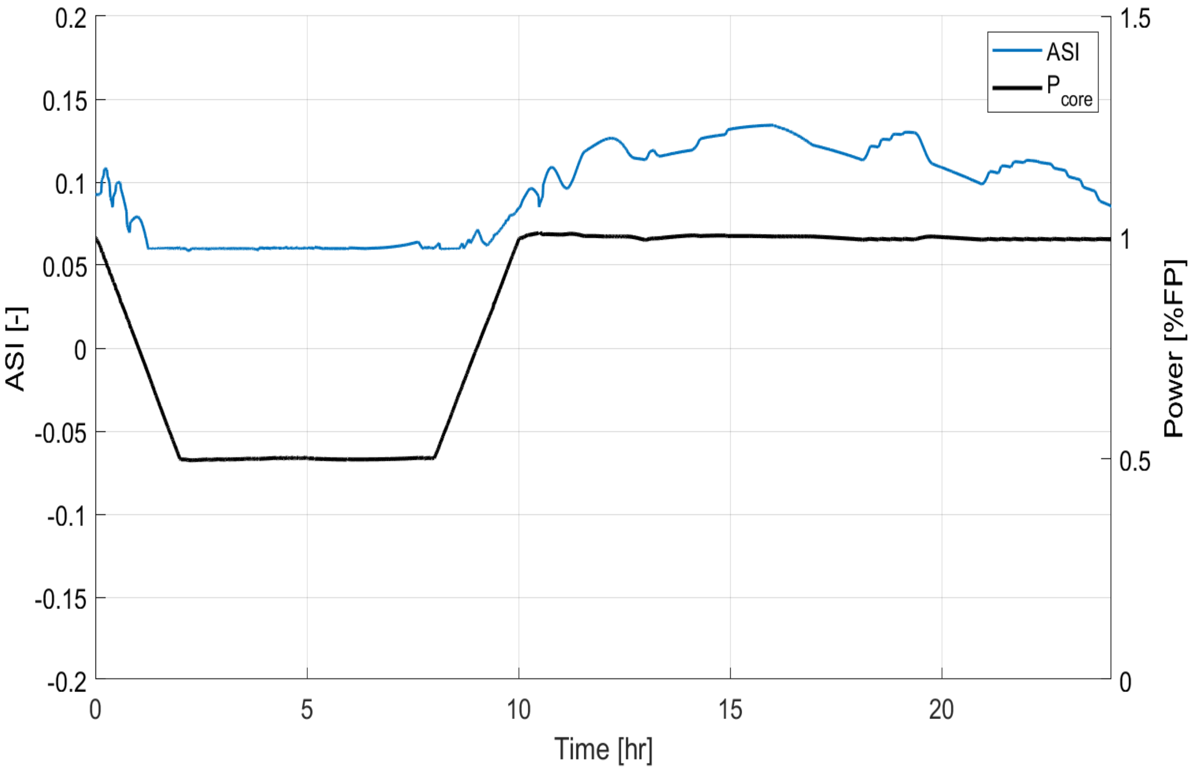
Initial cycle simulated radial power profile.

- ✓ Unrodded core power profile.
- ✓ EOC is 90% of cycle length.

Inconel PSCEA simulation scenario (100-50-100):

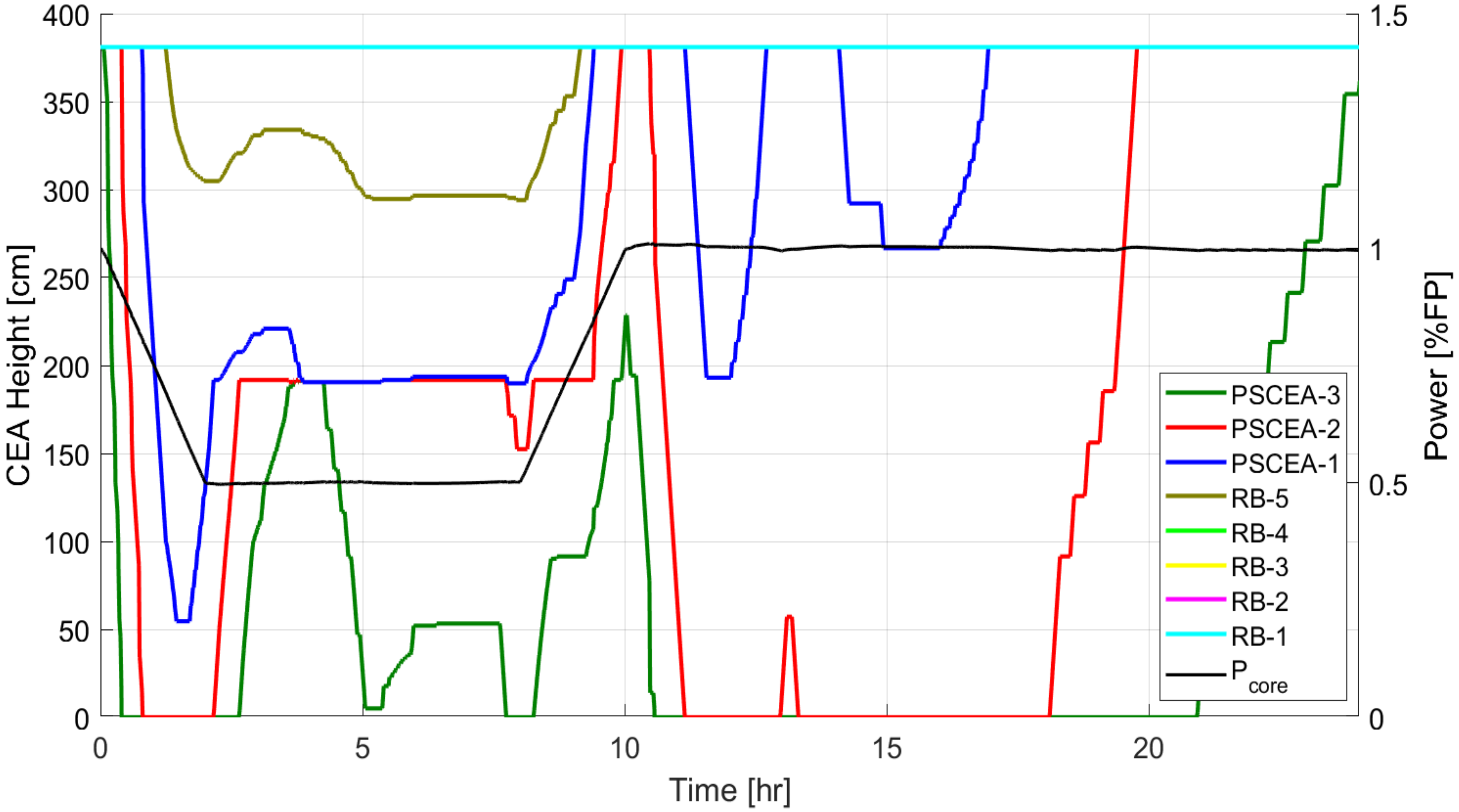


The target and core power along with boron scenario.



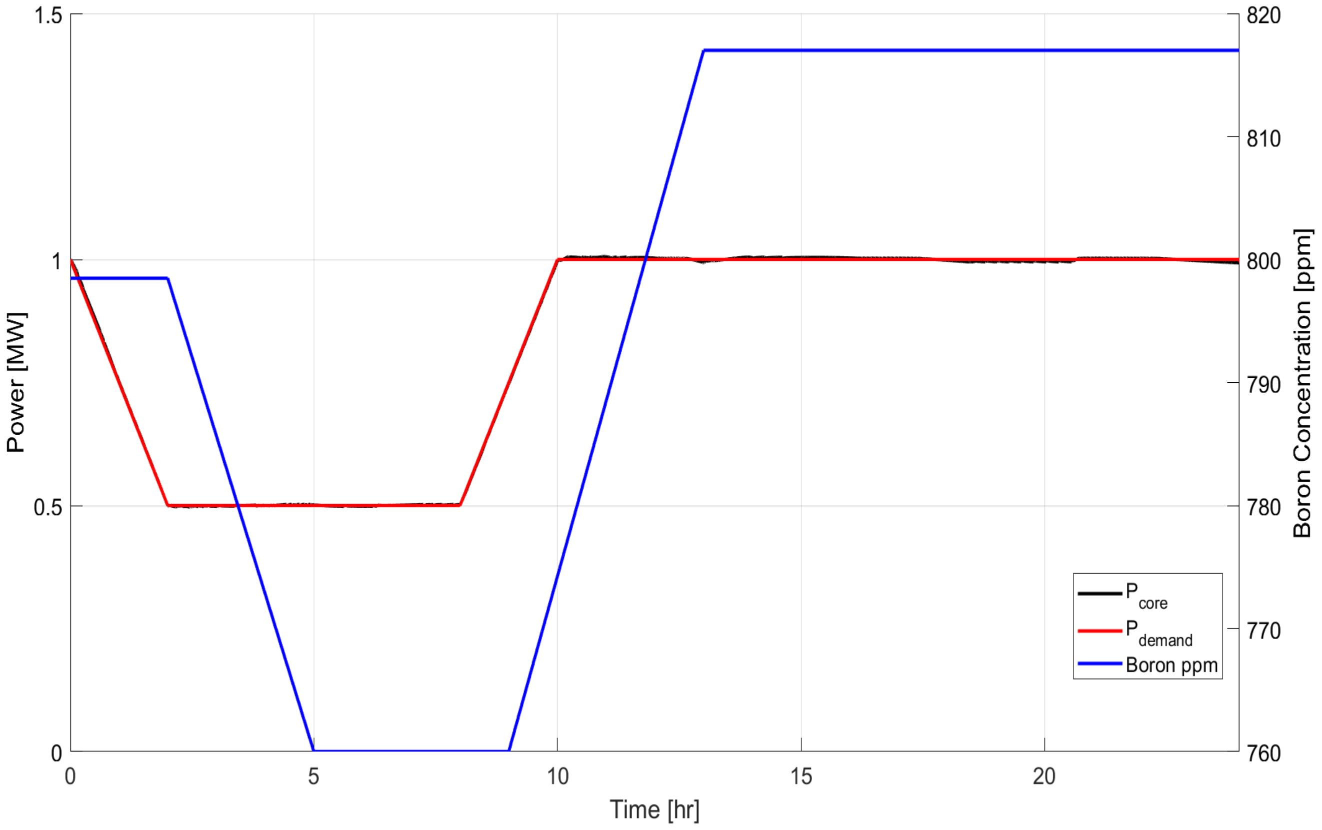
Core Power Vs. the ASI value during 24-hr LFO scenario.

Inconel PSCEA simulation scenario (100-50-100):

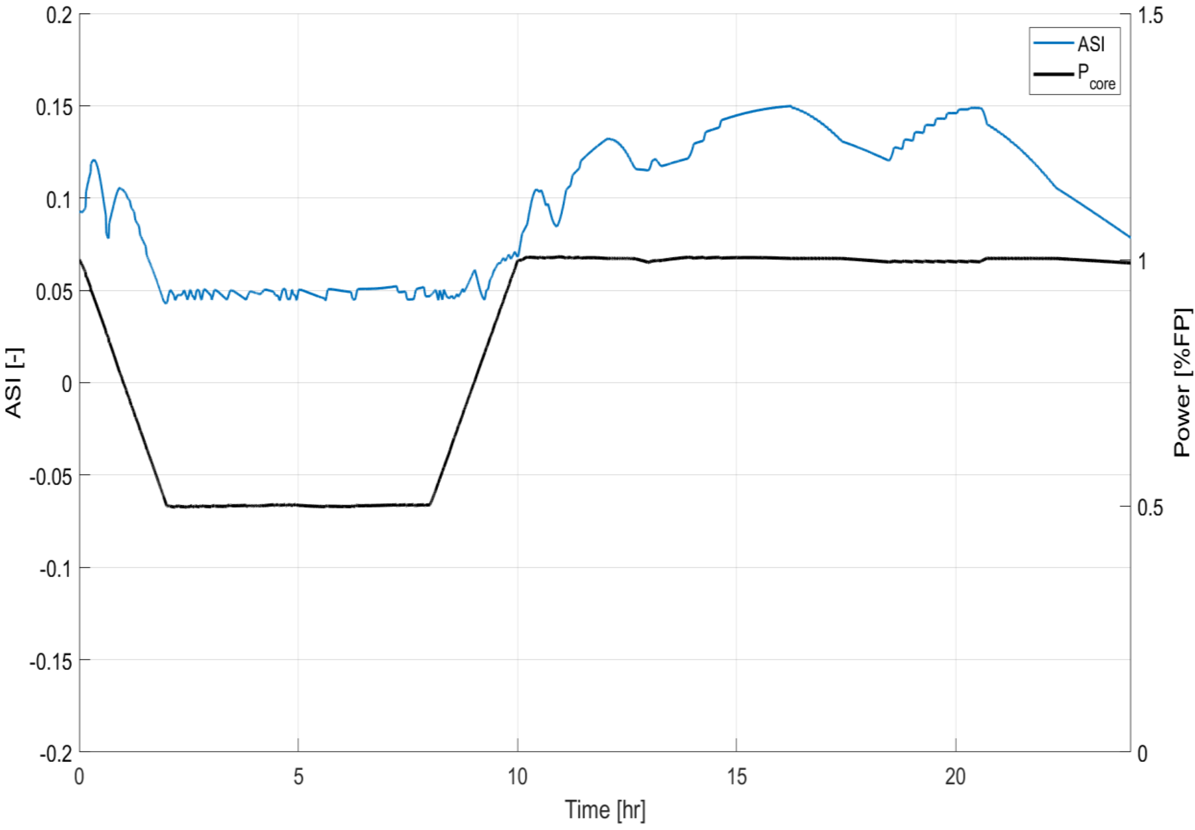


CEA insertion during the LFO simulation

Mn-PSCEA simulation scenario (100-50-100):



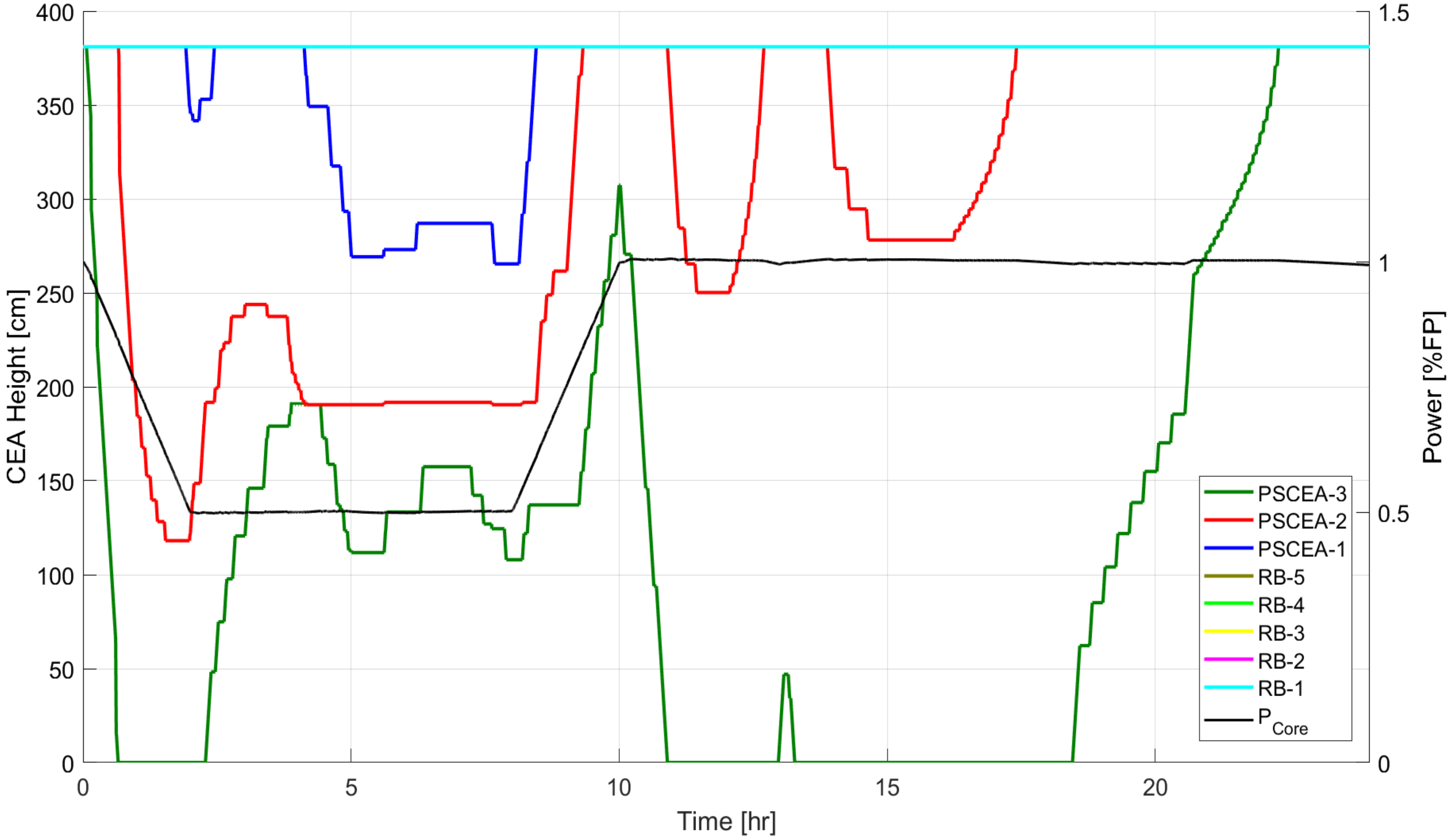
The target and core power along with boron scenario.



Core Power Vs. the ASI value during 24-hr LFO scenario.

Results(8/8)

Mn-PSCEA simulation scenario (100-50-100):



CEA insertion during the LFO simulation

Conclusion & Future Work

Conclusion & Future Work

- **Conclusion:**

- Load-Follow Operation (LFO) was performed to APR1400 initial cycle, Mode-K+ control logic was also utilized in this simulation.
- Using the time-dependent deterministic code KANT, the analysis shows that ASI and temperature were successfully controlled during the 24-hour Beginning of Cycle (BOC) condition.

- **Future Work:**

- Steam generator coupling will be considered for a more realistic simulation of the inlet temperature change with time.
- The simulation at the EOC will be done to evaluate the effect of PSCEA absorber replacement on LFO performance.

References

[1] OECD, "Technical and Economic Aspects of Load Following with Nuclear Power Plants", Nuclear Development, June 2011.

[2] Yonghee Kim, MoonGhu Park, "Evaluation of Load Follow Performance of Korean Next Generation Reactor (KNGR)," PHYSOR, 2000.

[3] "APR1400 Design Control Document Tier 2", APR1400-K-X-FS-14002-NP, REVISION 0, DECEMBER 2014.


THANK YOU !