Multi-Physics Simulation For Load Follow Operation

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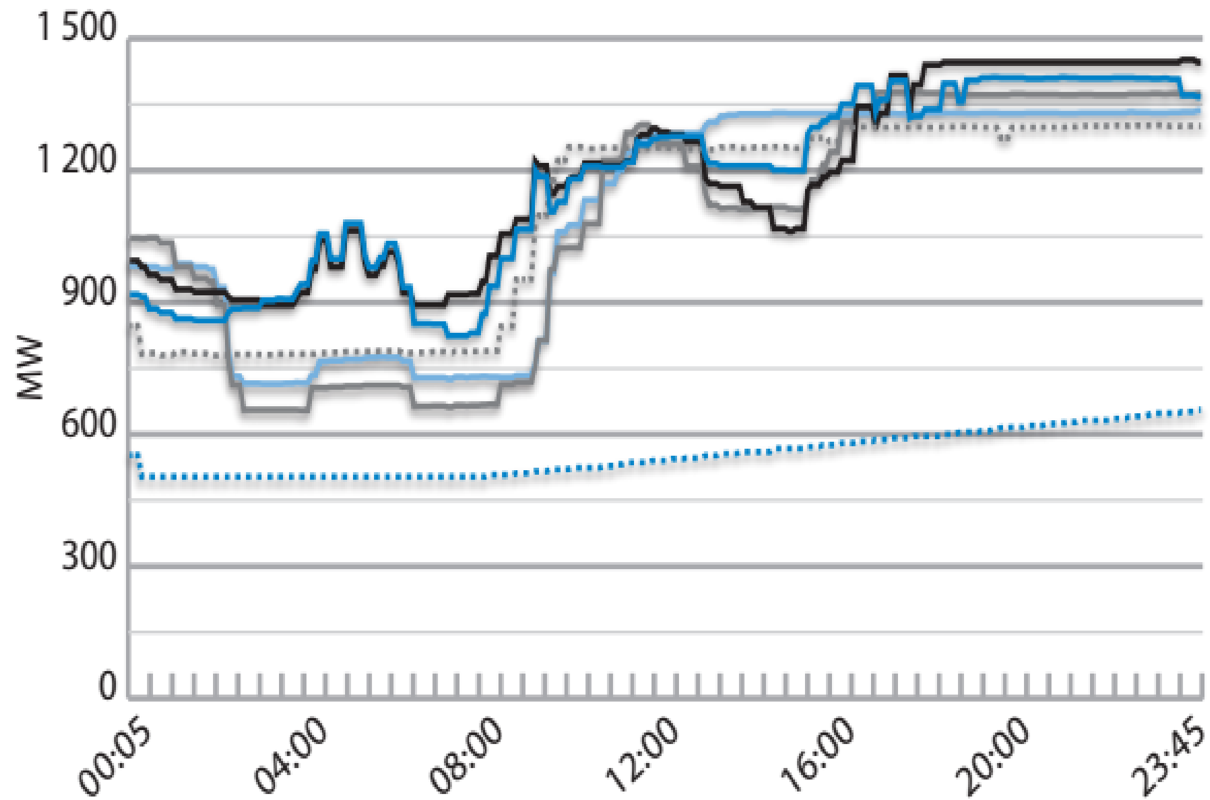
Introduction

- Recently, utilities have been considering LFO for a number of reasons:
  - to improve the maneuverability of their NPPs for technology export,
  - to balance intermittent energy generation as the government expands the deployment of large scale renewable power plants, and
  - to accommodate changes in electricity market.

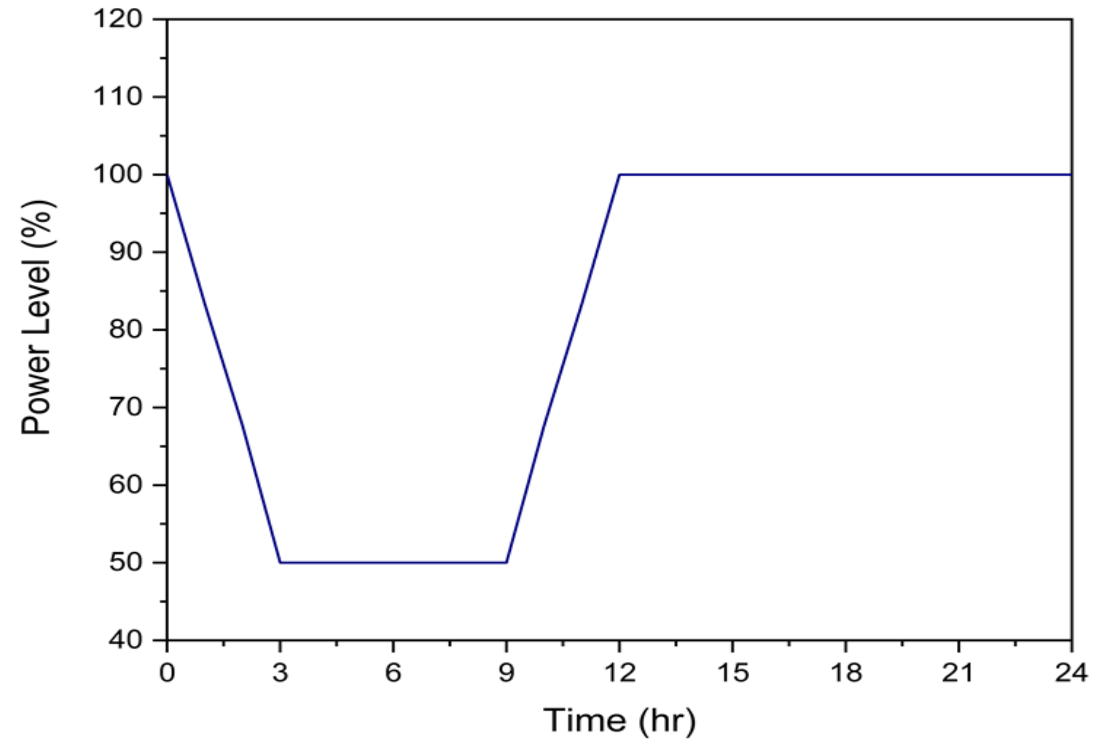


A. Lokhov, "Technical and economic aspect of load following with nuclear power plants", Nuclear Energy Agency, OECD, June (2011)

Global Development Status of LFO Schemes

Country	Load Follow Mode	Commercial Experience
USA	ABB/CE	None
USA	MODE-A	Some
USA	MSHIM	None
France	MODE-G	In Use
France	MODE-X	Some
Germany	KWU	Some
KOREA	MODE-K	None

Korean MODE-K



S. Y. Oh, J. H Chang, J. K. Park, Mode K – A Core Control Logic for Enhanced Load Follow Operations of A Pressurized Water Reactor, Nuclear Technology, May (2001)

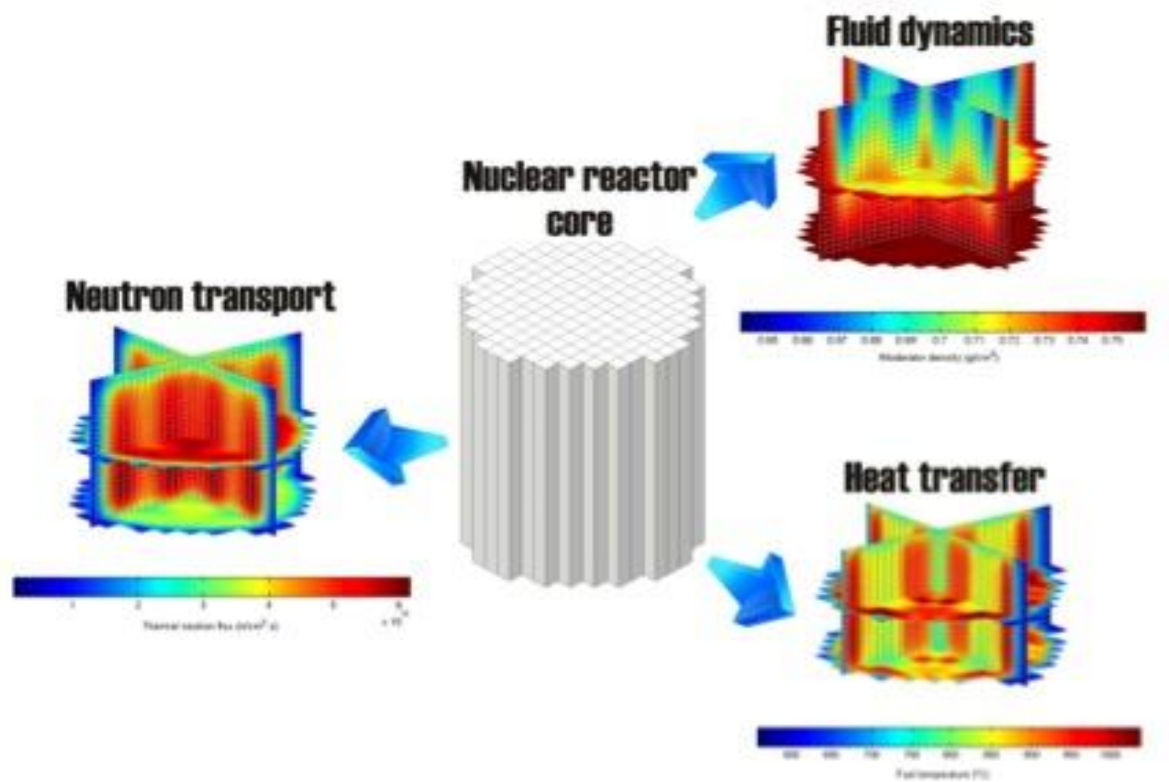
Literature Review

1. J. Choi, Soo-Youl Oh, IN-Ho Song, Yung-Joon Hah, Jung-Eui Kuh and Un-Chul Lee, Advanced Load Follow Operation Mode for Korean Standard Nuclear Power Plants, NET (1992).
2. M. Park, J. Choe, D. Lee, E. Lee, "Application of RAST-K to Simulation of OPR1000 Daily Load Follow Operation", KNS Autumn Meeting, Pyeongchang, Korea, October, (2014).
3. M. Park, J. Choe, D. Lee, E. Lee , Verification of RAST-K Capability for Simulation of OPR1000 Daily Load Follow Operation by Mode K, KNS Autumn Meeting, Pyeongchang, Korea, October, (2014).
4. F. Zhao, S. Wua, P. Wanga, H. Songa, X. Weia, S. Revankarb, "Modeling and load follow simulation of CPR1000 Nuclear Power Plant implementing Mechanical Shim control strategy", NED (2019).
5. M. Muniglia, et al., Design of a Load Following Management for a PWR Reactor Using an Optimization Method. M&C 2017, Jeju, South Korea.
6. M. Muniglia, et al., A Multi-Physics PWR Model for the Load Following, ICAPP, 2016, San Francisco, United States.

Multi-Physics Simulation

- To evaluate the operational feasibility for load follow operation, it is necessary to use high-fidelity simulations to determine the detailed response of the nuclear power plant.

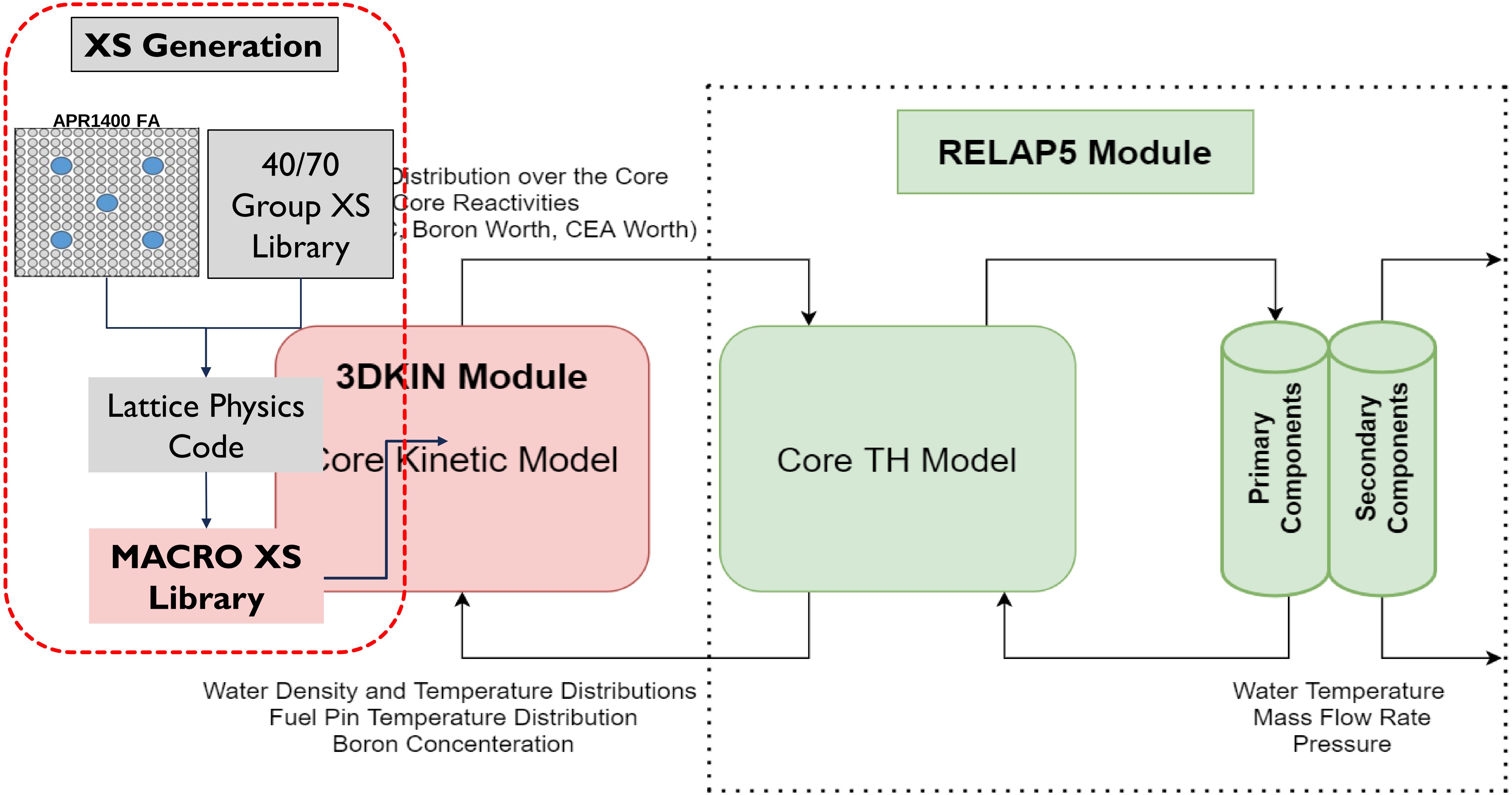
- Best Estimate TH System codes can provide such predictions for plant response under LFO if coupled to 3D nodal kinetics solvers.



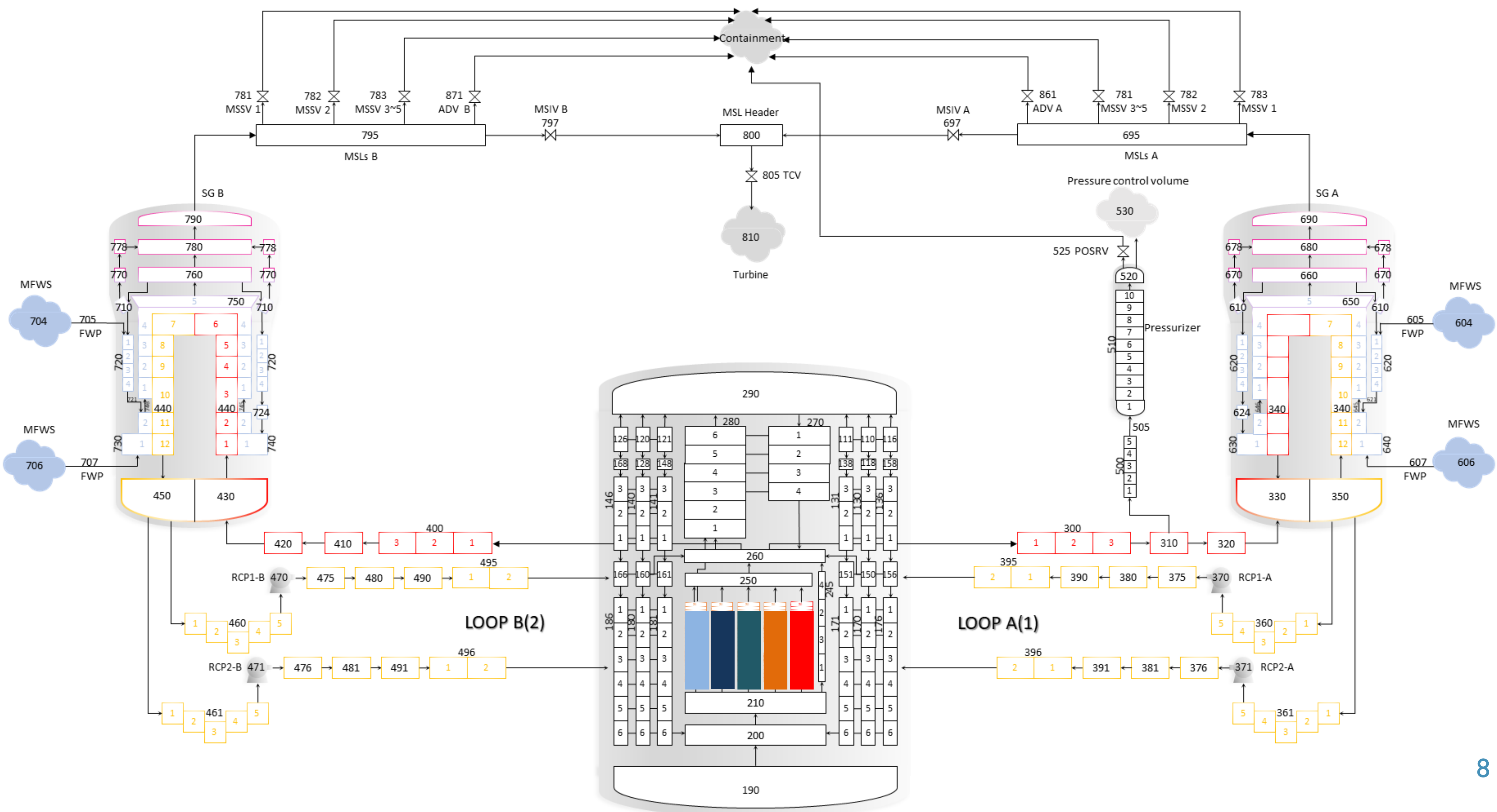
RELAP5/SCDAPSIM/MOD3.4/3DKIN

RELAP/SCDAPSIM/MOD3.x User Reference Manual, Volume I: "Advanced Fluid Systems Thermal Hydraulics Analysis", ISS, (2019)
NESTLE V5.2.1; "Few-Group Neutron Diffusion Equation Solver Utilizing the Nodal Expansion Method for Eigenvalue, Adjoint, Fixed-Source Steady-State, and Transient Problems"; NCSU; (2003).

RELAP5/3DKIN Coupled Simulation

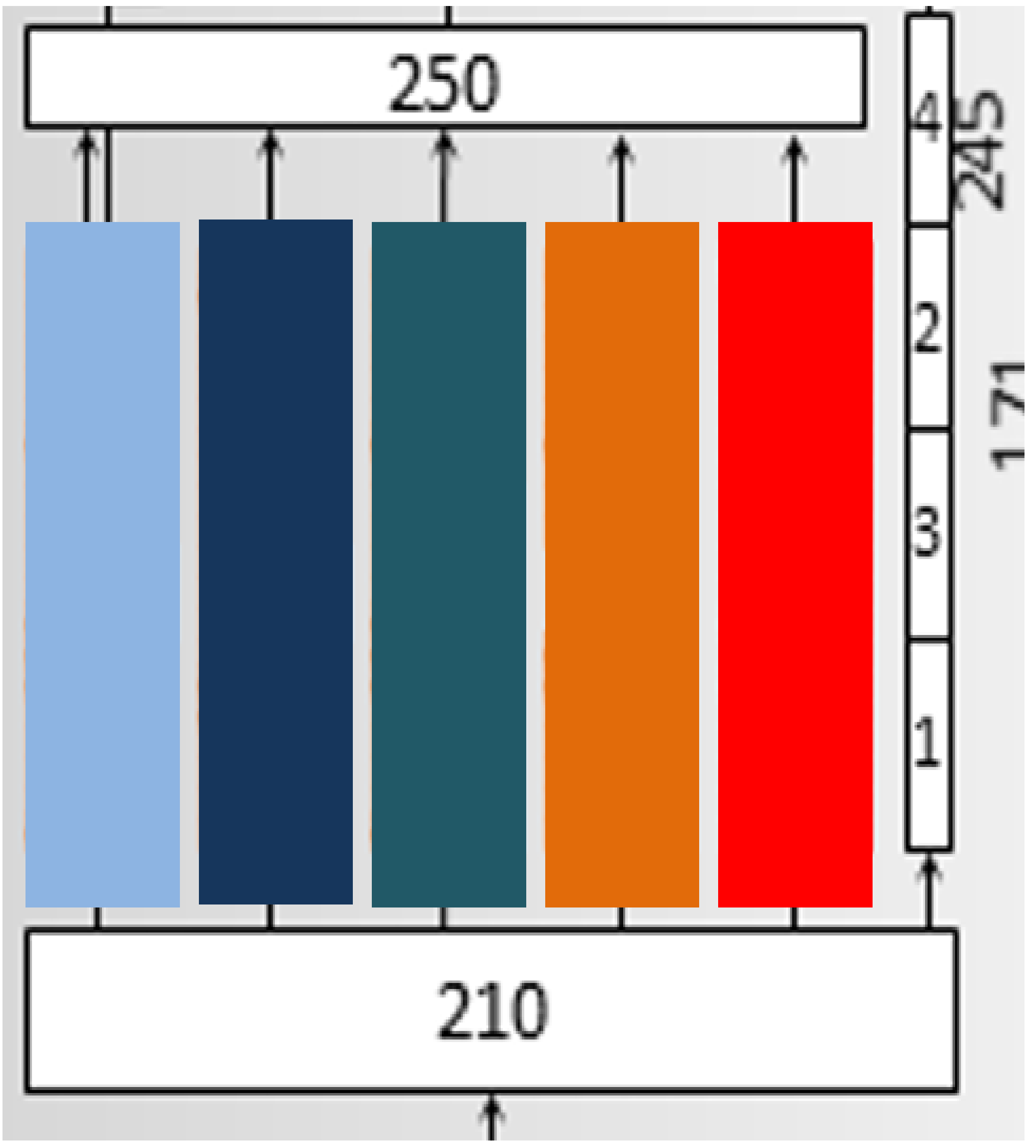


APR1400 RELAP5 Model

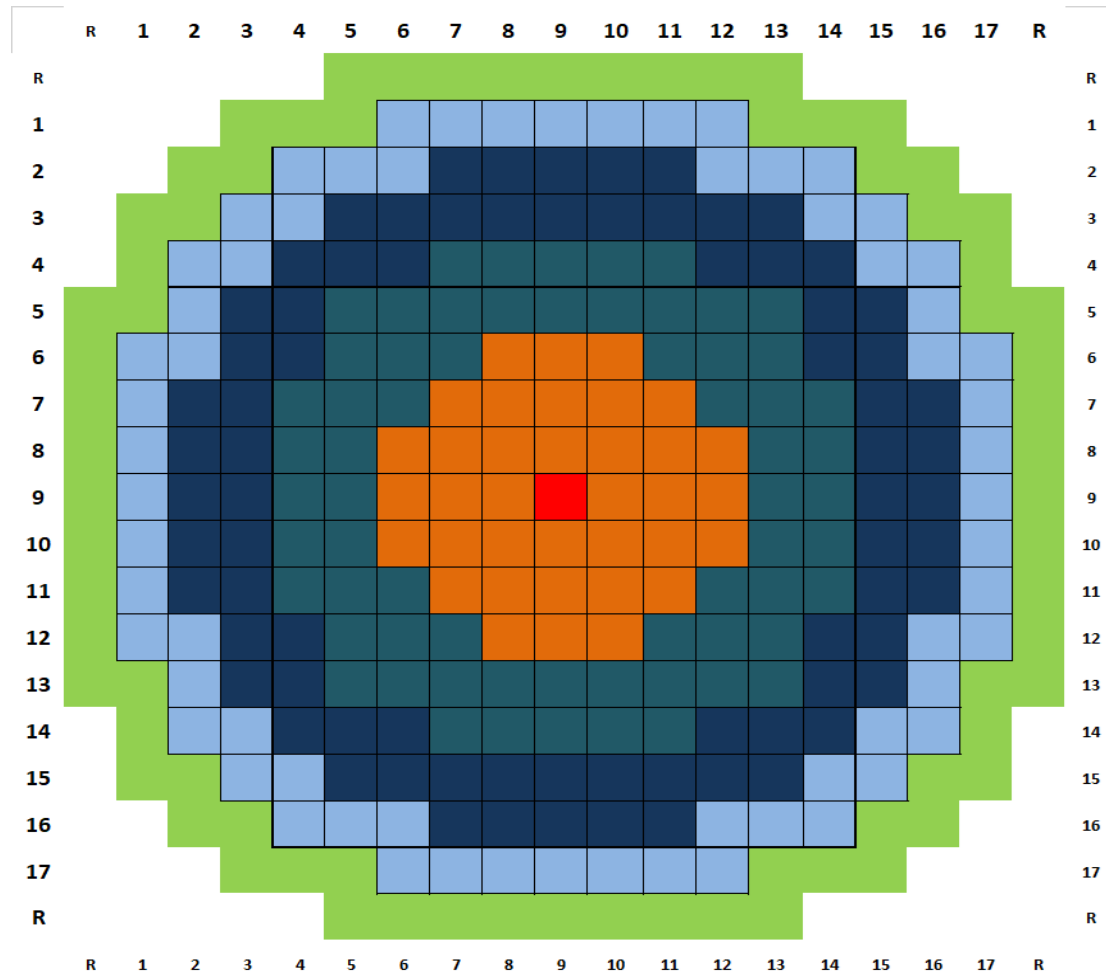


APR1400 RELAP5 Core Model

Core Side View



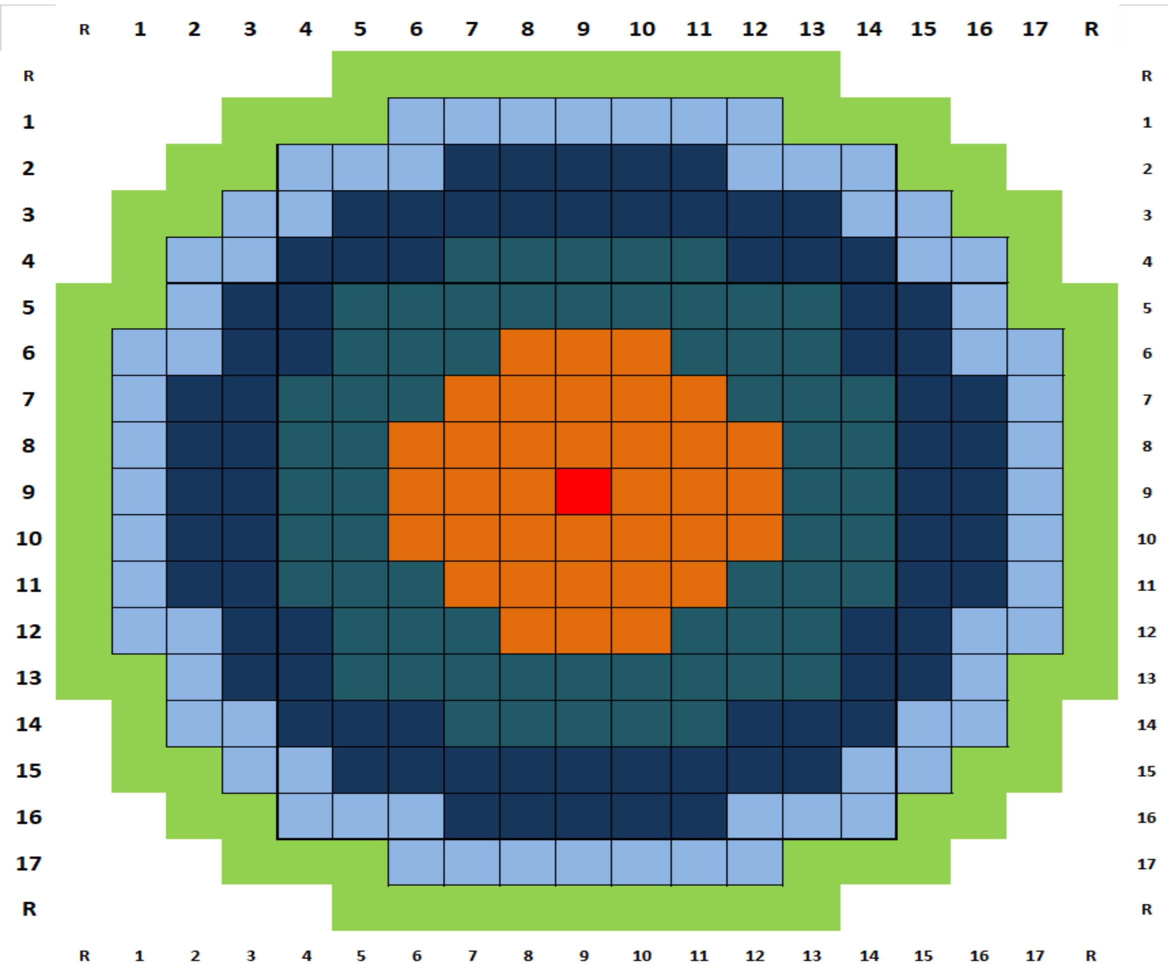
Core Top View



Chan ID		# FAs	64
Chan ID		# FAs	64
Chan ID		# FAs	1

Chan ID		# FAs	76
Chan ID		# FAs	36
Chan ID		**Water Reflector**	

APR1400 3DKIN Core Model



Chan ID		# FAs	64
Chan ID		# FAs	64
Chan ID		# FAs	1

Chan ID		# FAs	76
Chan ID		# FAs	36
Chan ID		**Water Reflector**	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1						0	S	0	R3	0	S	0						1
2				0	0	SDA	0	SDB	0	SDB	0	SDA	0	0				2
3			R4	0	R2	0	PS	0	R5	0	PS	0	R2	0	R4			3
4		0	0	SDB	0	SDB	0	R1	0	R1	0	SDB	0	SDB	0	0		4
5		0	R2	0	R4	0	0	0	R3	0	0	0	R4	0	R2	0		5
6	0	SDA	0	SDB	0	PS	0	SDA	0	SDA	0	PS	0	SDB	0	SDA	0	6
7	S	0	PS	0	0	0	R3	0	0	0	R3	0	0	0	PS	0	S	7
8	0	SDB	0	R1	0	SDA	0	R2	0	R2	0	SDA	0	R1	0	SDB	0	8
9	R3	0	R5	0	R3	0	0	0	R5	0	0	0	R3	0	R5	0	R3	9
10	0	SDB	0	R1	0	SDA	0	R2	0	R2	0	SDA	0	R1	0	SDB	0	10
11	S	0	PS	0	0	0	R3	0	0	0	R3	0	0	0	PS	0	S	11
12	0	SDA	0	SDB	0	PS	0	SDA	0	SDA	0	PS	0	SDB	0	SDA	0	12
13		0	R2	0	R4	0	0	0	R3	0	0	0	R4	0	R2	0		13
14		0	0	SDB	0	SDB	0	R1	0	R1	0	SDB	0	SDB	0	0		14
15			R4	0	R2	0	PS	0	R5	0	PS	0	R2	0	R4			15
16				0	0	SDA	0	SDB	0	SDB	0	SDA	0	0				16
17						0	S	0	R3	0	S	0						17
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	

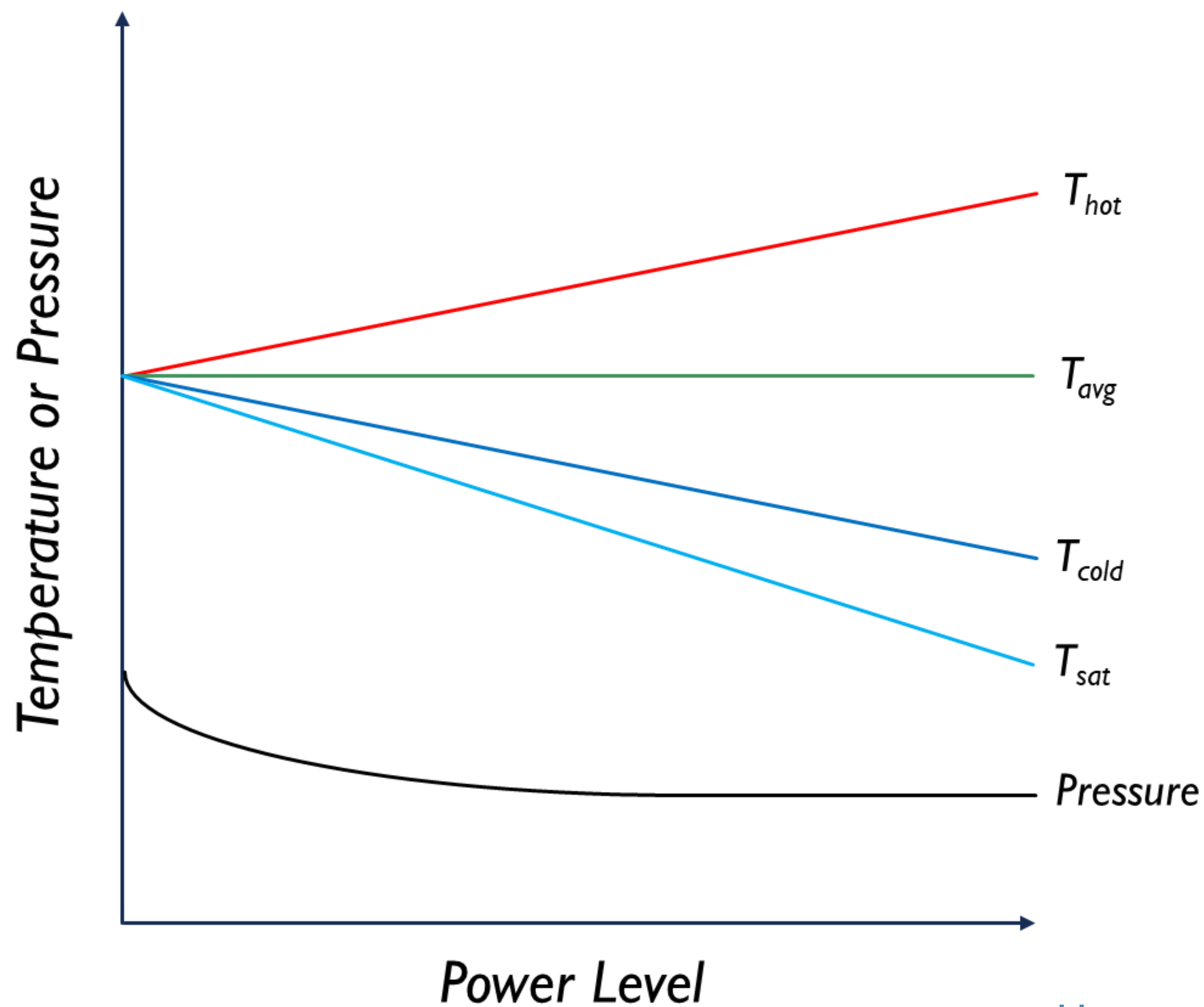
R5	Regulating CEA #5	PS	Part Strength CEA
R4	Regulating CEA #4	SDA	Shutdown CEA #A
R3	Regulating CEA #3	SDB	Shutdown CEA #B
R2	Regulating CEA #2	S	Spare CEA Position
R1	Regulating CEA #1	0	No CEA

KEPCO & KHNP., "APR1400 Design Control Document Tier 2", APR1400-K-X-FS-14002-NP, Revision 3, August (2018).

Load Follow Implementation

- The coolant average temperature is kept constant while the hot leg temperature increases and the cold leg temperature decreases as the power increases.
- **The main advantage** is that the moderator temperature coefficient (MTC) does not have a large impact on reactivity.
- **The main disadvantage** is that there are large variations in steam pressure and temperature, assuming the steam valve position is fixed.

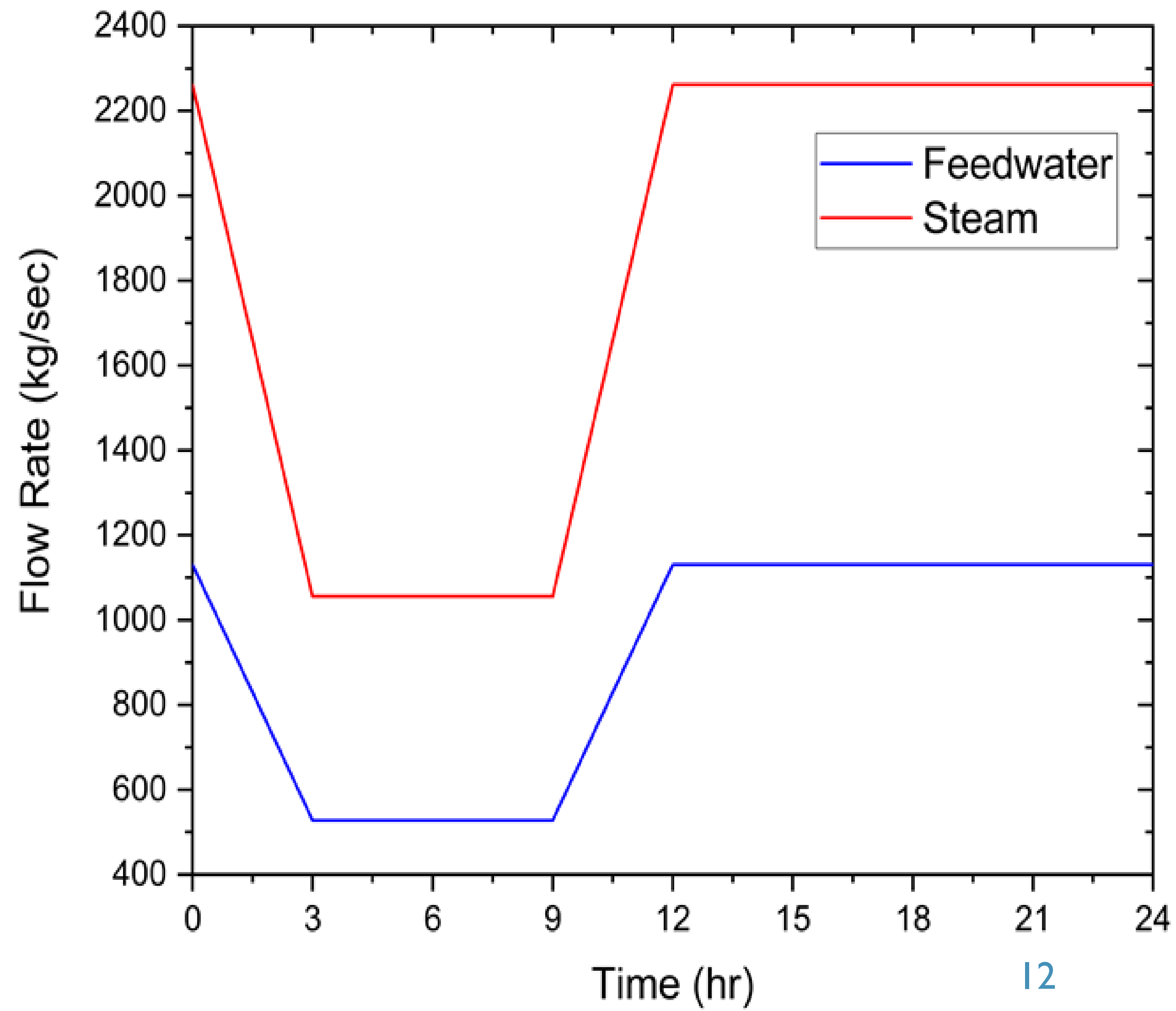
Constant T_{avg} Mode



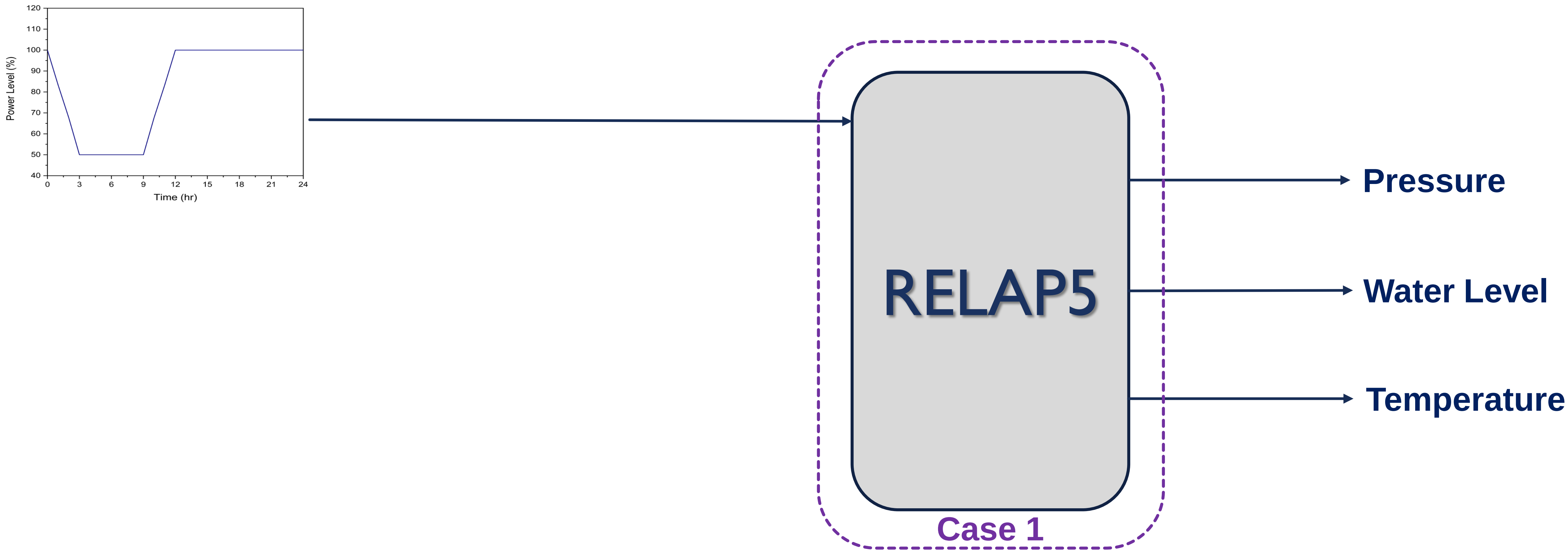
Load Follow Implementation

- The cold leg temperature is kept constant while both the hot leg and coolant average temperatures increase as the power increases.
- **The main advantage** of this mode is that the SG pressure does not change with power change.
- This mode is intended to provide a balance between the needs of the primary and secondary systems.

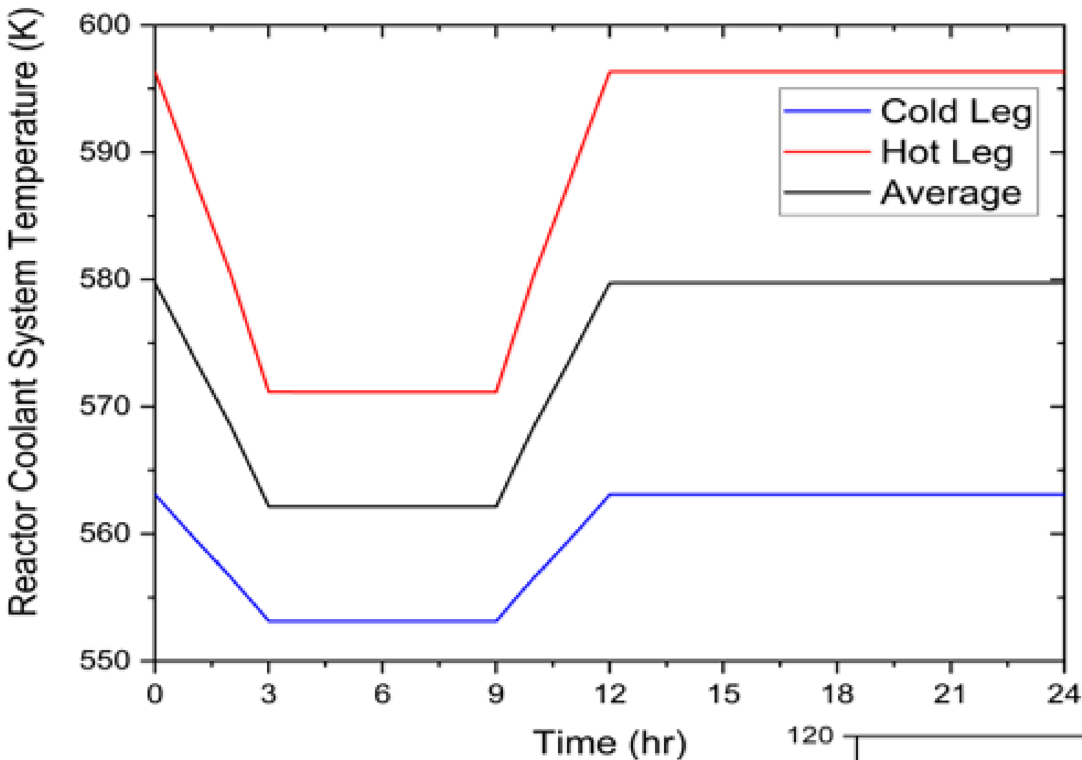
Sliding T_{avg} Mode

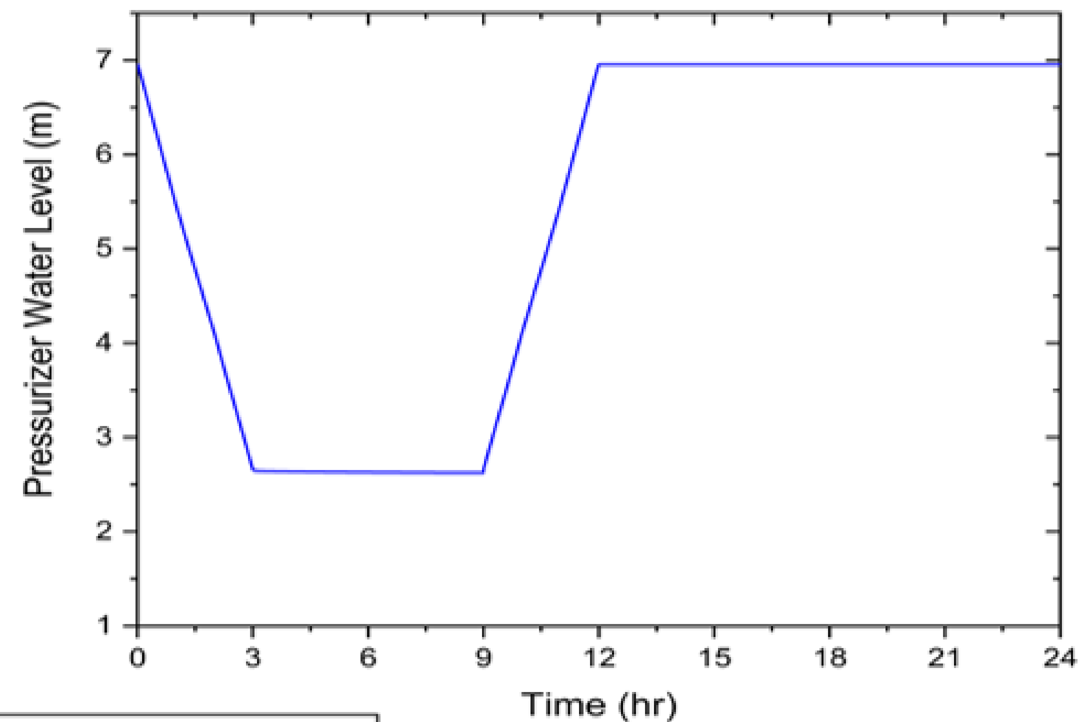


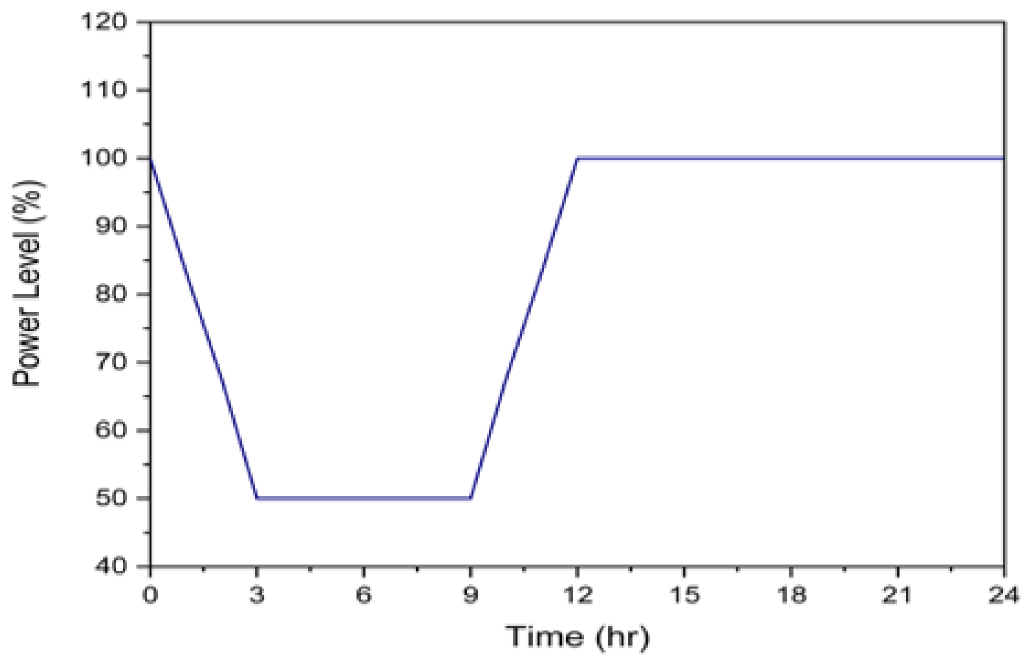
Case Studies



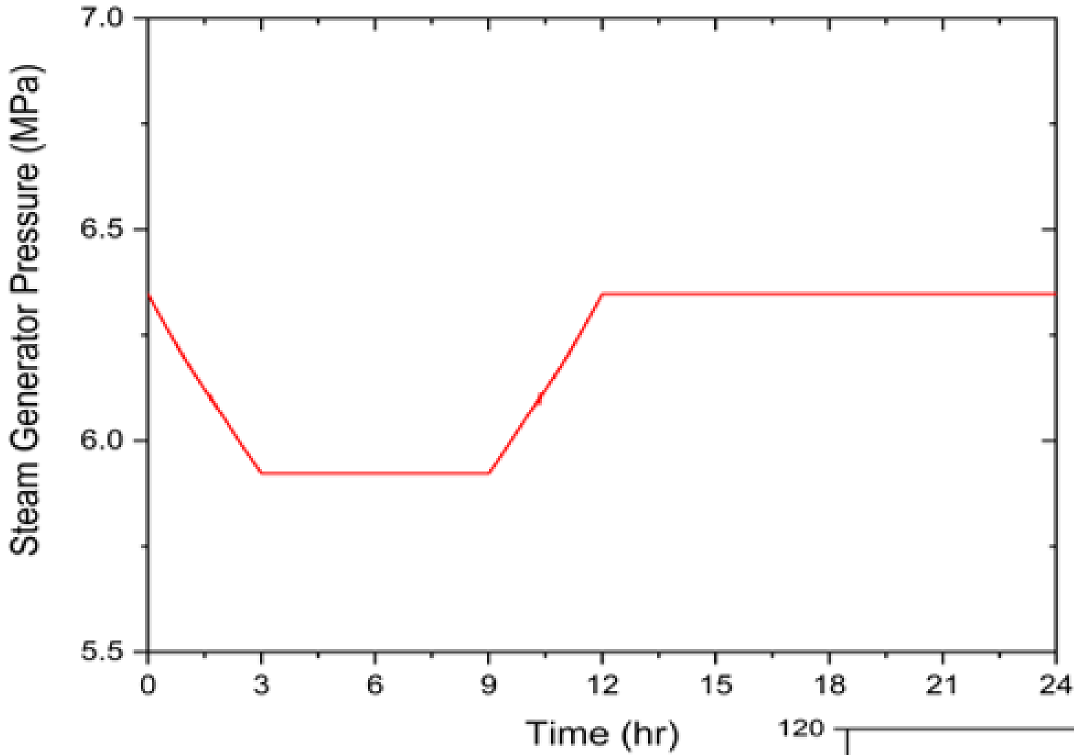
Case 1: Primary System Results

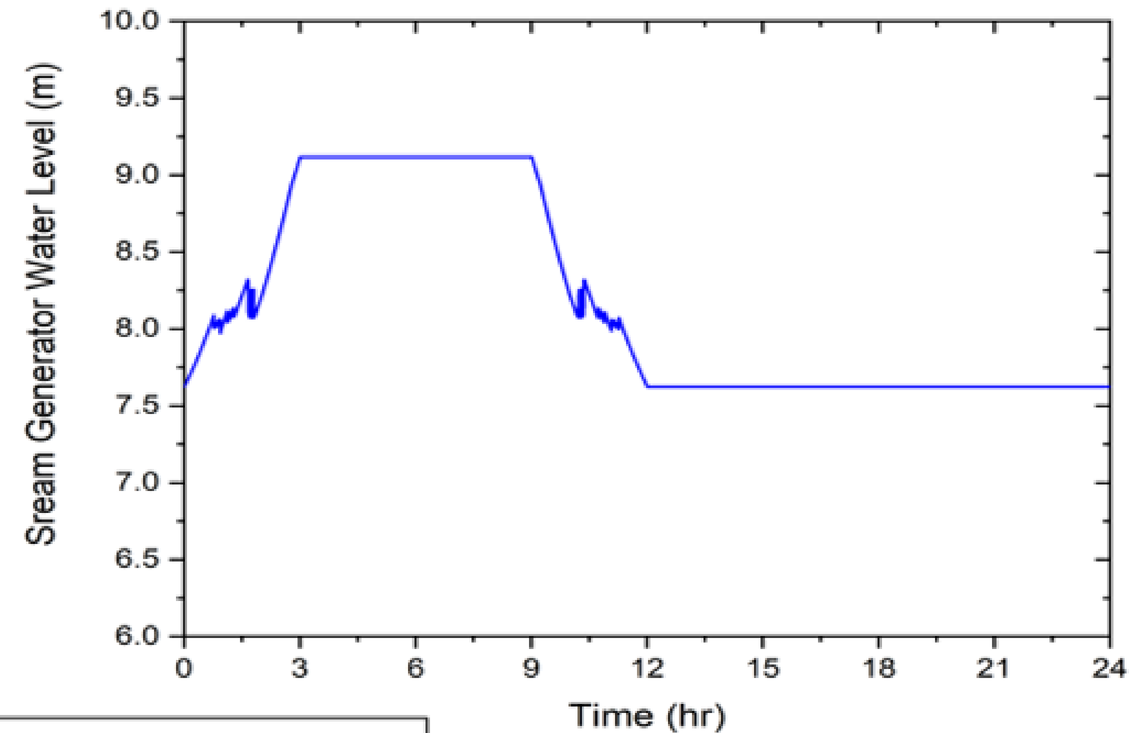


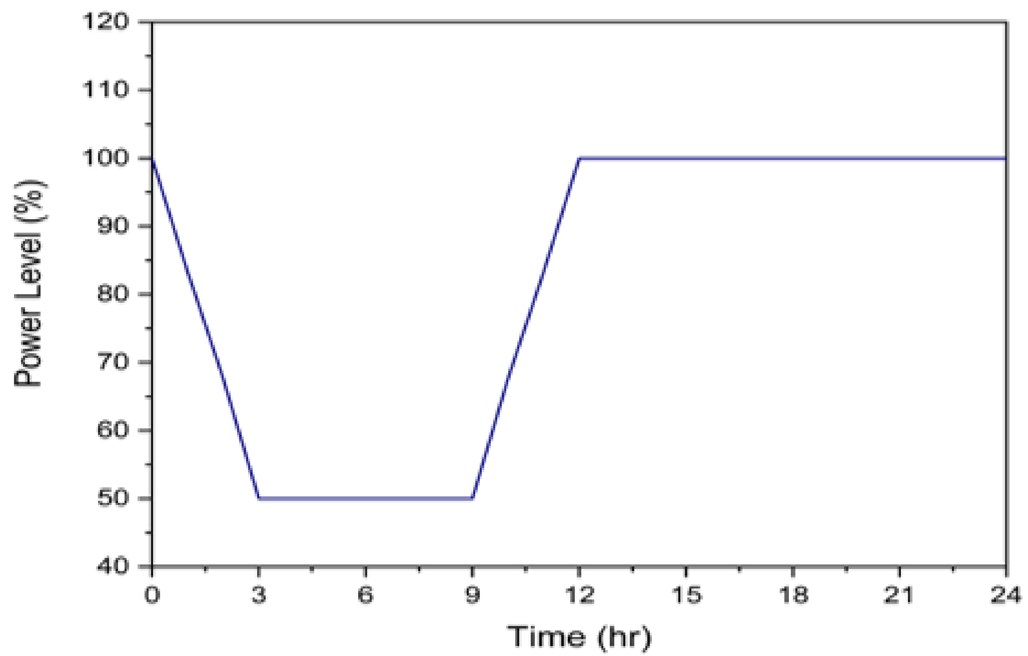




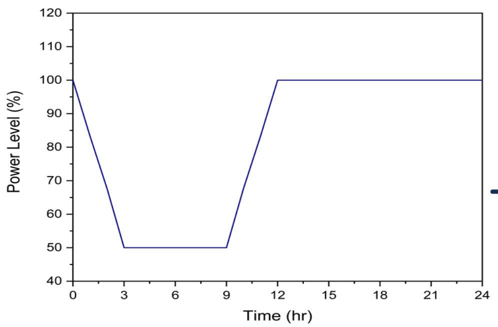
Case 1: Secondary System Results

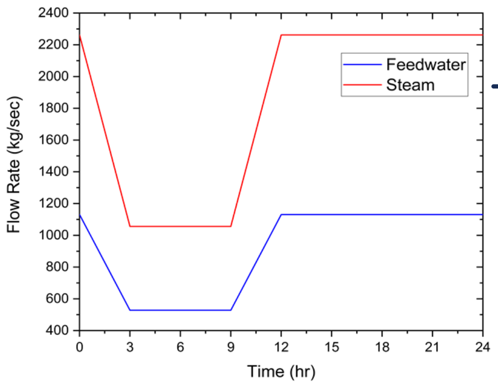


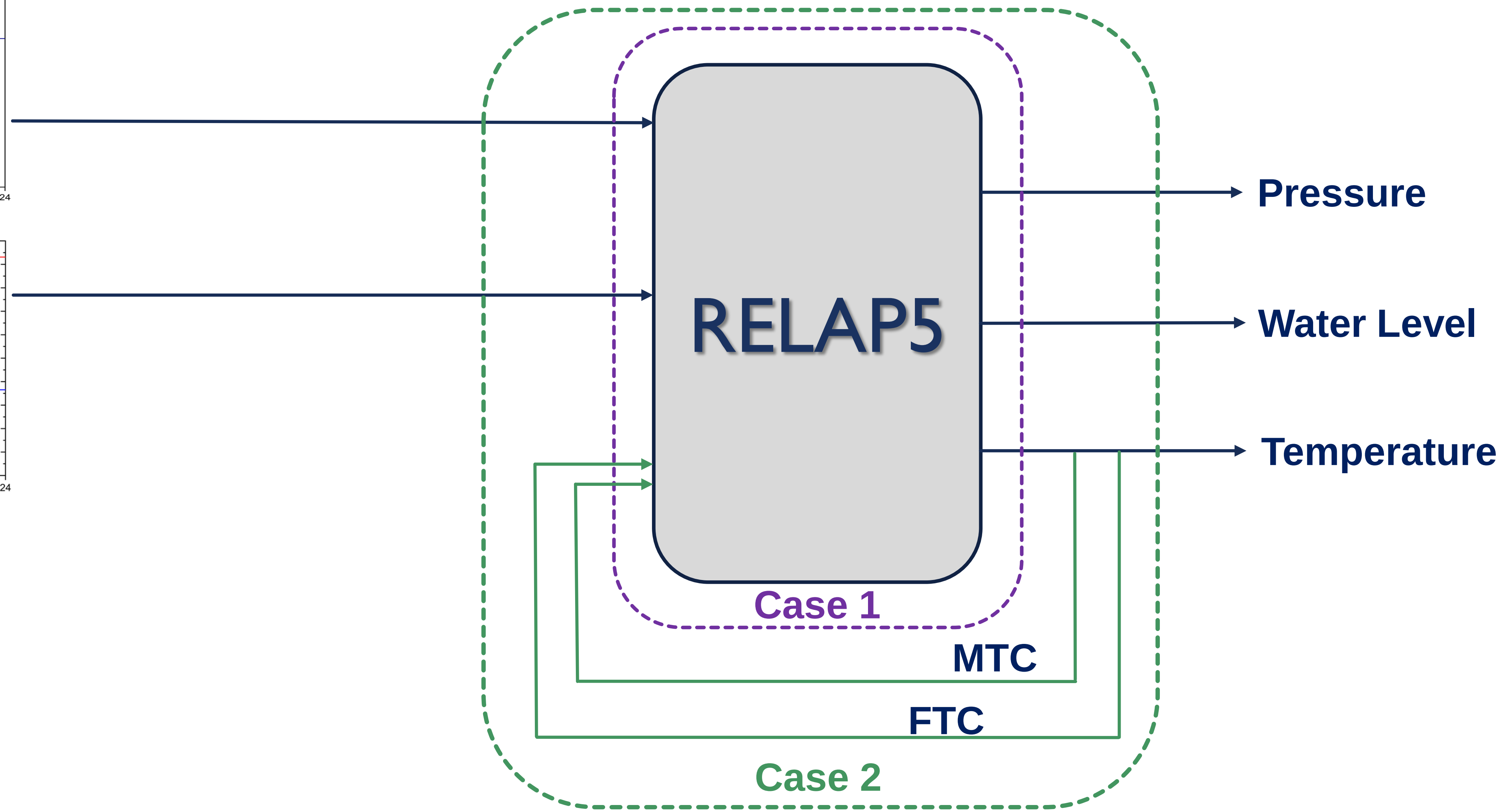




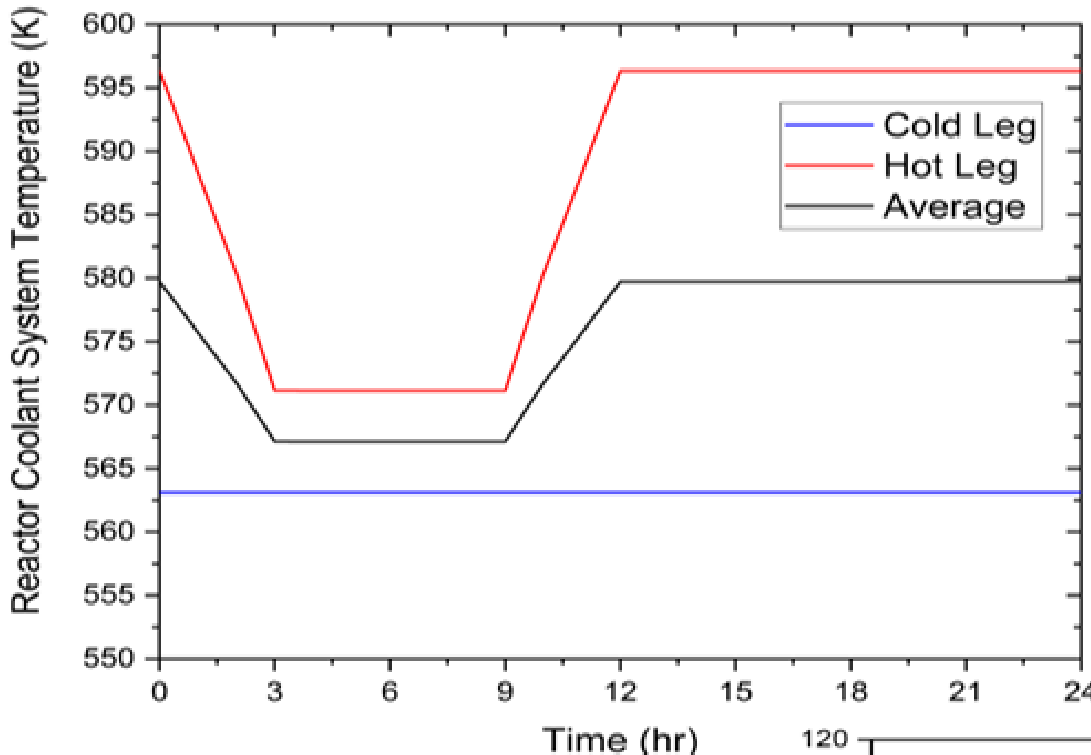
Case Studies

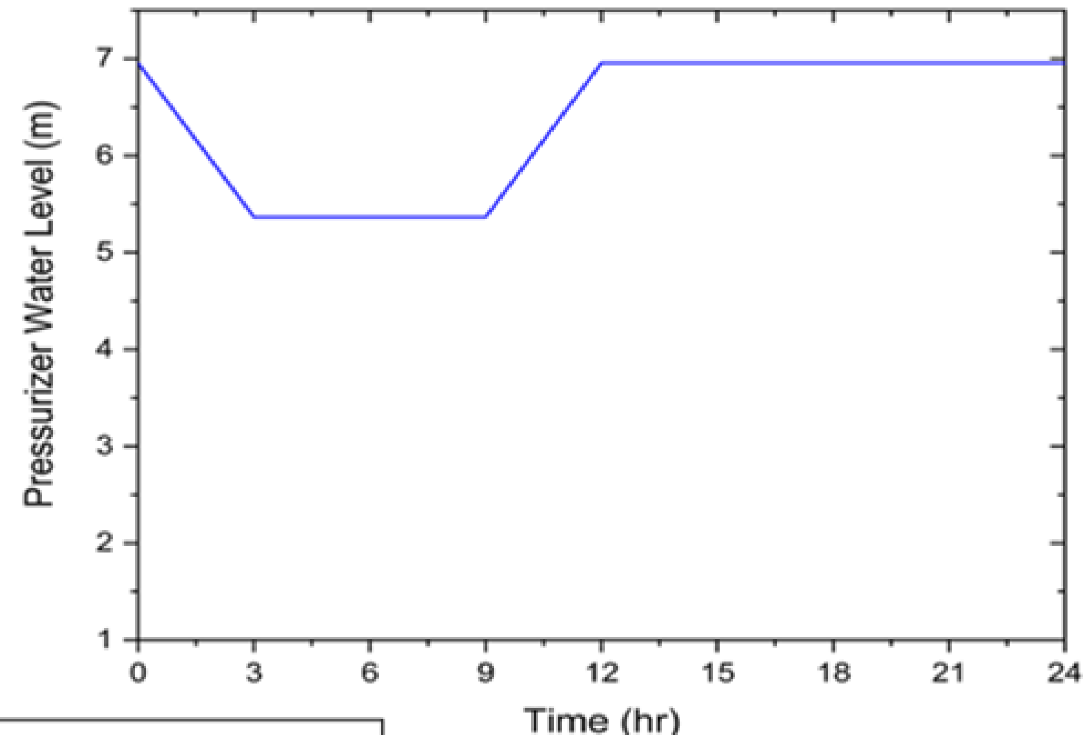


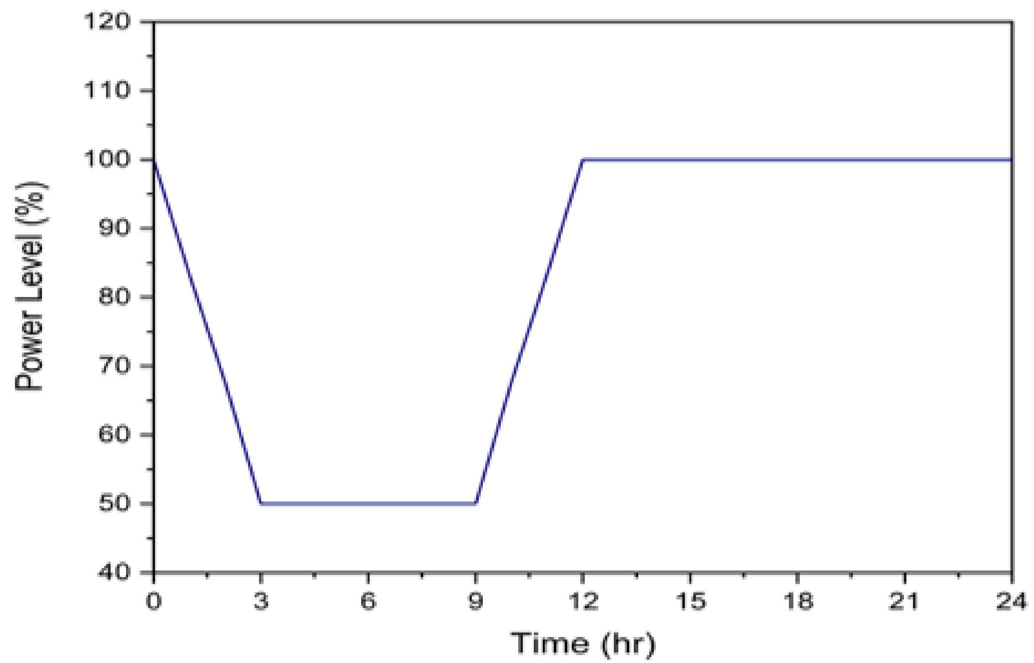




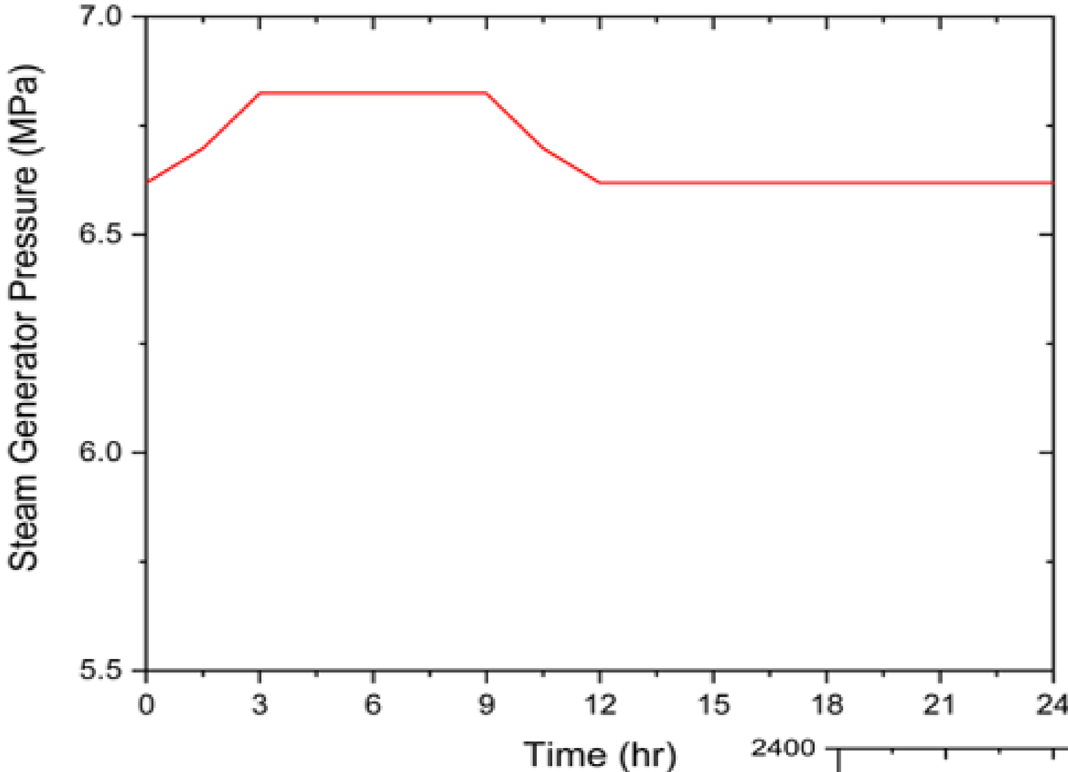
Case 2: Primary System Results

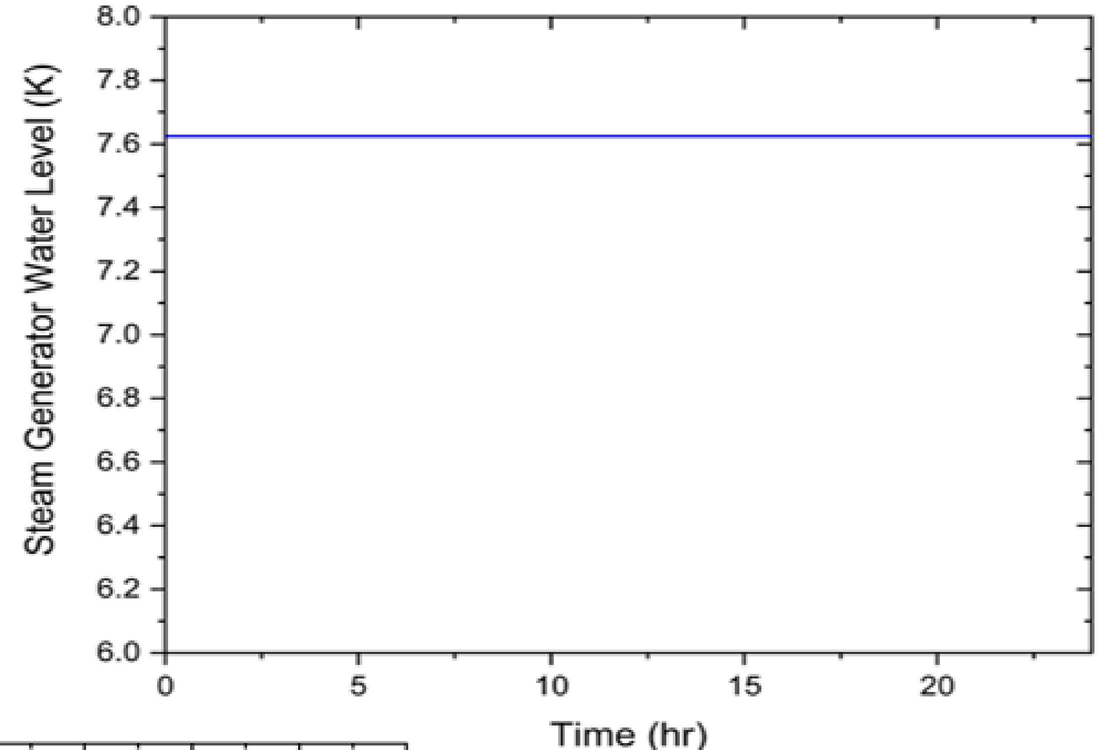


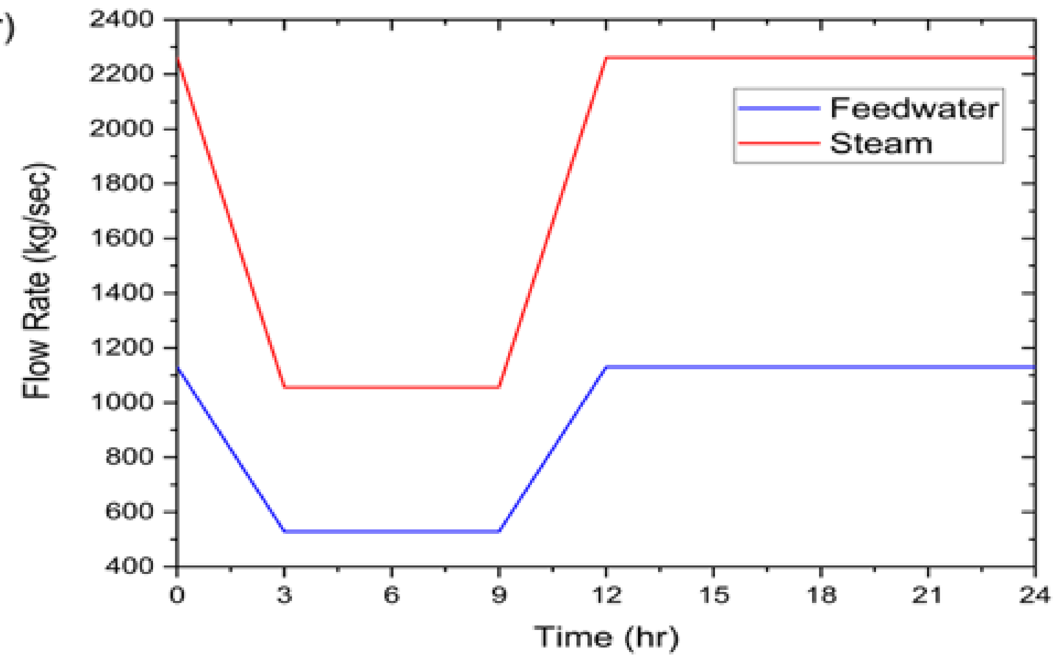




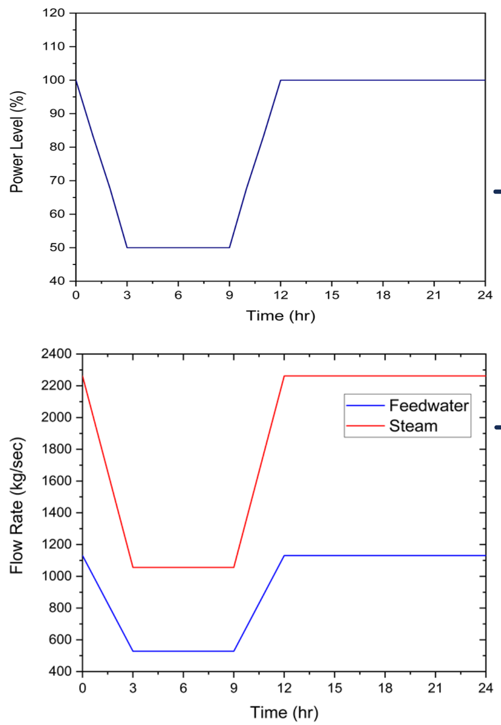
Case 2: Secondary System Results

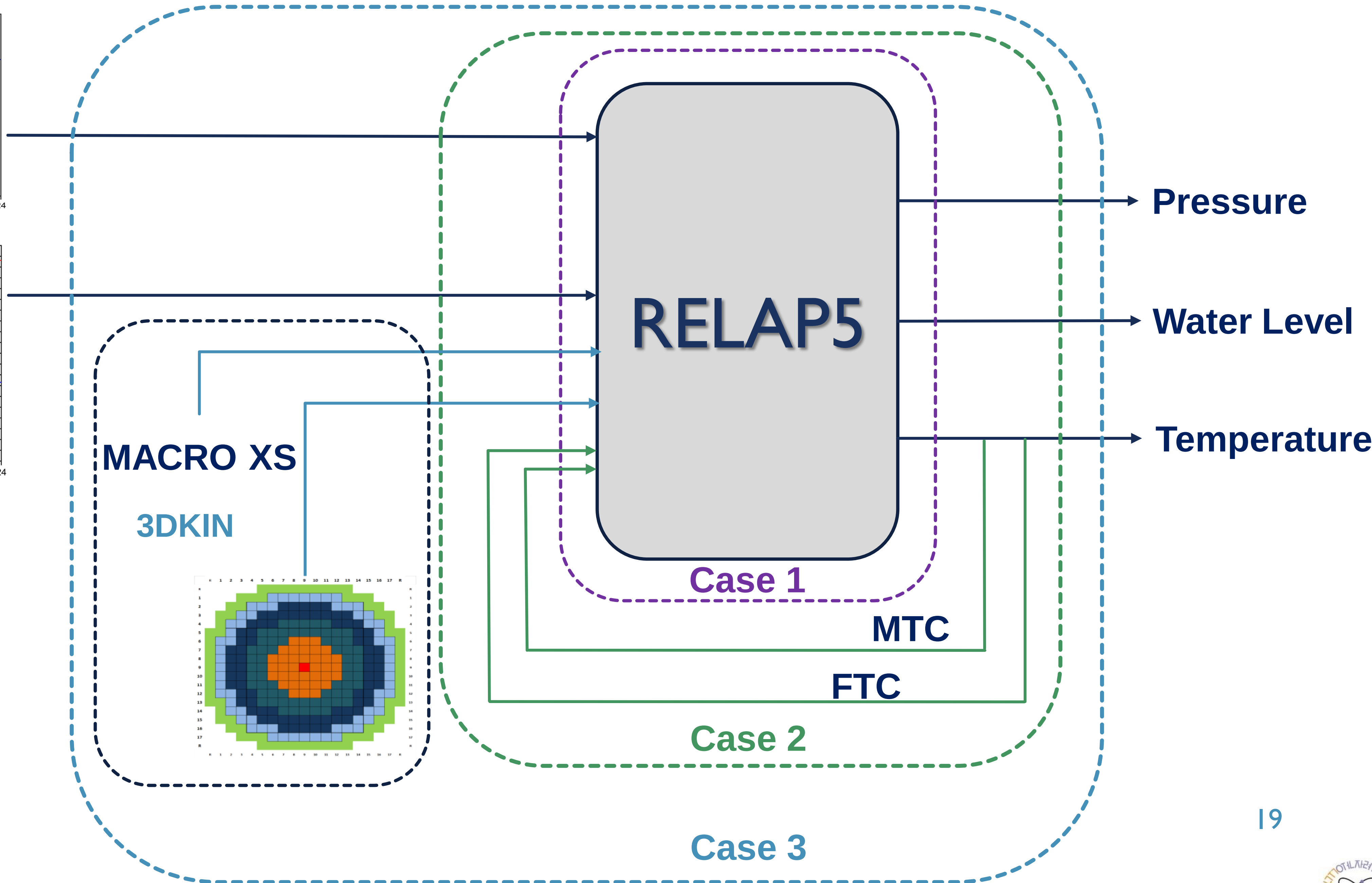






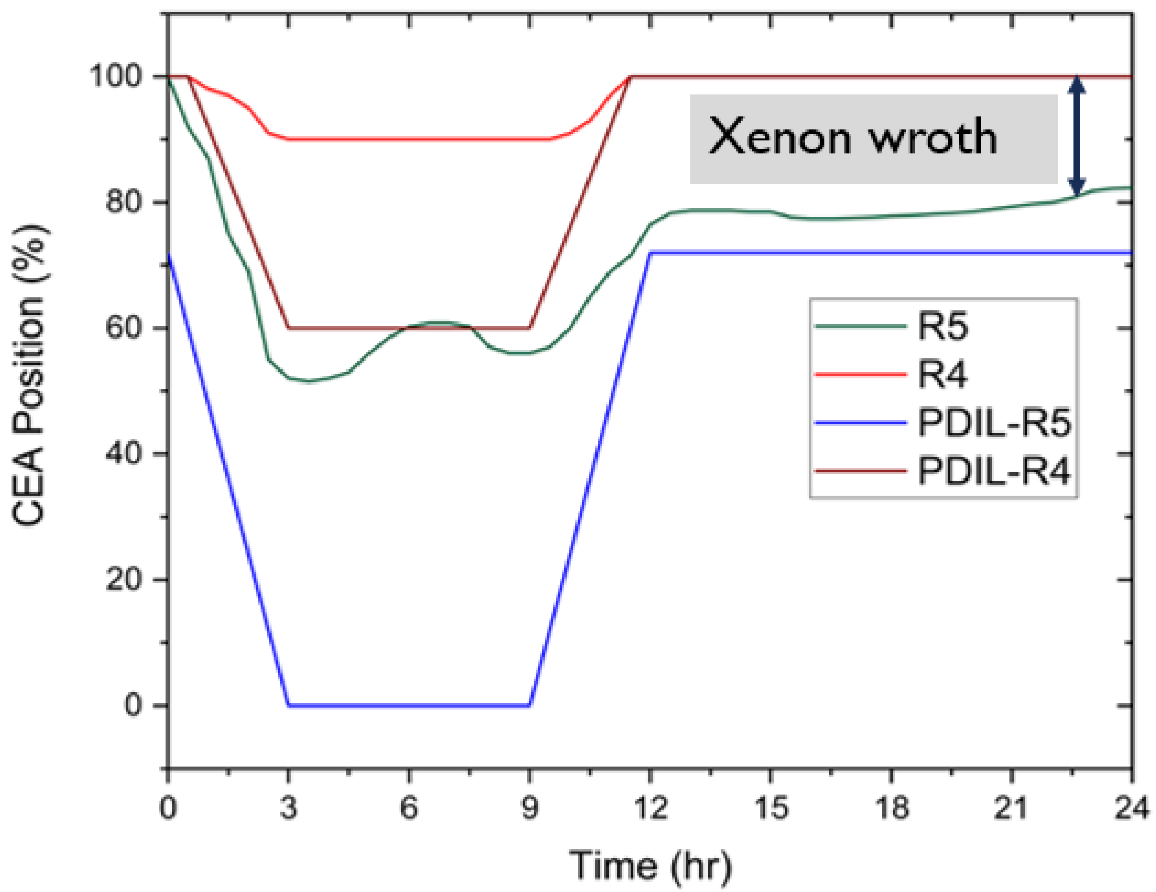
Case Studies



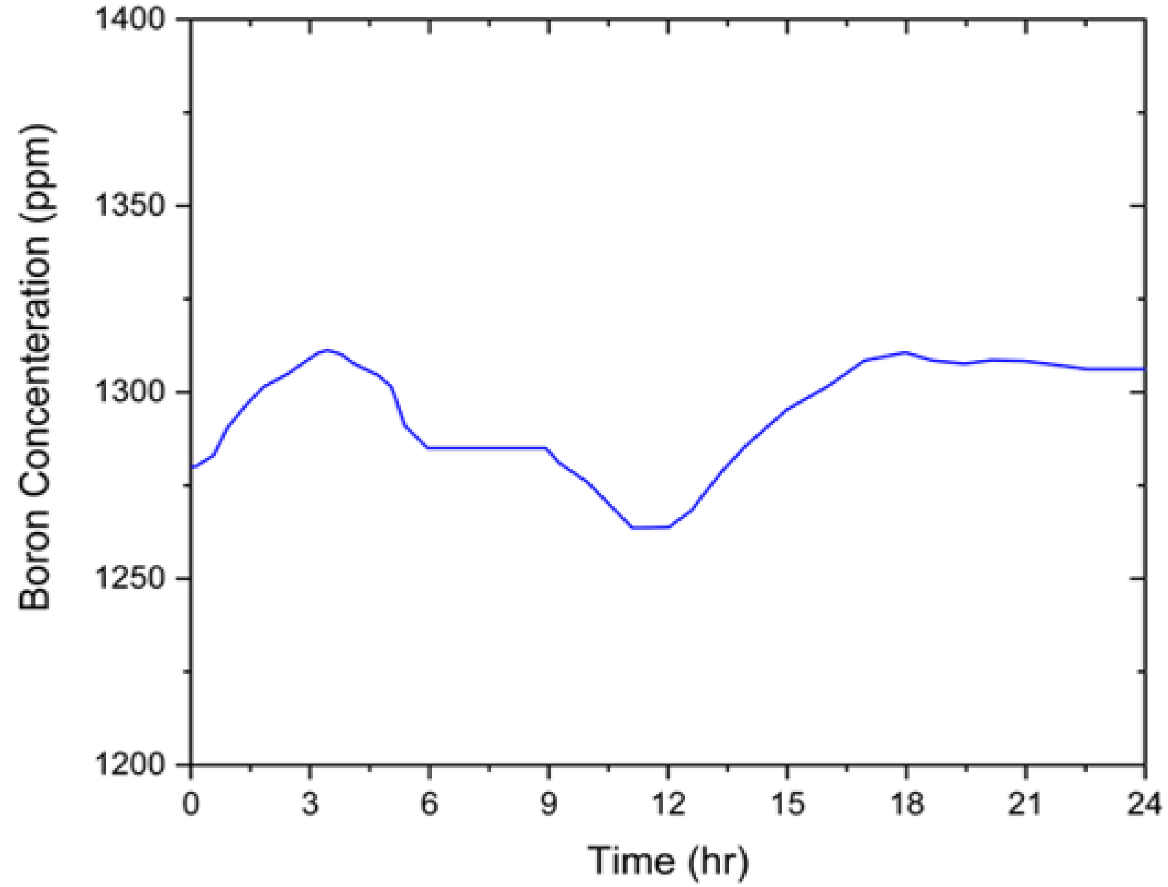


Case 3: Core Neutronics Results

CEA Position (%)



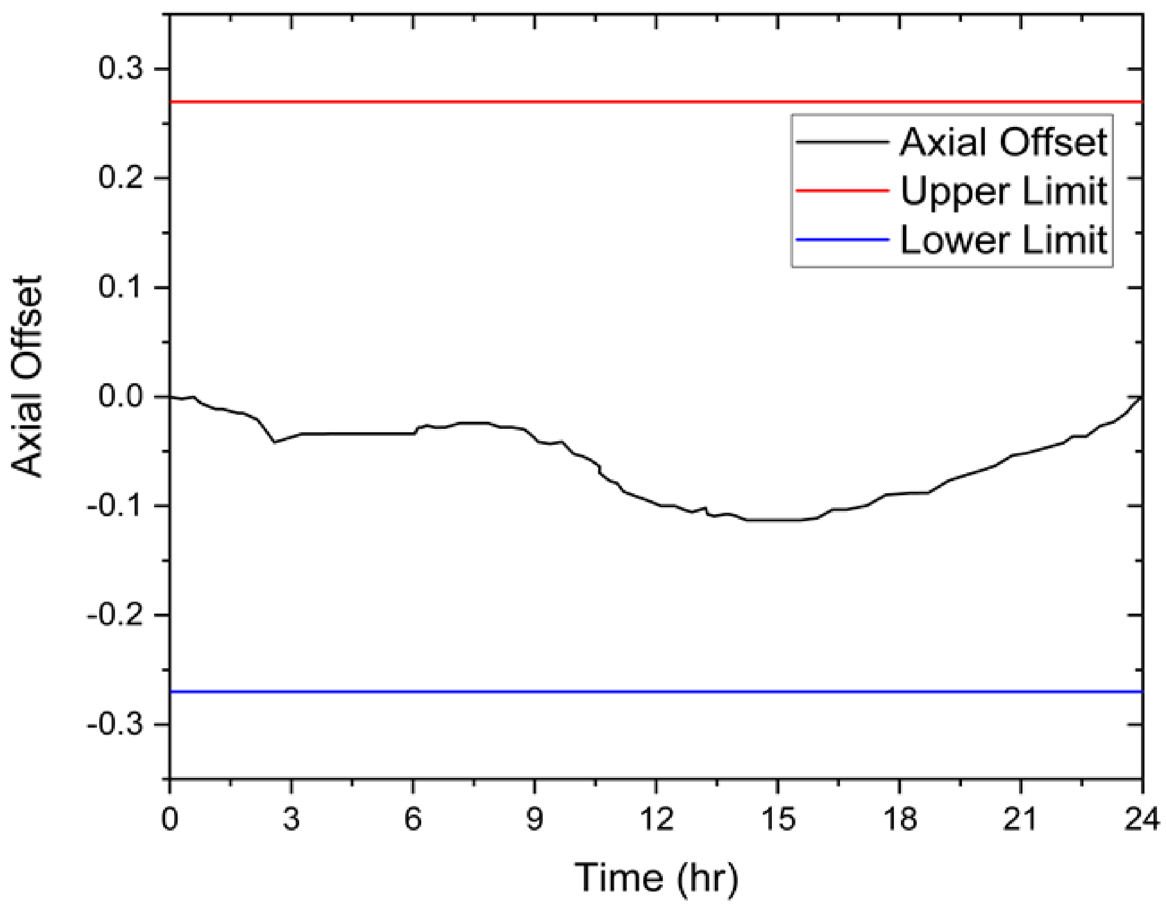
Boron Concentration (PPM)



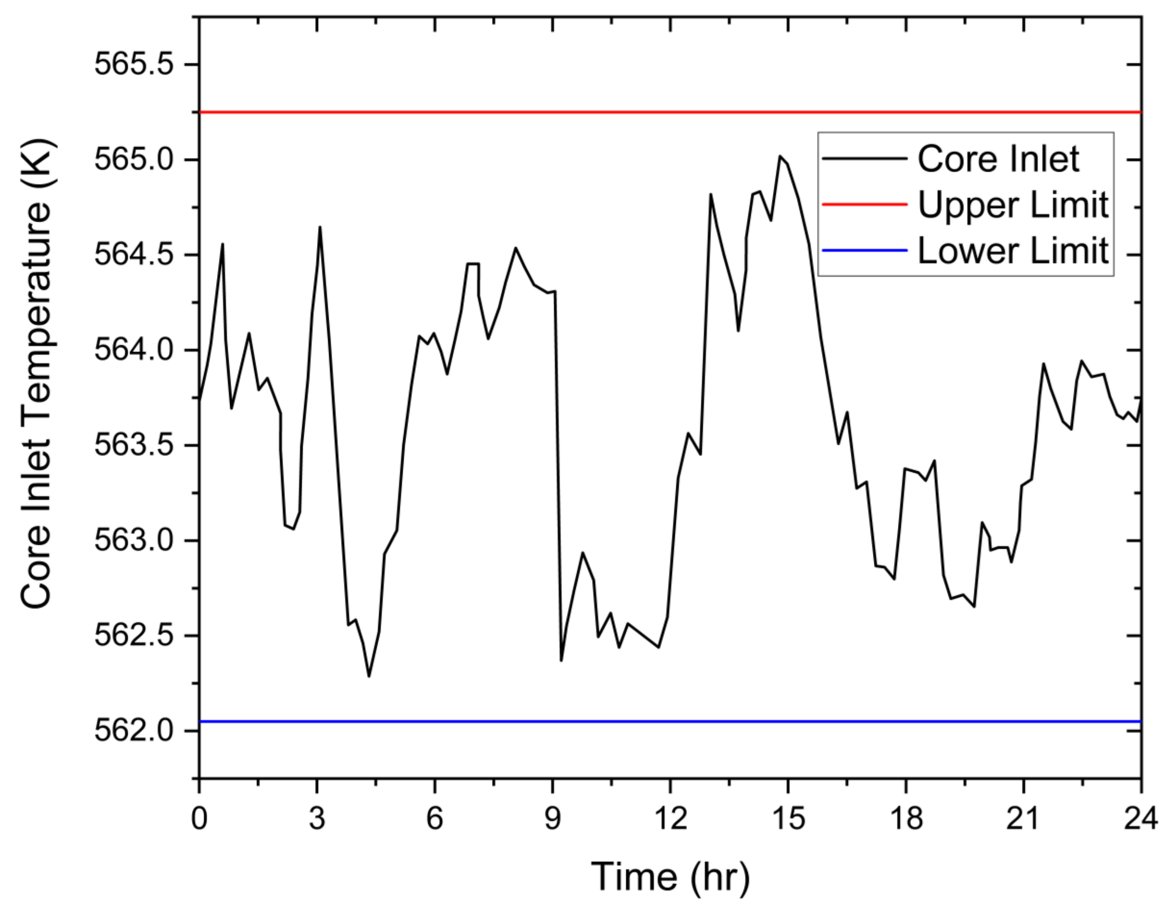
PDIL: Power Dependent Insertion Limit
R5: Regulating control element assembly # 5
R4: Regulating control element assembly # 4

Case 3: Core Neutronics Results

Axial Offset (AO)



Core Inlet Temperature (T_{in})



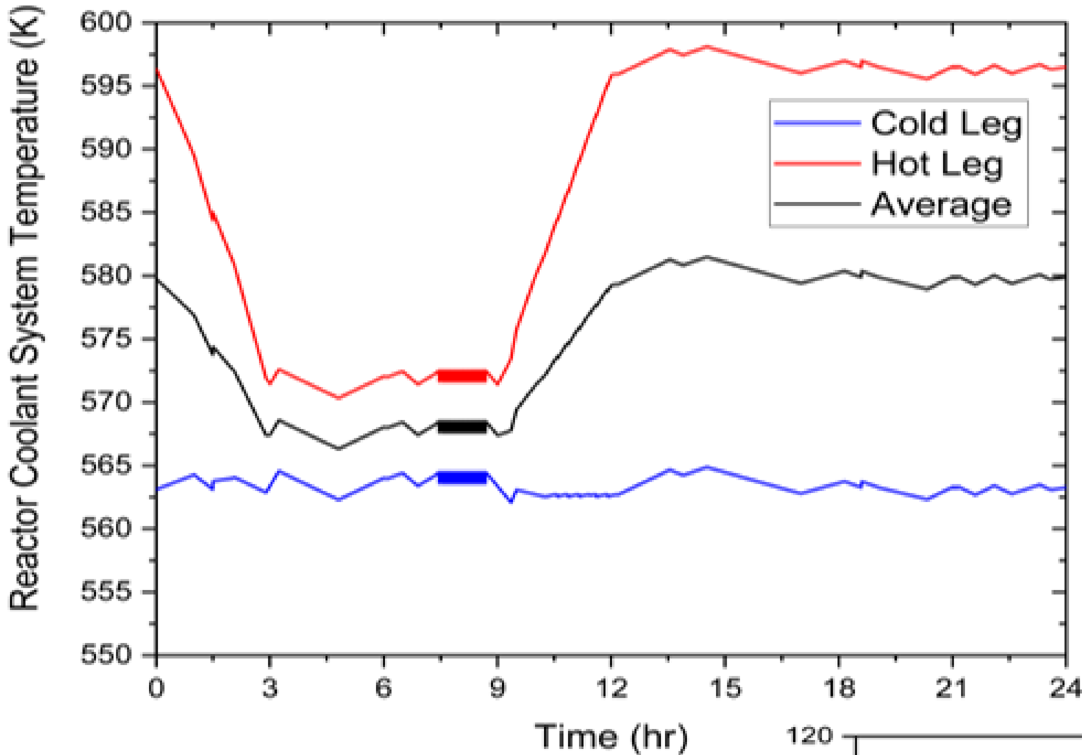
$$AO = \frac{P_T - P_B}{P_T + P_B}$$

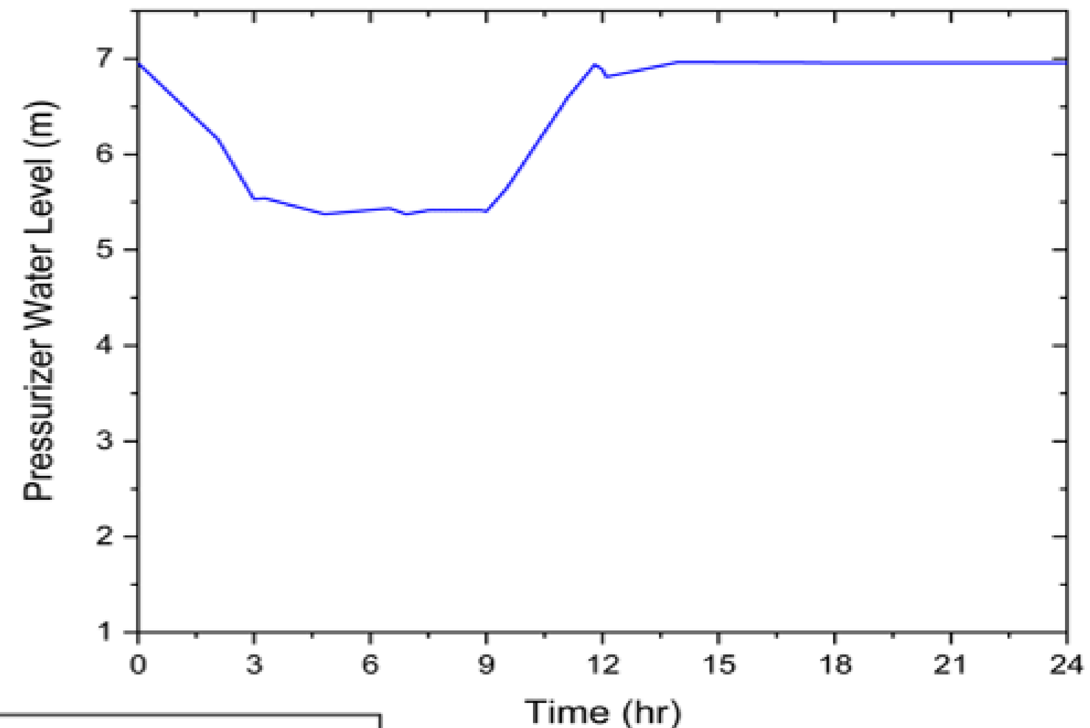
PT: Power in the upper half of the core
PB: Power in the upper half of the core

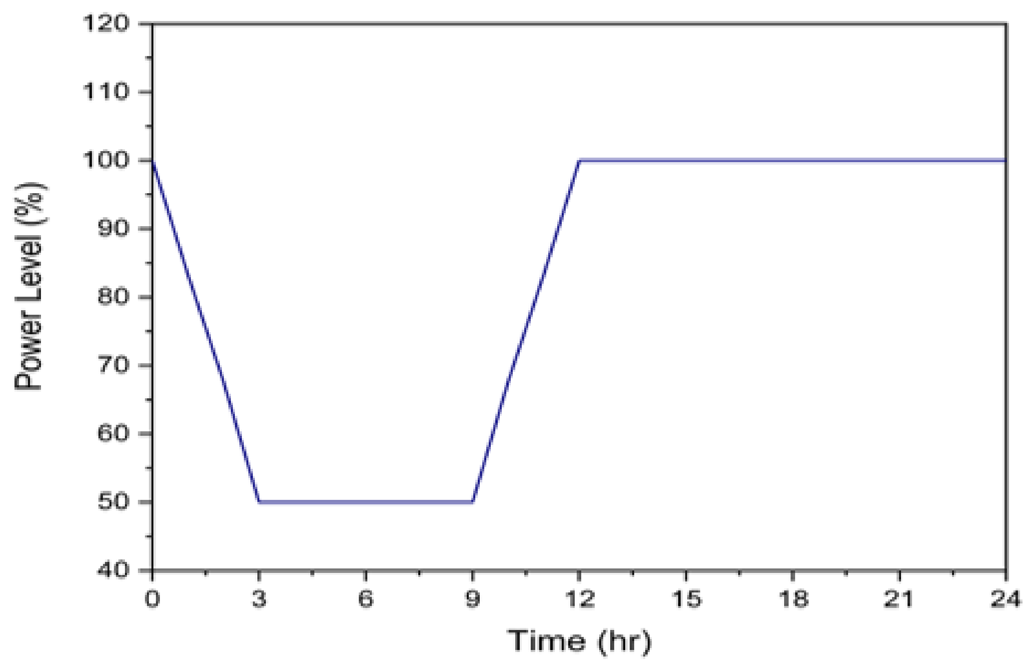
Case 3: Core Neutronics Results

Parameter		Simulation Result	COLR Limit
3D Pin Peaking Factor (Fq)	100%	1.762	2.43
	50%	2.587	4.86
Axial Offset		-0.146	±0.27

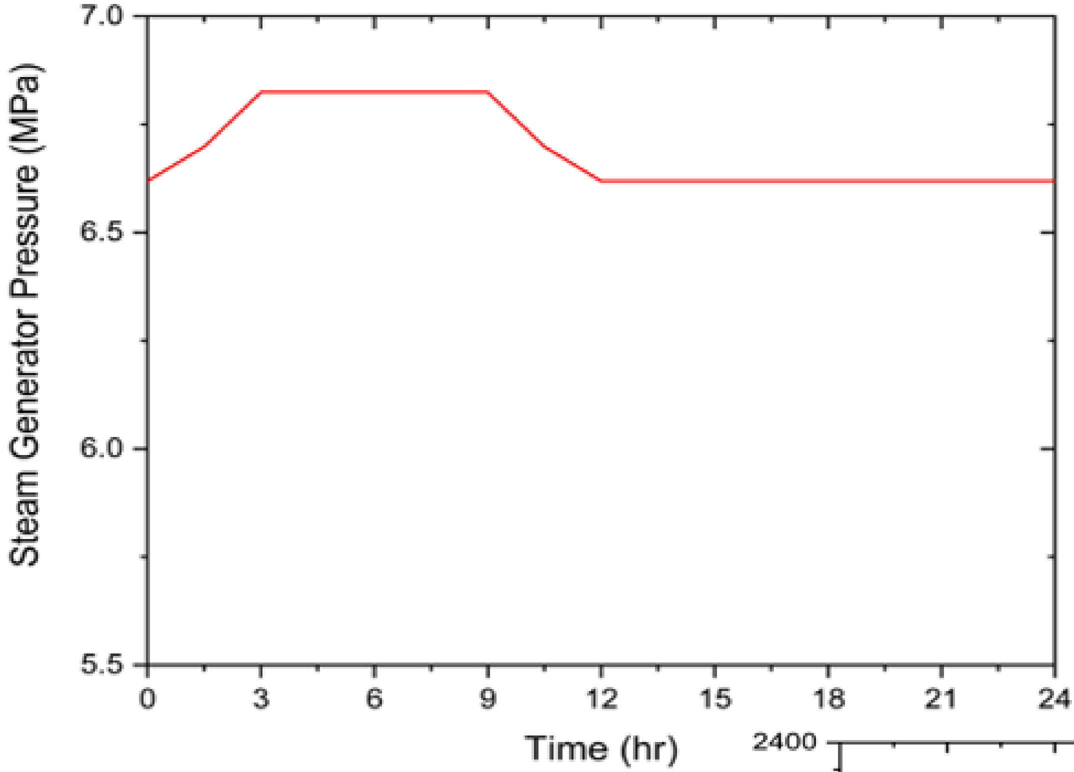
Case 3: Primary System Results

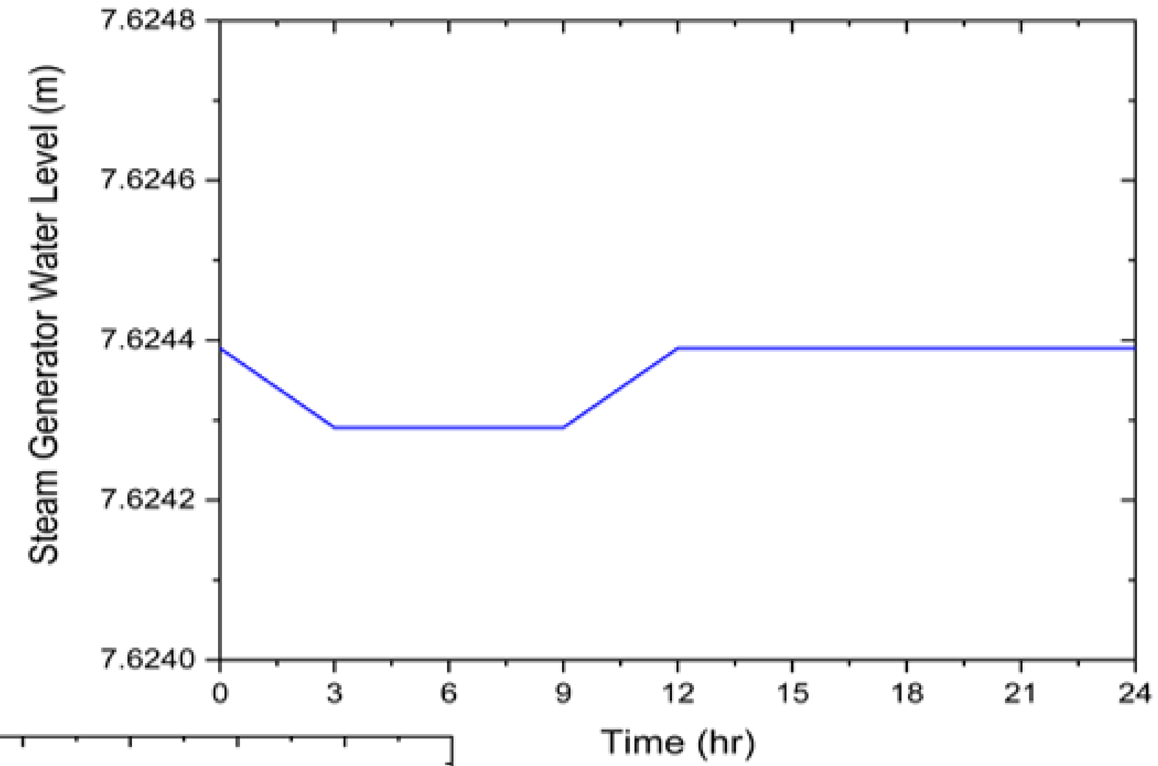


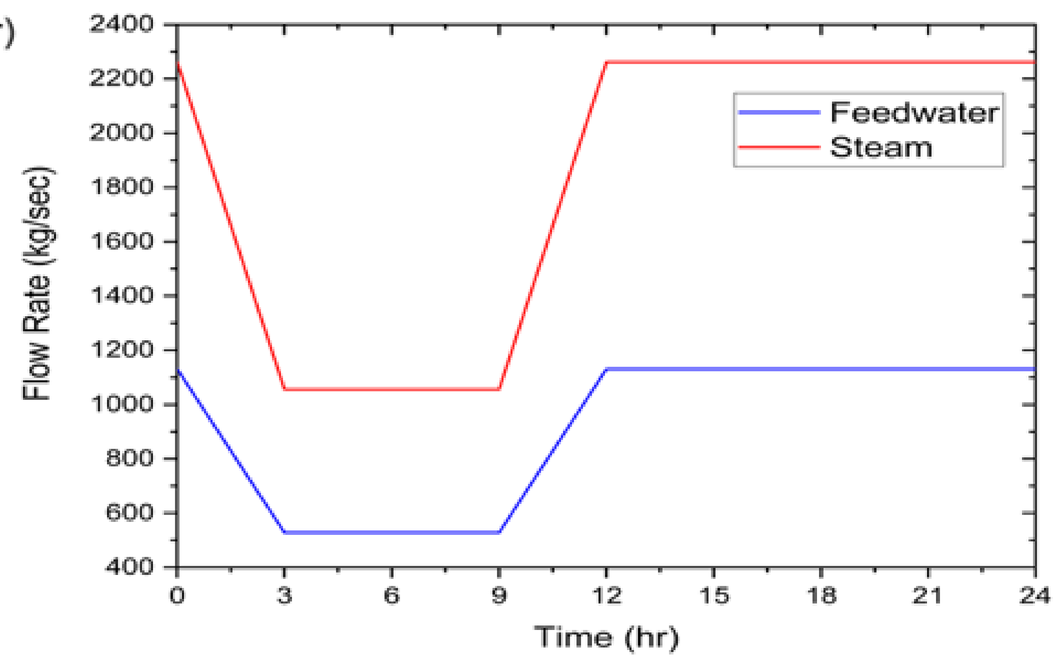




Case 3: Secondary System Results

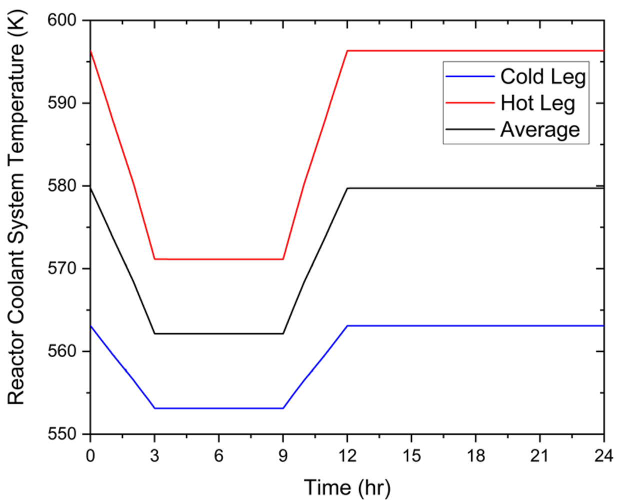


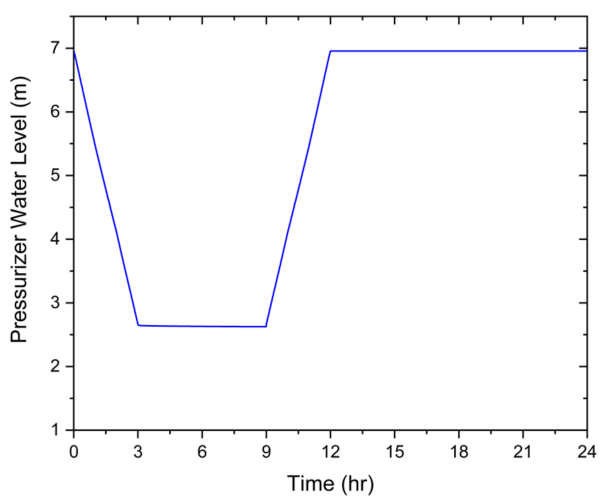




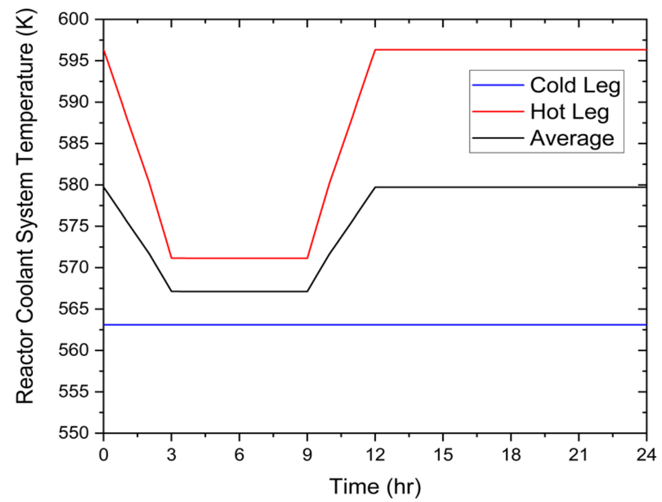
Case 3: Results Comparison

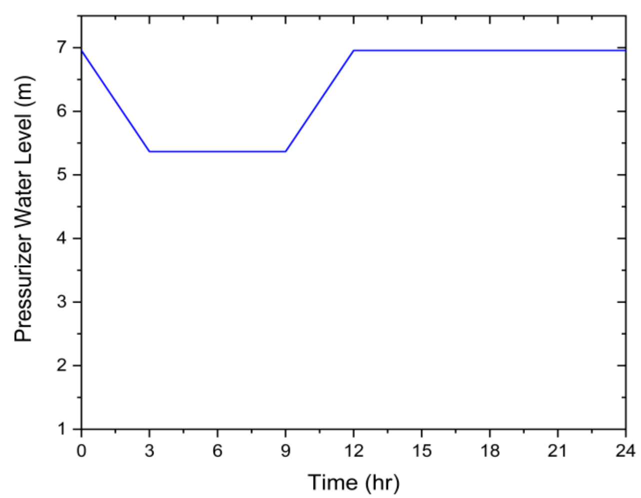
Case 1



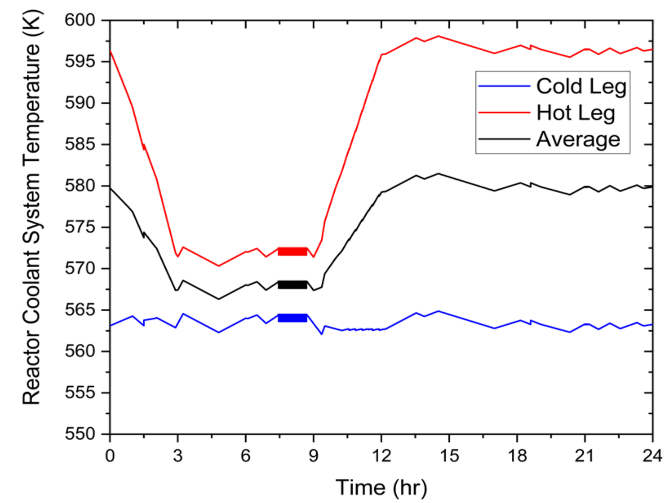


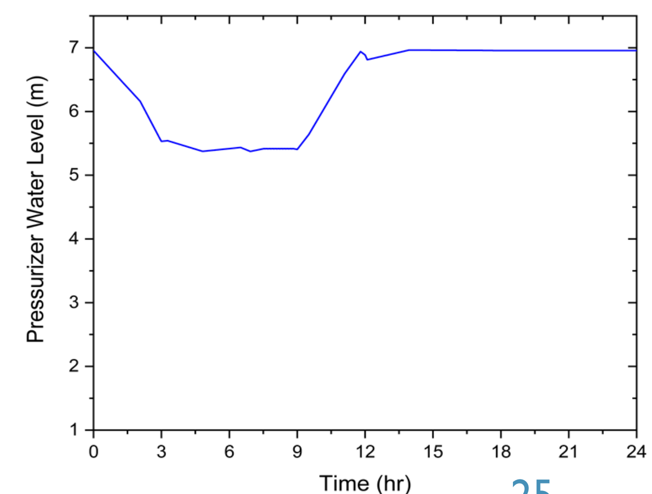
Case 2





Case 3





Conclusions

- Three simulations were performed to analyze APR1400 under LFO for one cycle load using Mode-K.
- Coupled RELAP5/3DKIN simulation (Case 3) showed better results compared to (Case 1) and (Case 2) in term of plant response.
- The main limitation of this work is the absence of benchmarking data or APR1400 real-plant data for LFO to compare with the results from this research.

Future Work

- The TH model for APR1400 need more improvements to implement more robust control systems for main feedwater system and turbine control valve.
- For generalization, additional work should be performed to analyze the plant response through the entire cycle not only beginning of cycle (BOC) as it was performed in this research.
- The long term goal of this research is to check the operability of APR1400 under different LFO scenarios with different power change rates at different burnup states in order to obtain the plant operational map for load follow operation.

Thank You!

Acknowledgment

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