Dynamic System Modeling & PID Controller Design for a Molten Salt Microreactor

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December 6th, 2023

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About the Author

Experience

B.S Chemical Engineering (2015-2019) - Michigan Technological University
M.S. Nuclear Engineering (2021-2023) - University of Idaho - NRC Fellow
Modeling and Simulation Intern at Idaho National Lab

Select Publications

Root, S. J., et al., 2023. Thermodynamic analysis on xenon stripping to shorten restart time in molten salt microreactors.
Nuclear Engineering and Design 414, 112606

Root, S. J., et al., 2023. Cyber hardening of nuclear power plants with real-time nuclear reactor operation, 1. preliminary operational testing.
Progress in Nuclear Energy 162, 104742

Outline

Background

Gen-IV

- Complete re-designs
- Smaller footprint
- Deployability
- Versatility

Molten Salt Reactors

Microreactors

Background

Gen-IV

Molten Salt Reactors

- High temperature
- Low pressure
- High specific heat

Microreactors

Background

Gen-IV

Molten Salt Reactors

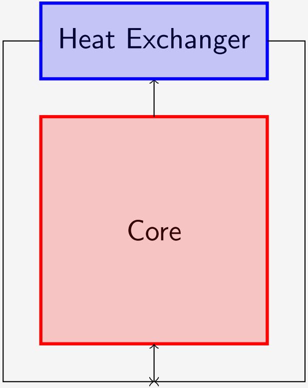
Microreactors

- Less than 50 MW
- Assembly line manufacturing
- Deliver/installation vs. construction

Fuel/Primary Coolant

- Self-Contained liquid fueled molten salt micro-reactor
- 10 year design
- 10 MWth using HALEU UF_4 dissolved in $FLiNaK$
- Natural circulation driven

Control Drums



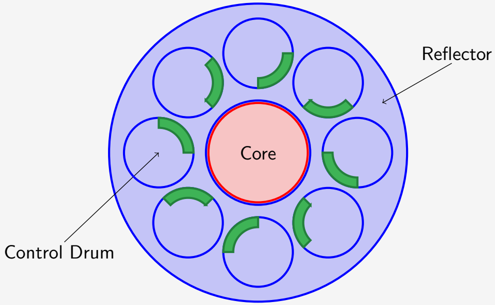
Simplified schematic drawing of an MSNB

Molten Salt Nuclear Battery

Fuel/Primary Coolant

Control Drums

- Criticality is manipulated using axial control drums
- Neutron absorber plate covering cylinders of neutron reflector
- Drums are rotated to point more absorber towards the core to insert negative control reactivity



MsNB Control Drums

Previous and Present Work

Neutronics [3]

- Control drums give a uniform axial and radial flux profile for all reactivity insertions
- Control drum vs. reactivity curve is sinusoidal

Thermal Hydraulics [4]

Process Control

[3] Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor. Master's thesis, University of Idaho

[4] Carter, J. P., 2022. Multi-physics investigation of a natural circulation molten salt micro-reactor that utilizes an experimental in-pile device to improve core physics and system thermal-hydraulic performance. Ph.D. thesis, University of Idaho

Previous and Present Work

Neutronics [3]

Thermal Hydraulics [4]

- Transient simulations can be reduced to 1D and still correspond to STAR-CCM+
- Stable autonomous load following for relatively small ramp function power demand transients

Process Control

[3] Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor. Master's thesis, University of Idaho

[4] Carter, J. P., 2022. Multi-physics investigation of a natural circulation molten salt micro-reactor that utilizes an experimental in-pile device to improve core physics and system thermal-hydraulic performance. Ph.D. thesis, University of Idaho

Neutronics [3]

Thermal Hydraulics [4]

Process Control

- Design controller *compliment* the autonomous capabilities provided by the passive feedback mechanisms
- Allow larger faster, more aggressive power changes
- Return MSNB to steady-state operation faster

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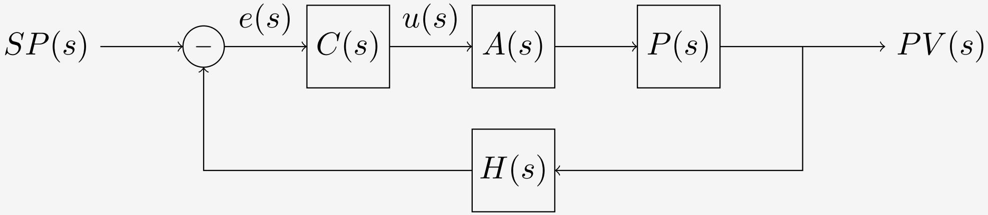
[3] Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor. Master's thesis, University of Idaho

[4] Carter, J. P., 2022. Multi-physics investigation of a natural circulation molten salt micro-reactor that utilizes an experimental in-pile device to improve core physics and system thermal-hydraulic performance. Ph.D. thesis, University of Idaho

Control Theory

Feedback Control



PID Control

$$u(t) = \underbrace{K_P e(t)}_{\text{Proportional}} + \underbrace{K_I \int_0^t e(t)dt}_{\text{Integral}} + \underbrace{K_D \frac{de(t)}{dt}}_{\text{Derivative}}$$

PID Control

$$u(t) = \underbrace{K_P e(t)}_{\text{Proportional}} + \underbrace{K_I \int_0^t e(t)dt}_{\text{Integral}} + \underbrace{K_D \frac{de(t)}{dt}}_{\text{Derivative}}$$

Proportional

- Control output is manipulated in proportion to the error defined by the proportional gain constant
- High gain yields an aggressive controller that is prone to overshooting the set-point
- Low gain may result in steady-state offset

Integral

Derivative

PID Control

$$u(t) = \underbrace{K_P e(t)}_{\text{Proportional}} + \underbrace{K_I \int_0^t e(t)dt}_{\text{Integral}} + \underbrace{K_D \frac{de(t)}{dt}}_{\text{Derivative}}$$

Proportional

Integral

- Considers cumulative error to help eliminate steady-state offset
- As the process variable settles around the set-point, the cumulative error approaches a constant value and the effect of the integral controller diminishes.

Derivative

PID Control

$$u(t) = \underbrace{K_P e(t)}_{\text{Proportional}} + \underbrace{K_I \int_0^t e(t)dt}_{\text{Integral}} + \underbrace{K_D \frac{de(t)}{dt}}_{\text{Derivative}}$$

Proportional

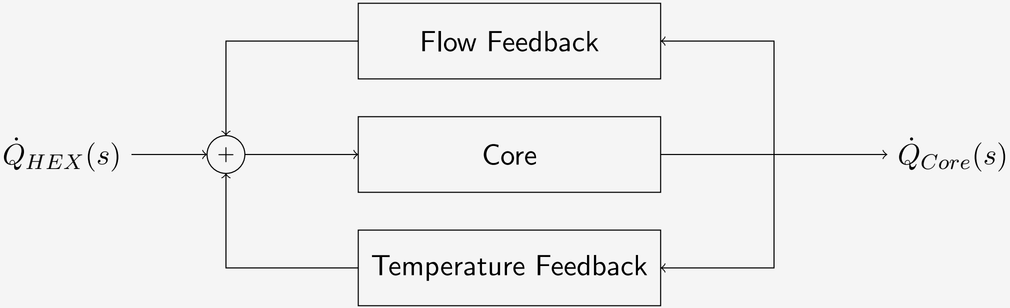
Integral

Derivative

- Estimates the time rate of change of the error to dampen overshoot
- Backs-off the proportional response when the process variable rapidly approaches the set-point
- Can be difficult to tune

Transport Delay Problem

Passive Feedback



Simplified block diagram of two primary passive feedback mechanisms in an MSNB

Passive Feedback
Temperature Reactivity

Doppler broadening

- Resonance peaks lower and broaden with increased temperature
- High kinetic energy of target nucleus introduces more relative uncertainty of the center-of-mass energy [5, Ch. 7]
- More epithermal neutrons absorbed by ^{238}U etc. [6, Ch. 6]

Thermal Expansion

[5] Kerlin, T. W. et al., 2019. Dynamics and Control of Nuclear Reactors. Knoxville, Tennessee: Elsevier Inc

[6] Duderstadt, J. J. et al., 1976. Nuclear Reactor Analysis. New York, NY: Wiley & Sons, first edition

Doppler broadening

Thermal Expansion

- Increased temperature leads to lower heavy metal density and smaller macroscopic fission cross-section at high temperature [3]
- Similar to moderator thinning in LWRs

[3] Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor. Master's thesis, University of Idaho

Passive Feedback
Flow Reactivity

Delayed Neutron Precursors

- Most fission events release daughter neutrons *promptly*
- Sometimes, unstable nuclides which decay by neutron emission are produced instead
- $t_{1/2}$ from less than a second to over a minute [7, Ch. 6]

$$^{87}Br \xrightarrow[56sec]{\beta^-} {}^{87}Kr^* \rightarrow {}^{86}Kr + n$$

Flowing Fuel

[7] Lamarsh, J. R. et al., 2001. Introduction to Nuclear Engineering. Upper Sadle River, New Jersey: Pretice Hall, third edition

Delayed Neutron Precursors

Flowing Fuel

- Precursors produced near the core exit and long lived precursors may emit their neutrons outside of the core
- These neutrons are effectively lost from the fission chain reaction [5, Ch. 3]
- Larger power transport requires a higher flow rate
- Greater delayed neutron losses
- Negative feedback

[5] Kerlin, T. W. et al., 2019. Dynamics and Control of Nuclear Reactors. Knoxville, Tennessee: Elsevier Inc

Main Operational Control Problem - Transport Delay

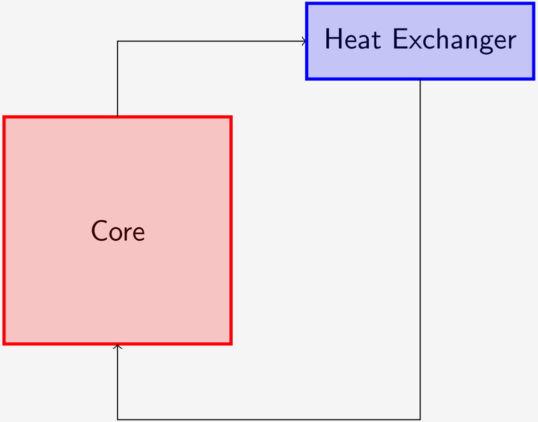
Dynamics associated with anticipated transients

- Natural circulation flow mode
- Passive feedback mechanisms
- Transport delays separating heat exchanger and core

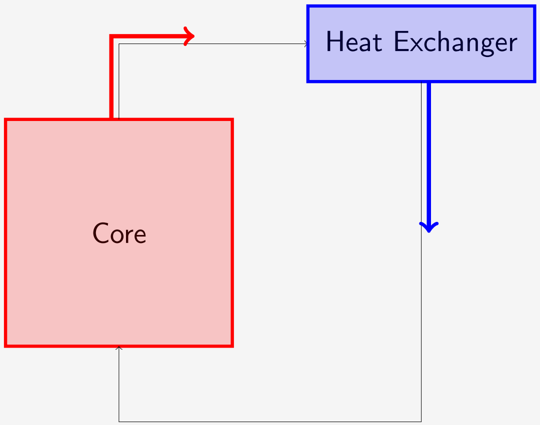
Thought Experiment

- Step increase in power demand to a steady-state critical MSNB
- Set-point is instantaneously equal to heat exchanger power consumption
- Ideal controller which produces rapid load following with minimal overshoot

Main Operational Control Problem - Transport Delay



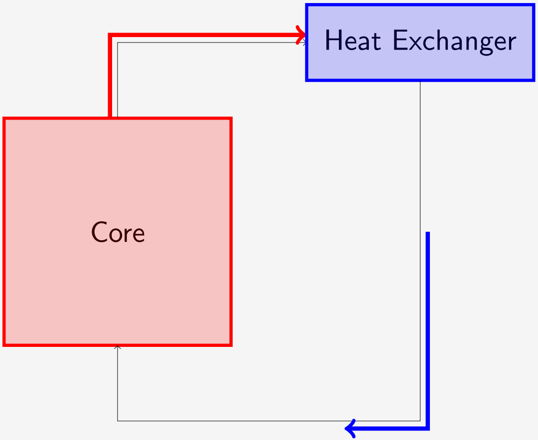
Simplified schematic drawing of a natural circulation MSNB



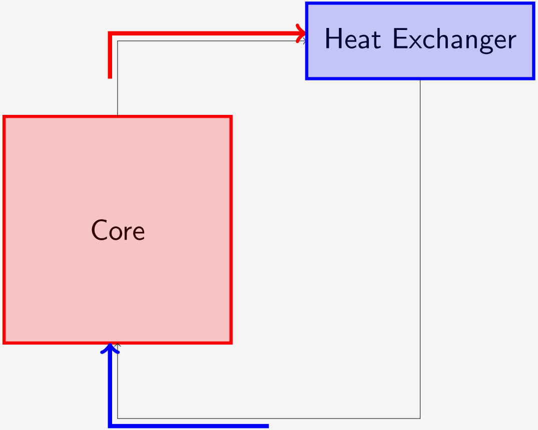
Simplified schematic drawing of a natural circulation MSNB

Main Operational Control Problem - Transport Delay

Heat Exchanger Perturbation

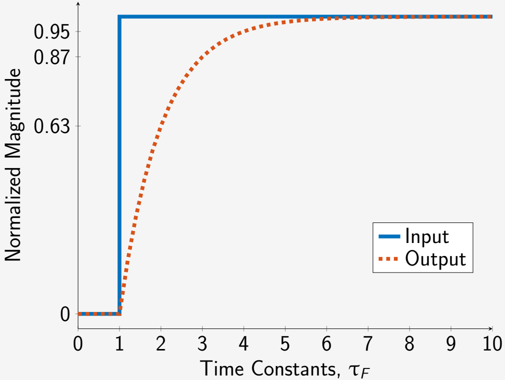


Simplified schematic drawing of a natural circulation MSNB

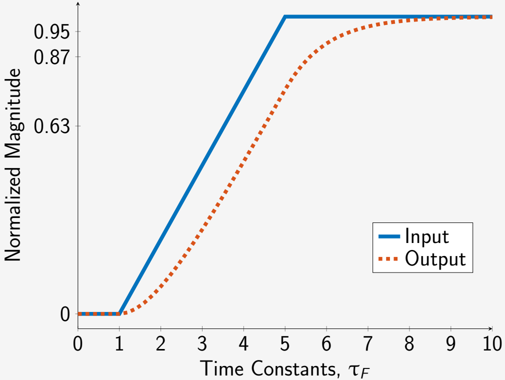


Simplified schematic drawing of a natural circulation MSNB

Pre-Filter



Pre-Filter on a step-function



Pre-Filter on a ramp-function

MSNB Control Loop

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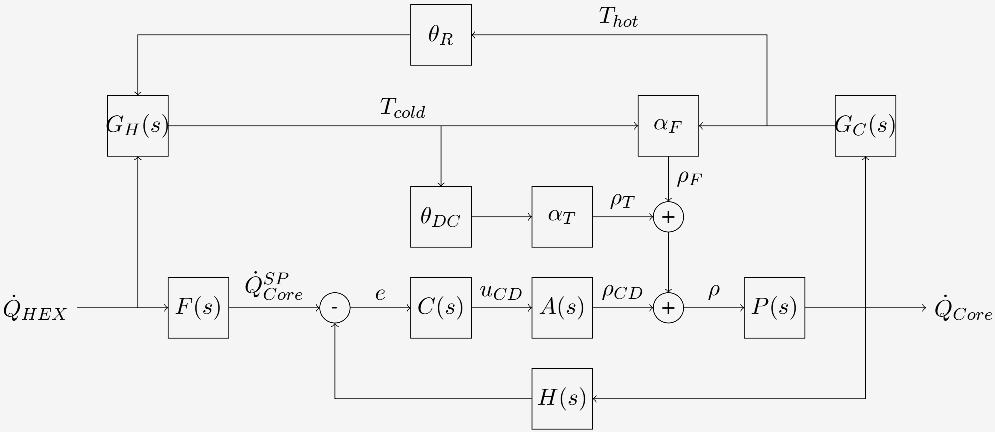
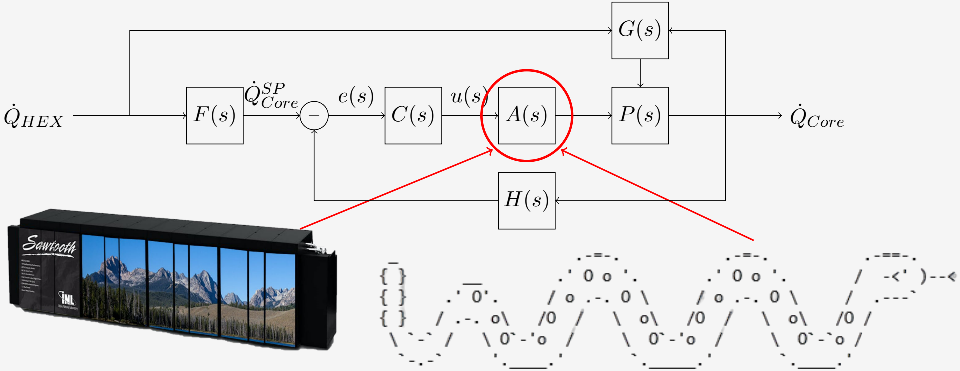
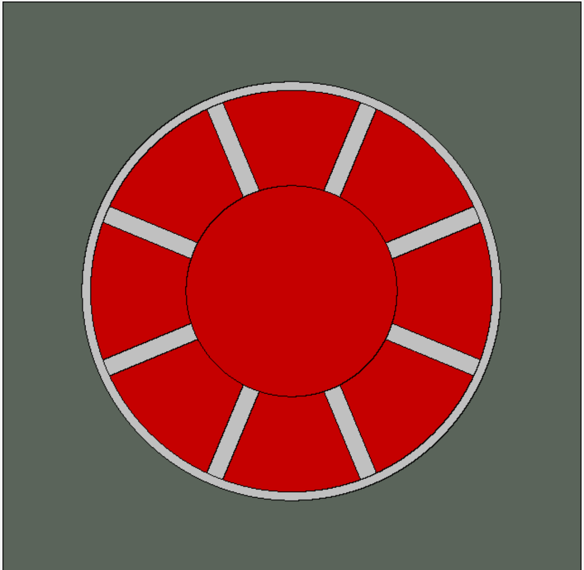


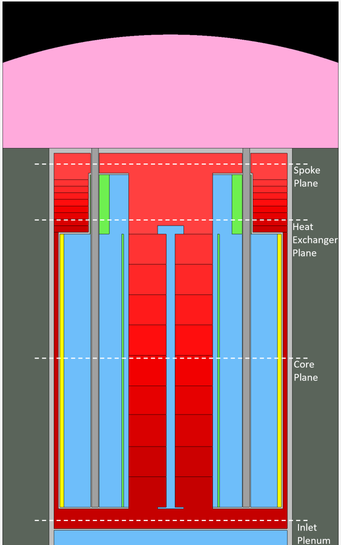
Neutronics Modeling

Serpent Modeling



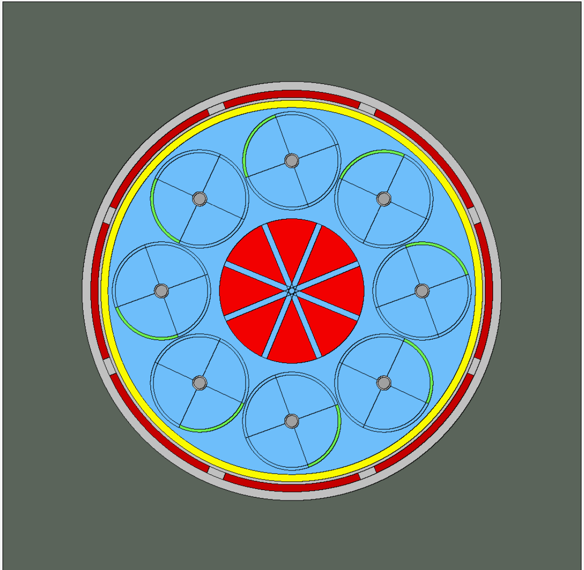
Geometry Specification

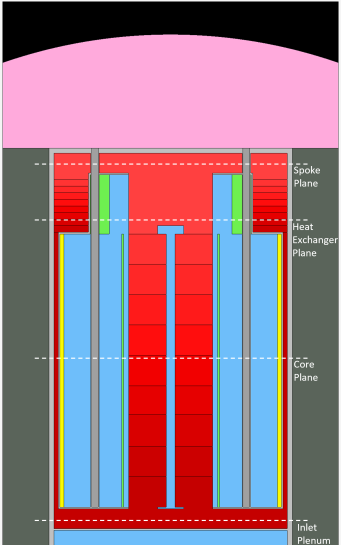




Geometry Specification

University of Idaho





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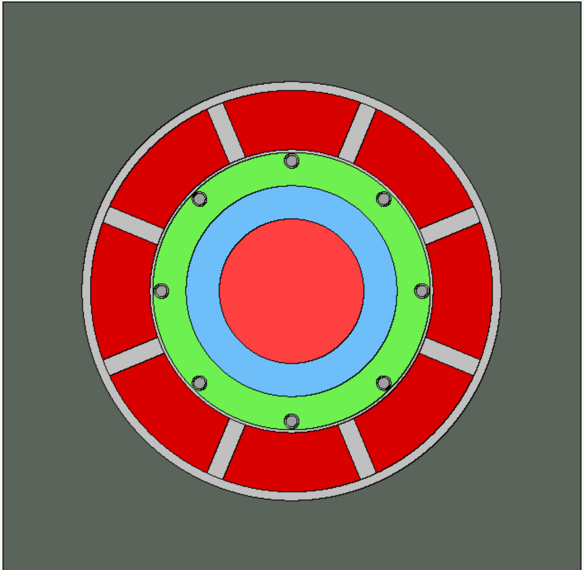

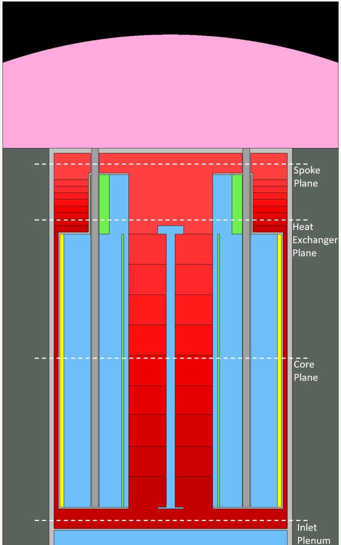

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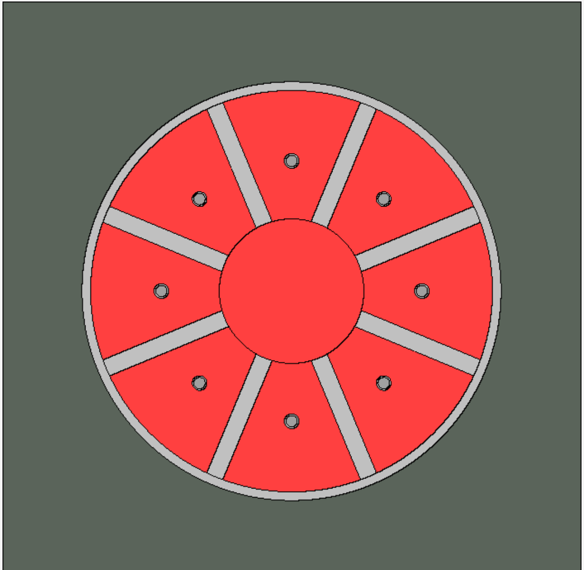

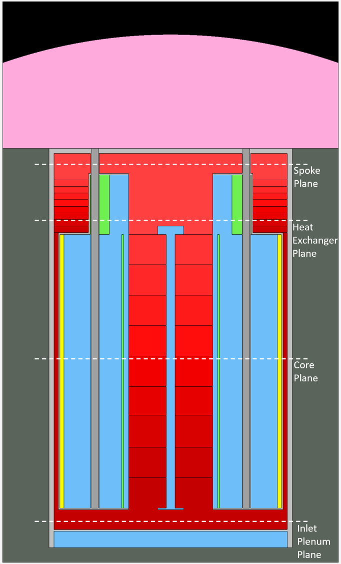

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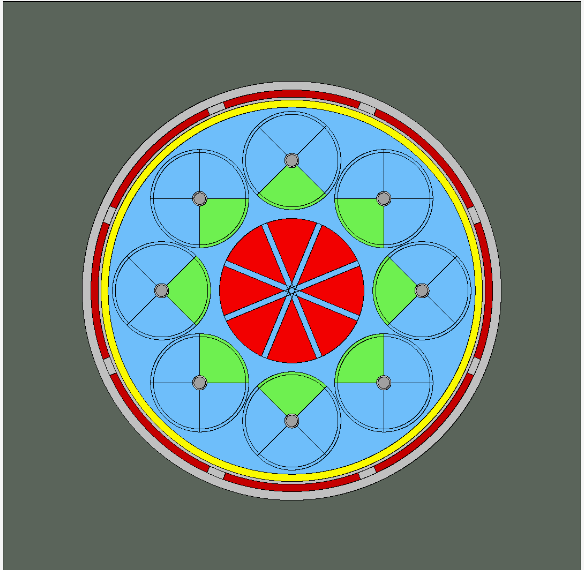

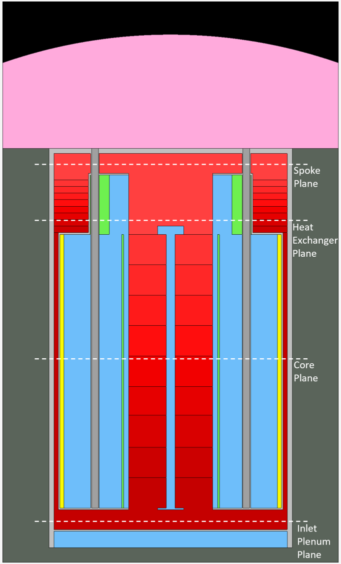

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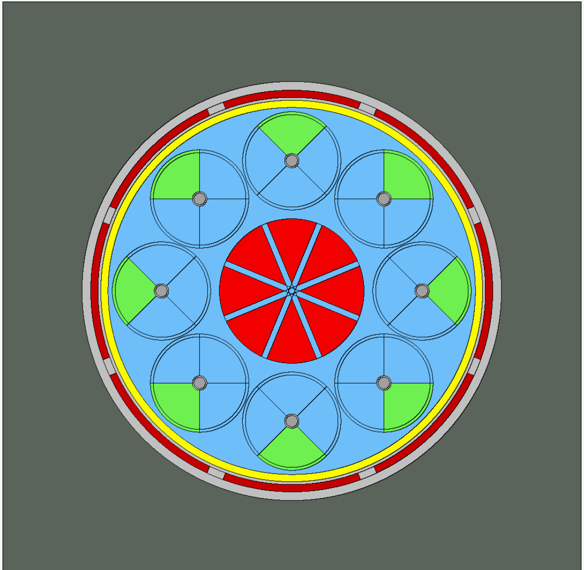

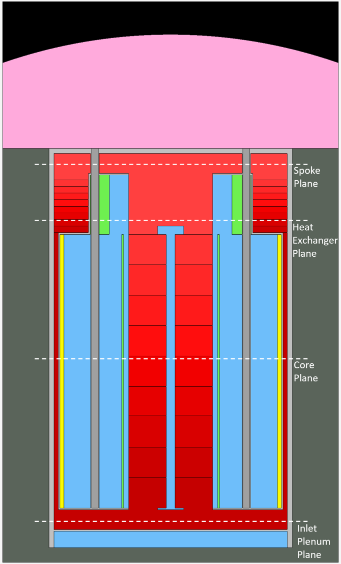

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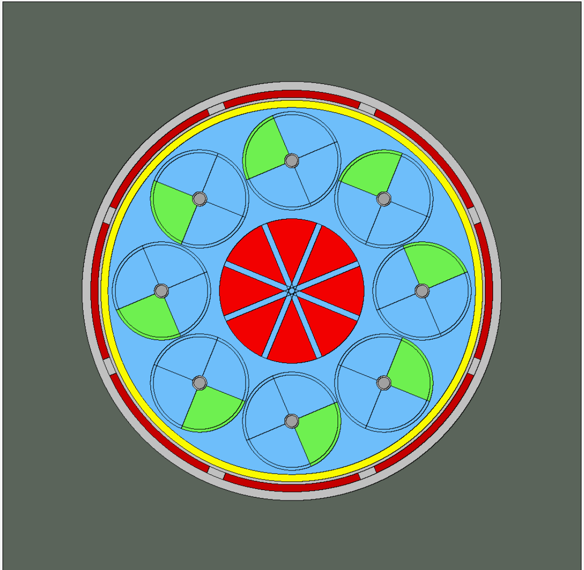

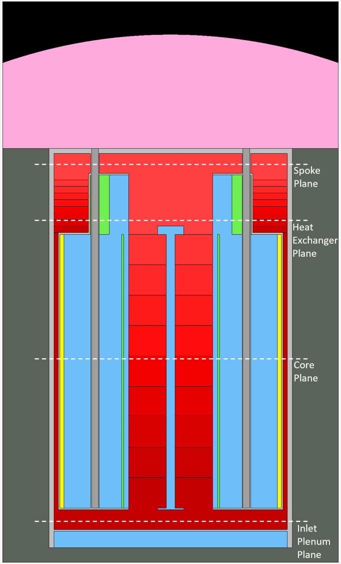

Physics Cards

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Criticality

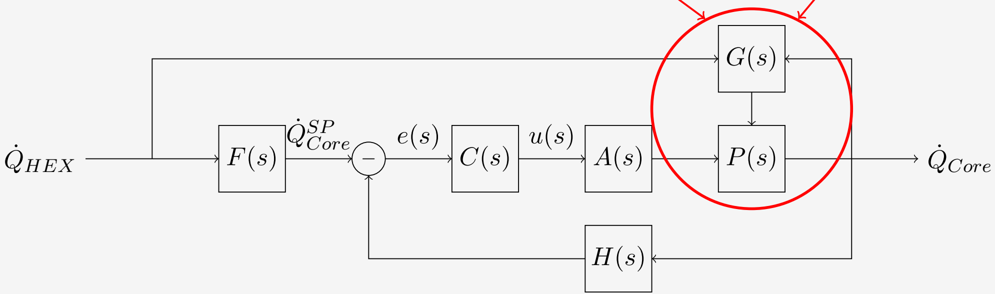
- Set Pop 1,000,000 500 100 1
- Conduct for all control drum angles
- Compare reactivity to angle to define actuator curve

Burn-Up

- Burn fuel salt to find composition after a certain amount of time - poisons, depletion of uranium
- Repeat criticality modeling to define actuator at a different point in time

Process Simulation

Process Simulation



Multi-Physics Approach

Natural Circulation (NC)

Updates flow rate by equating buoyant and frictional forces

$$v = \sqrt{2gh(\varrho_{cold} - \varrho_{hot})/\xi\varrho}$$

Reactor Point Kinetics (RPK)

Uniform-State Uniform-Flow (USUF)

Natural Circulation (NC)

Reactor Point Kinetics (RPK)

Updates core power by summing passive reactivity feedback

$$\rho_f = -\frac{L}{L+H}\beta_{eff}\left(1 - e^{-v\alpha_f}\right)$$

$$\Delta\rho_T = \alpha_T \Delta T$$

$$\tau = \frac{l^*}{\rho} + \frac{\beta_{eff} - \rho}{\lambda\rho + \dot{\rho}}$$

$$Q_{core}[t + \delta t] = Q_{core}[t]e^{\delta t/\tau}$$

Uniform-State Uniform-Flow (USUF)

Multi-Physics Approach

Natural Circulation (NC)

Reactor Point Kinetics (RPK)

Uniform-State Uniform-Flow (USUF)

Updates temperature profile based on flow rate and core/heat-exchanger powers

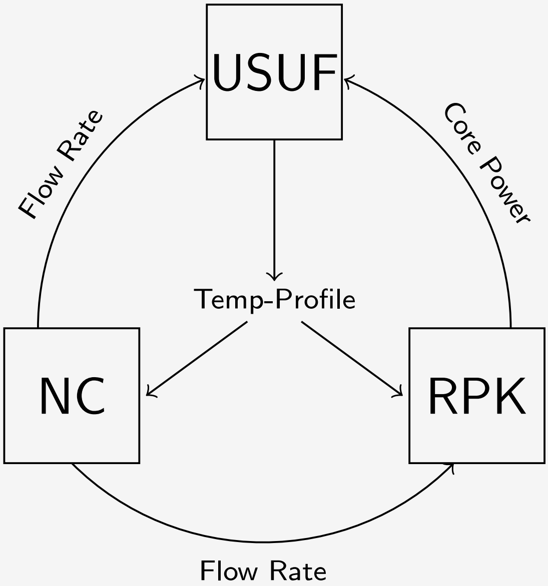
$$\delta x A_x \frac{d\varrho}{dt} = v A_x (\varrho_{in} - \varrho_{out})$$

$$mu_x = \varrho(T_x)\delta x A_x c_p \left({}^{T_x + T_r}/_{2}\right)(T_x - T_r)$$

$$\frac{d(mu)}{dt} = mu_{enter} - mu_{exit} + Q_{c.v.}$$

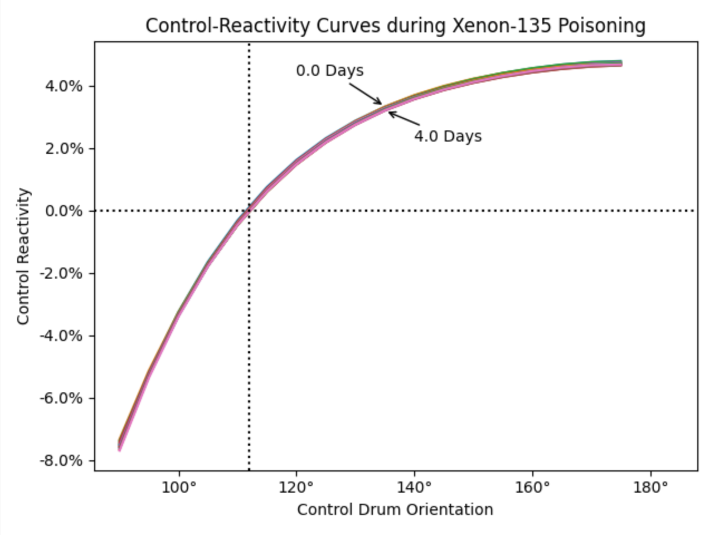
$$mu[t + \delta t] = mu[t] + \delta t \frac{d(mu)}{dt}[t]$$

Logic Flow

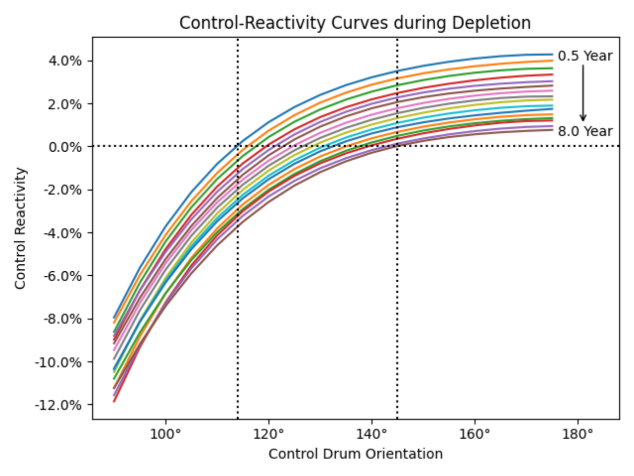


Control-Reactivity Curve

Control-Reactivity Curve

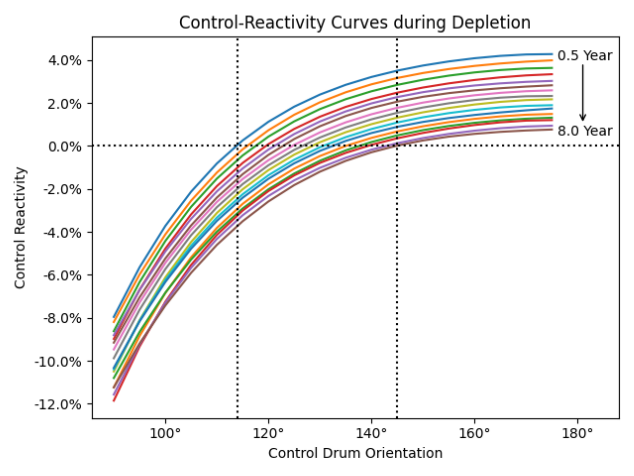


Control-Reactivity Curve



Control-Reactivity Curve

University of Idaho



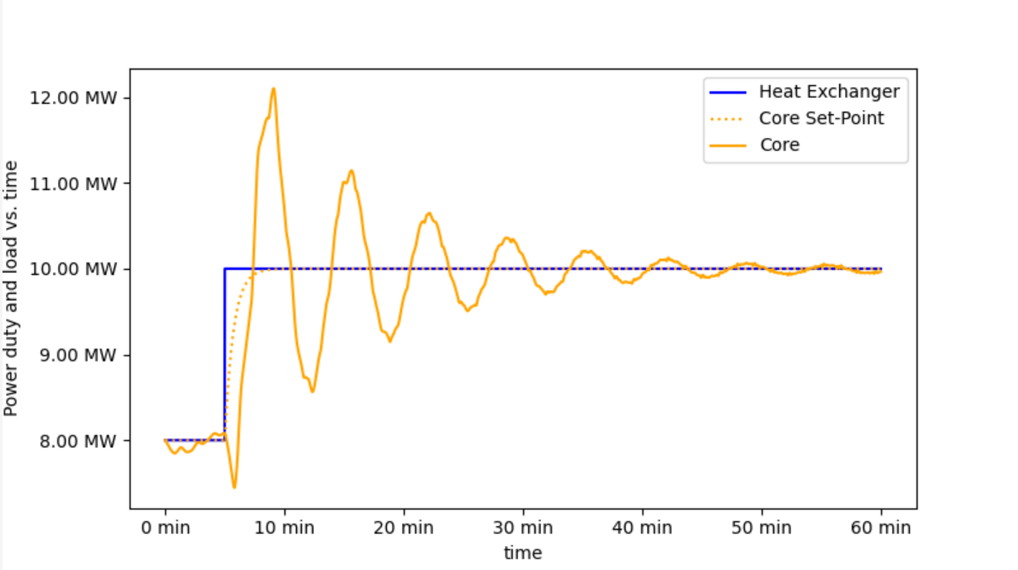
$$\rho = c_0 + c_1\theta + c_2\theta^2 + c_3\theta^3 + c_4\theta^4$$

Curve Fits

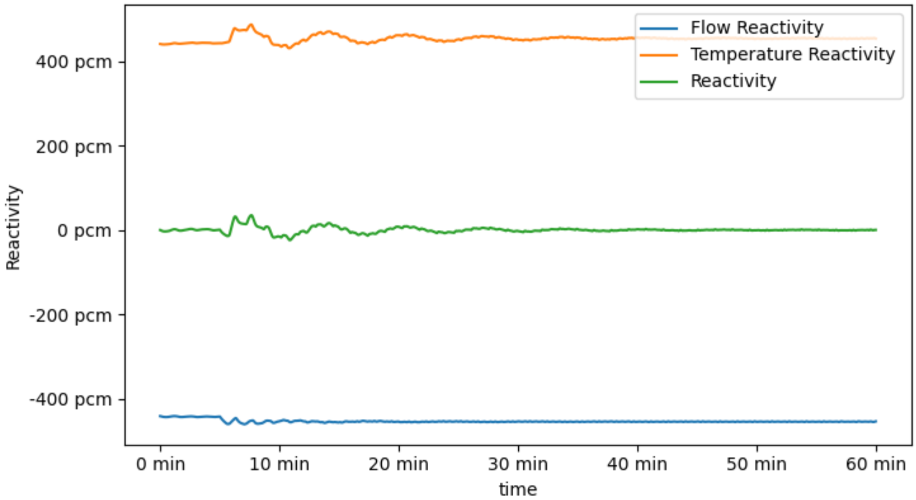
Years	$c_4 \times 10^9$	$c_3 \times 10^6$	$c_2 \times 10^4$	$c_1 \times 10^2$	c_0	root (^{o})	slope ($pcm/^o$)
0.0	-2.797	1.789	-4.361	4.829	-2.009	111.41	224.24
0.5	-2.755	1.755	-4.272	4.732	-1.976	113.69	203.69
1.0	-1.838	1.253	-3.253	3.826	-1.682	115.79	189.71
1.5	-2.533	1.632	-3.253	4.507	-1.909	117.38	175.96
2.0	-2.418	1.578	-3.930	4.440	-1.895	119.45	161.06
2.5	-1.461	1.026	-2.750	3.337	-1.515	121.06	152.71
3.0	-1.137	0.856	-2.425	3.070	-1.440	122.67	146.08
3.5	-2.054	1.357	-3.433	3.953	-1.727	124.58	130.85
4.0	-2.527	1.617	-3.967	4.438	-1.892	126.46	120.67
4.5	-2.869	1.831	-4.460	4.935	-2.081	128.35	111.30
5.0	-2.338	1.520	-3.785	4.291	-1.855	130.55	102.04
5.5	-1.471	1.054	-2.852	3.467	-1.585	132.29	93.34
6.0	-2.626	1.702	-4.211	4.729	-2.027	134.96	83.90
6.5	-1.672	1.141	-2.985	3.550	-1.607	137.45	77.56
7.0	-3.321	2.095	-5.036	5.492	-2.292	139.19	69.73
7.5	-2.419	1.579	-3.936	4.459	-1.932	142.69	59.45
8.0	-7.991	0.648	-1.960	2.623	-1.305	144.62	55.65

Up-Step

Autonomous Response



Autonomous Response



Controller Tuning

Ziegler Nichols Tuning Methodology

- P-Only Control
- Increase gain until sustained oscillations

Controller Parameters

Controller Tuning

Ziegler Nichols Tuning Methodology

- P-Only Control
- Increase gain until sustained oscillations
- Ultimate gain - 3×10^{-4} degree/kW
- Ultimate period - 45 seconds

Controller Parameters

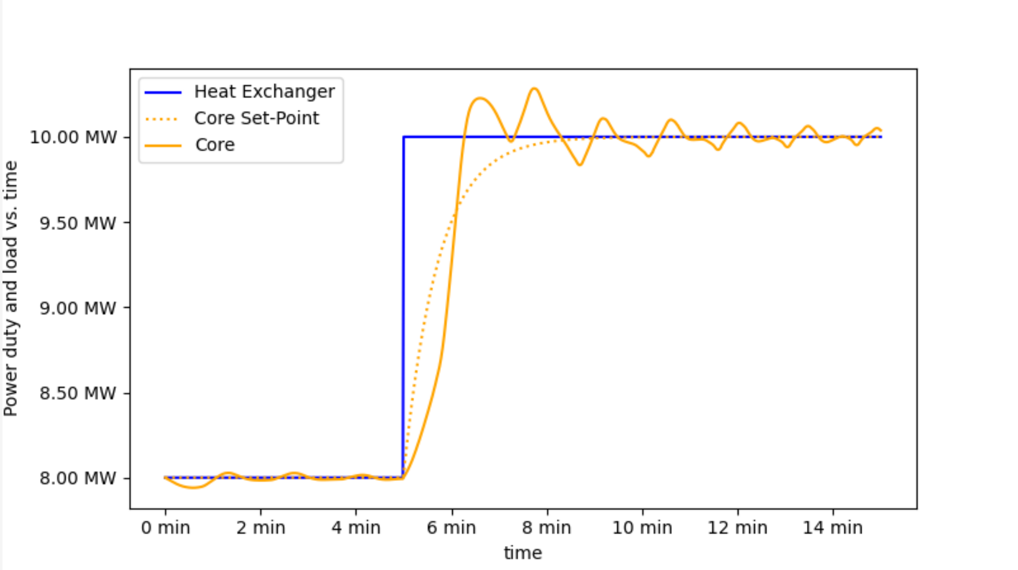
Controller Tuning

Ziegler Nichols Tuning Methodology

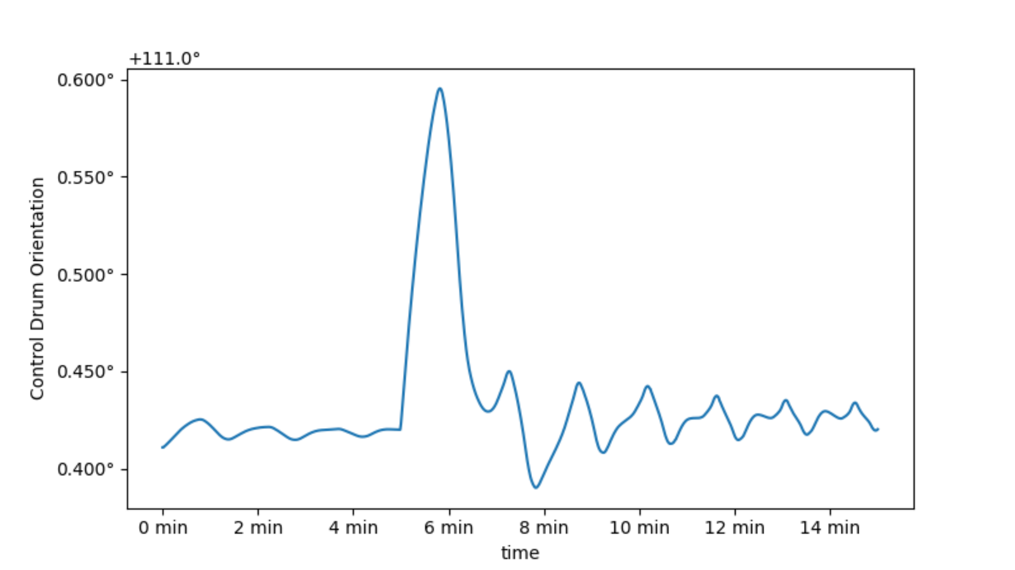
Controller Parameters

- Controller gain - 1.35×10^{-4} degree/kW at 0 years
- Controller-Actuator gain - 30.3 pcm/MW
- Integral time-constant - 37.5 seconds
- Derivative time-constant - 0 sec
- Controller bias - 111.41^{o} at zero years, 144.62^{o} at eight years

Controlled Response

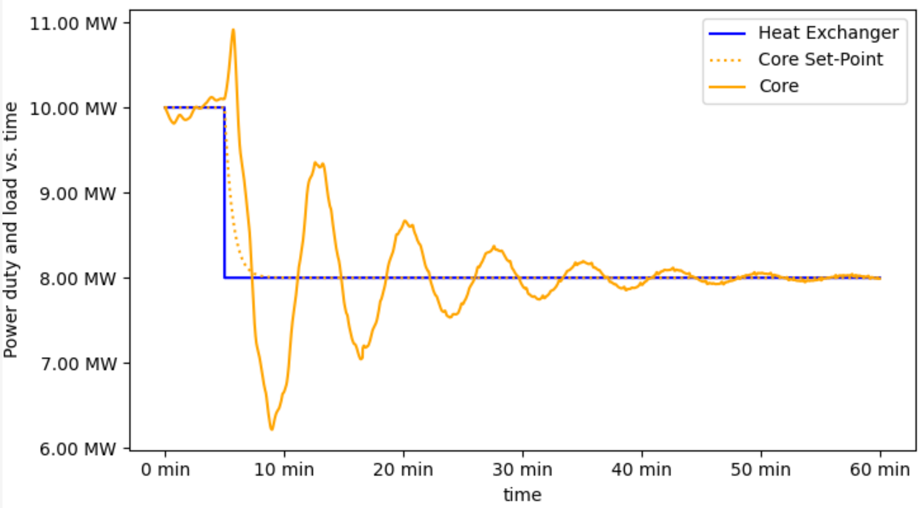


Controlled Response

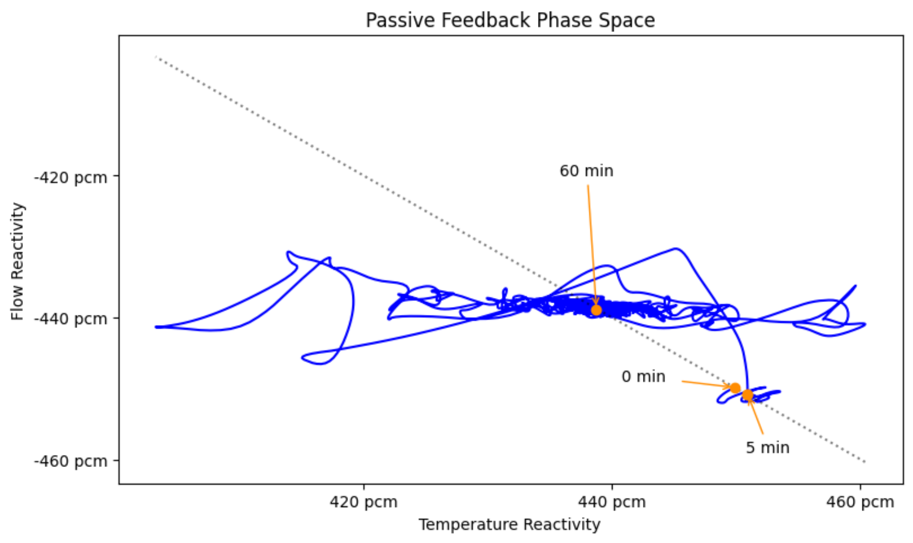


Down-Step

Autonomous Response

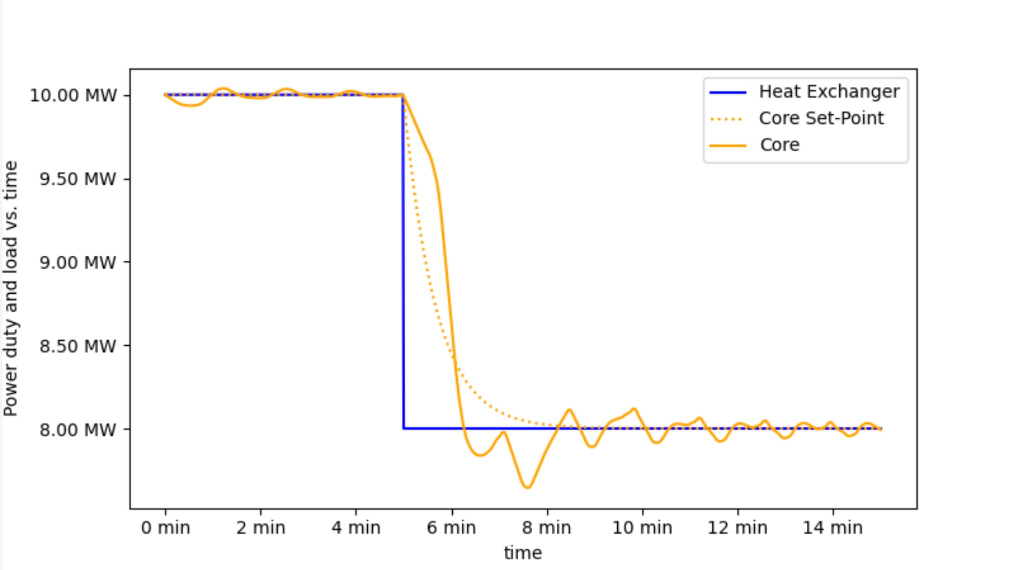


Autonomous Response

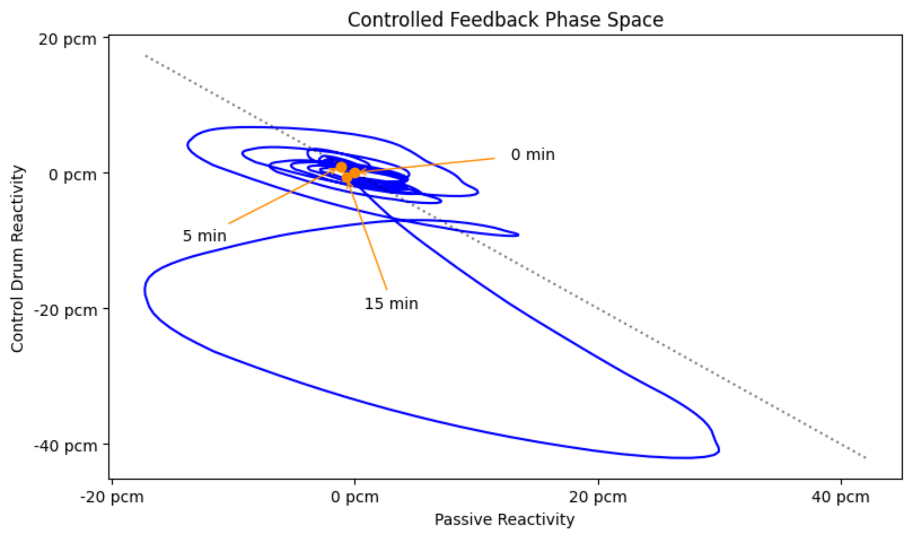


Controlled Response

University of Idaho

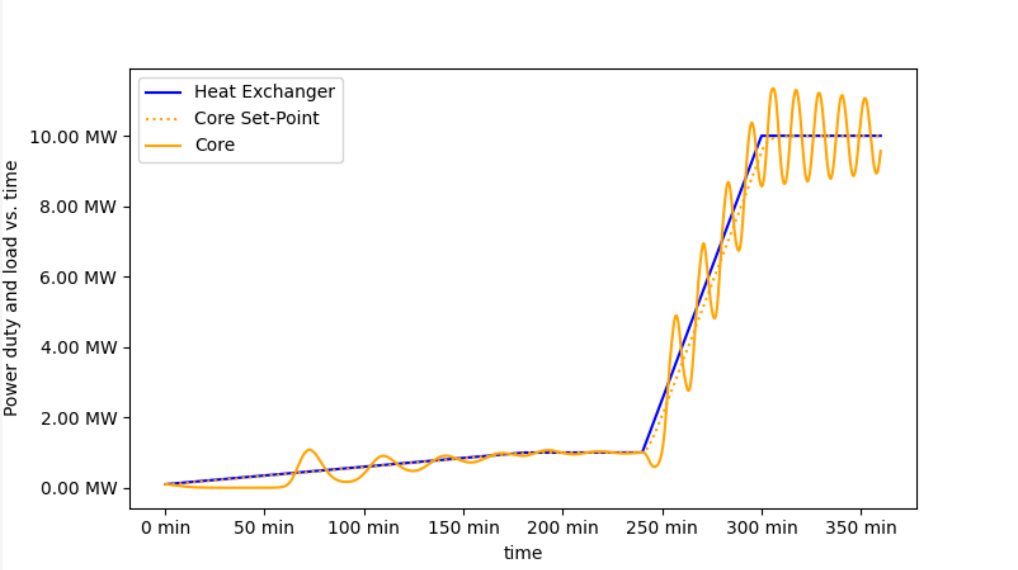


Controlled Response

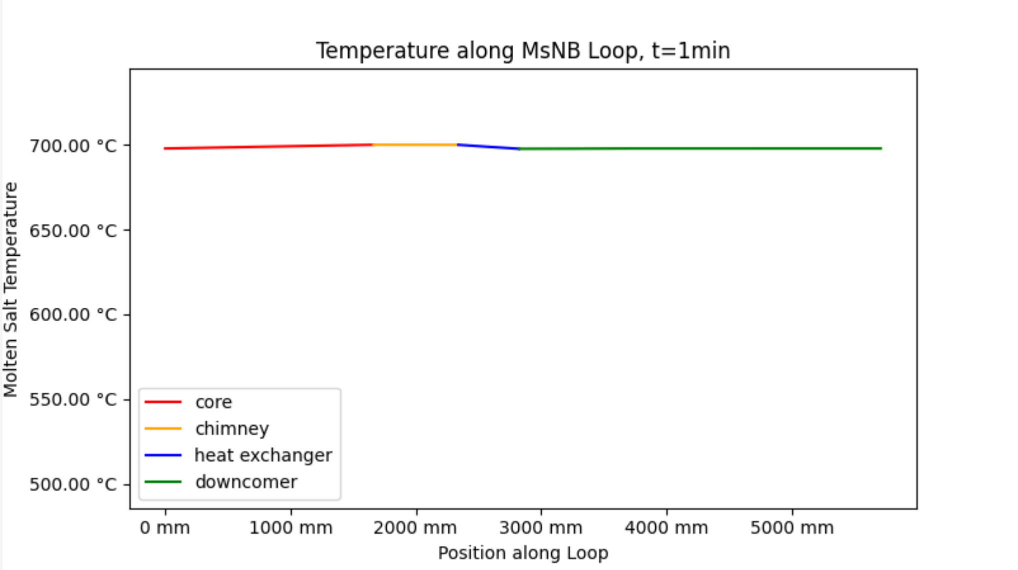


Start-Up

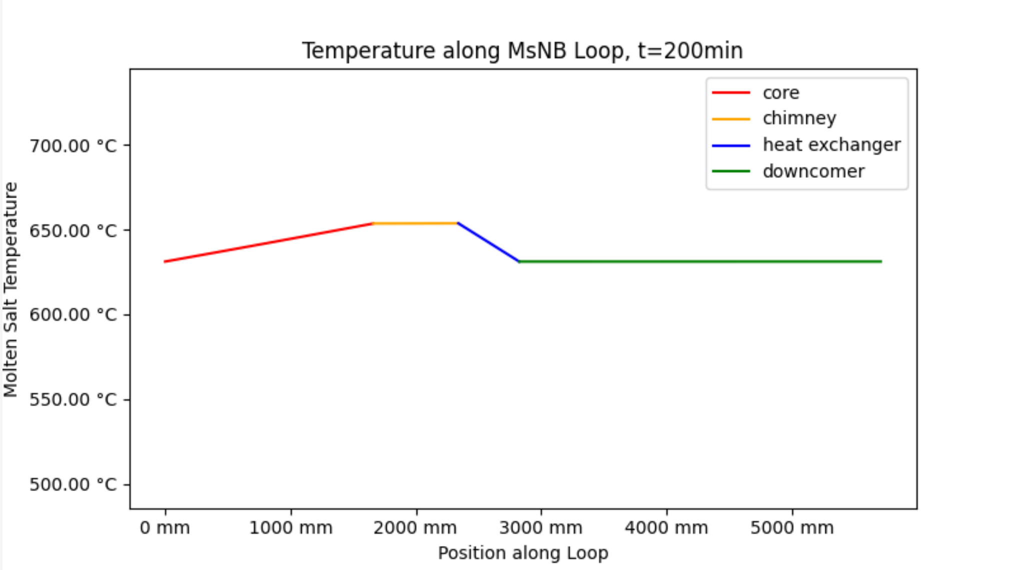
Autonomous Response



Autonomous Response



Autonomous Response



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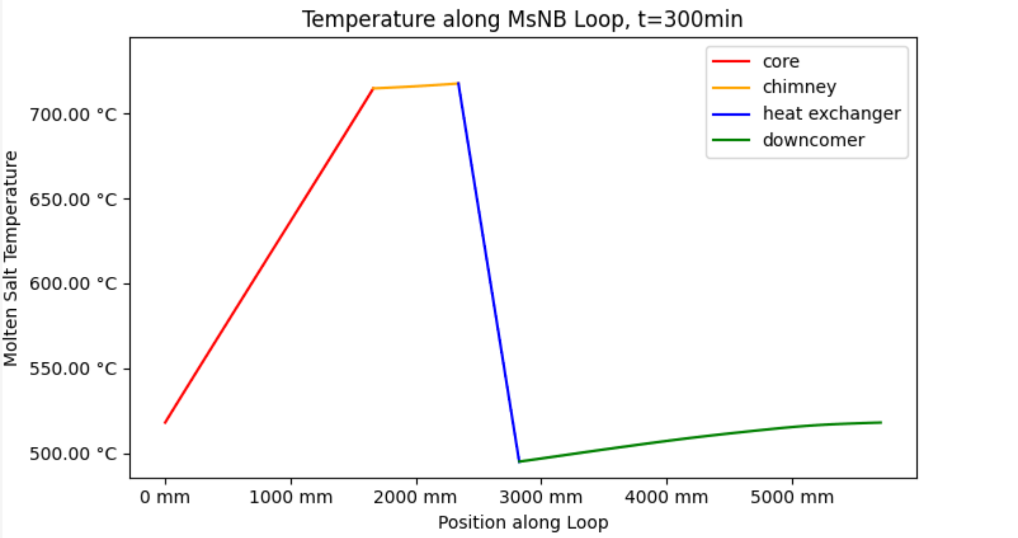

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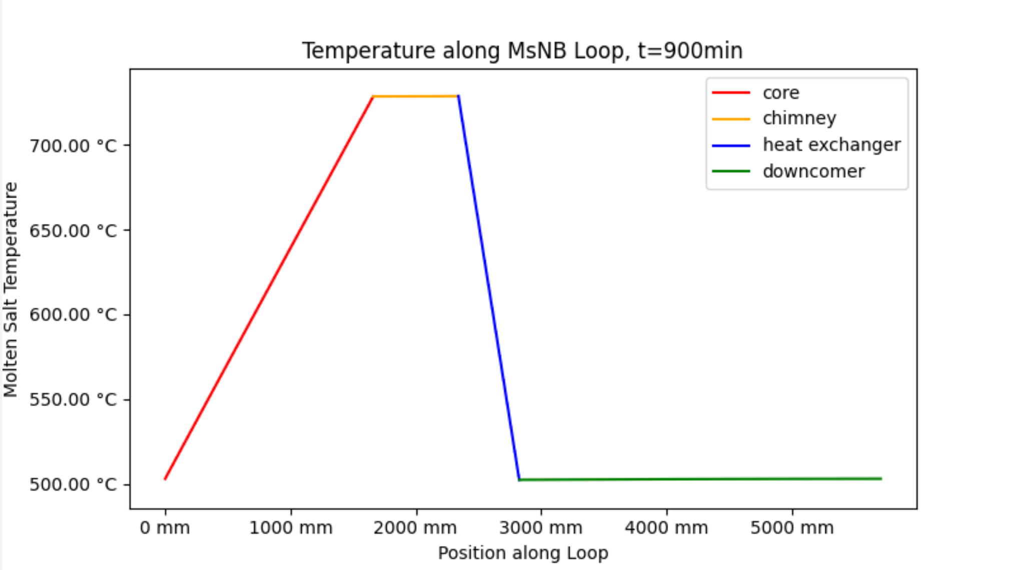

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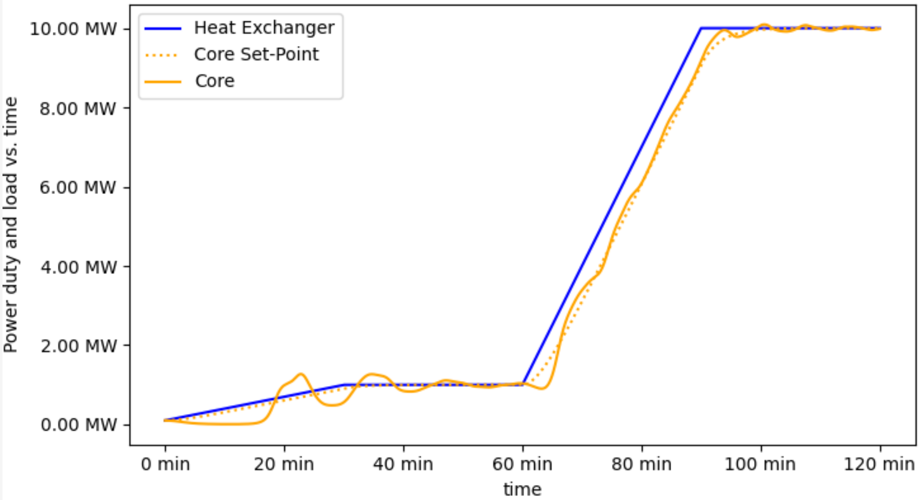

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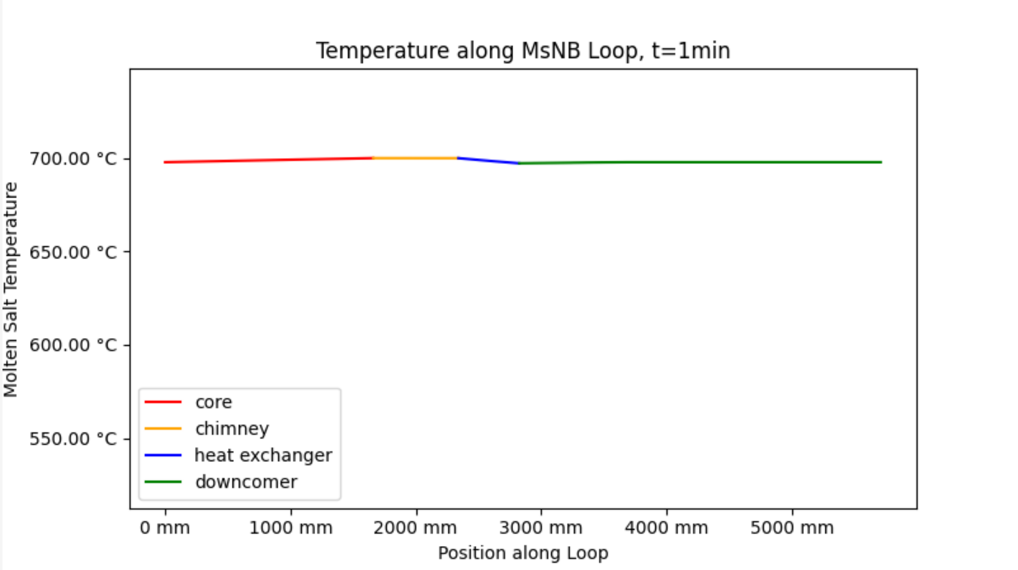

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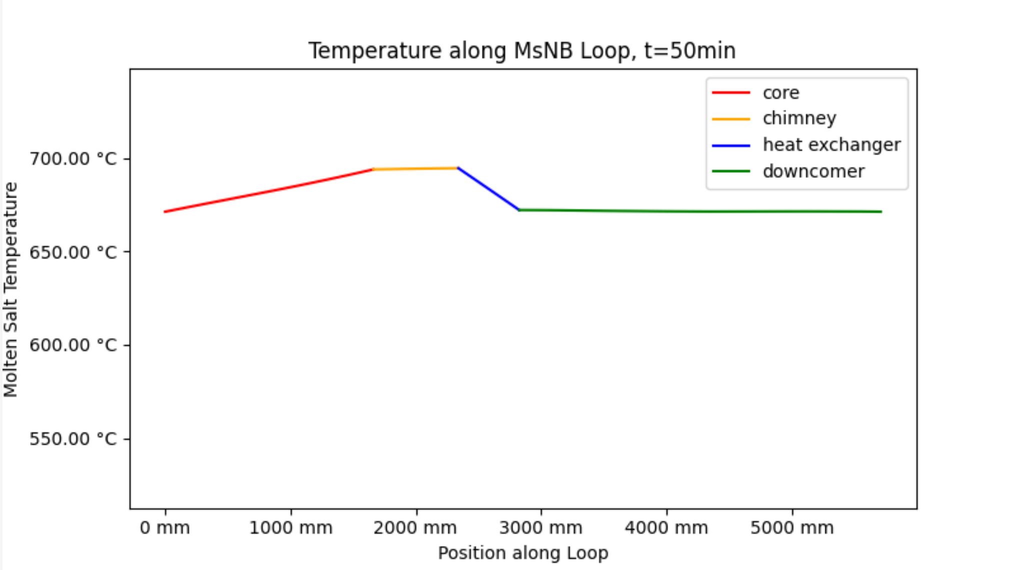

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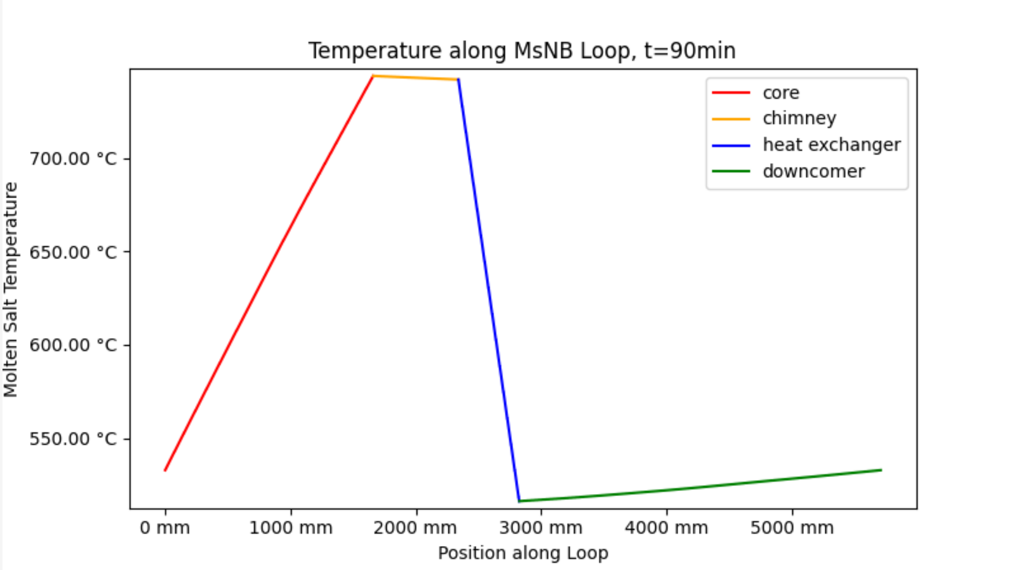

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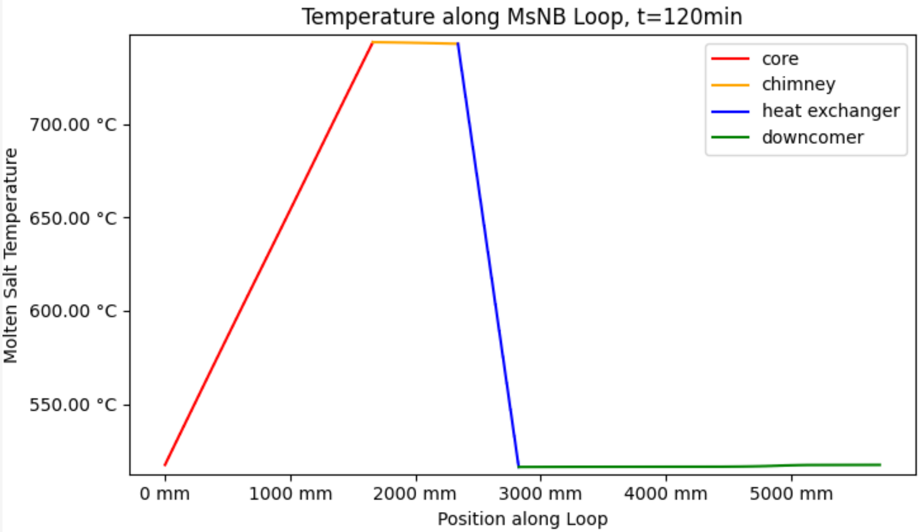
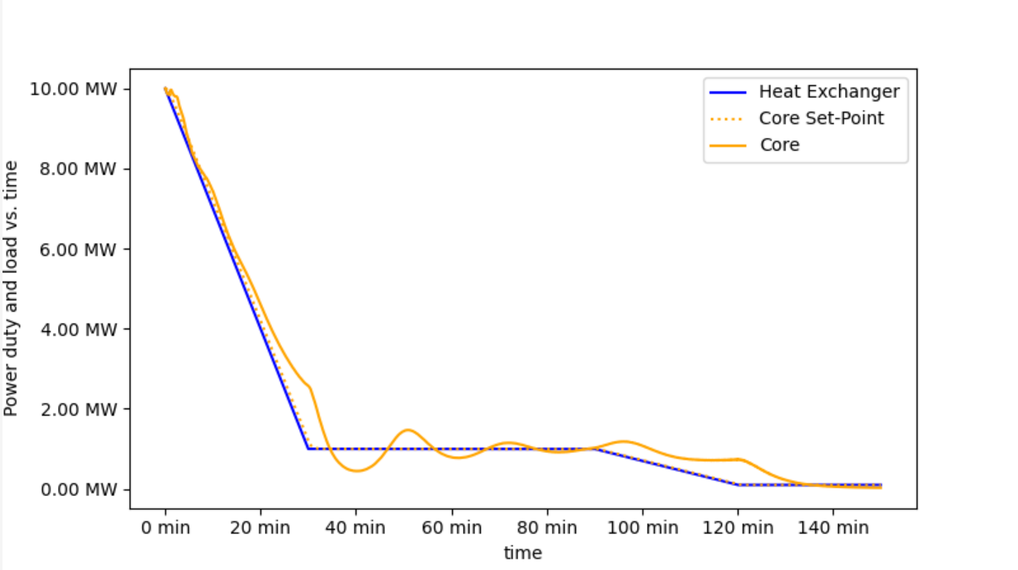


Shut-Down

Autonomous Response



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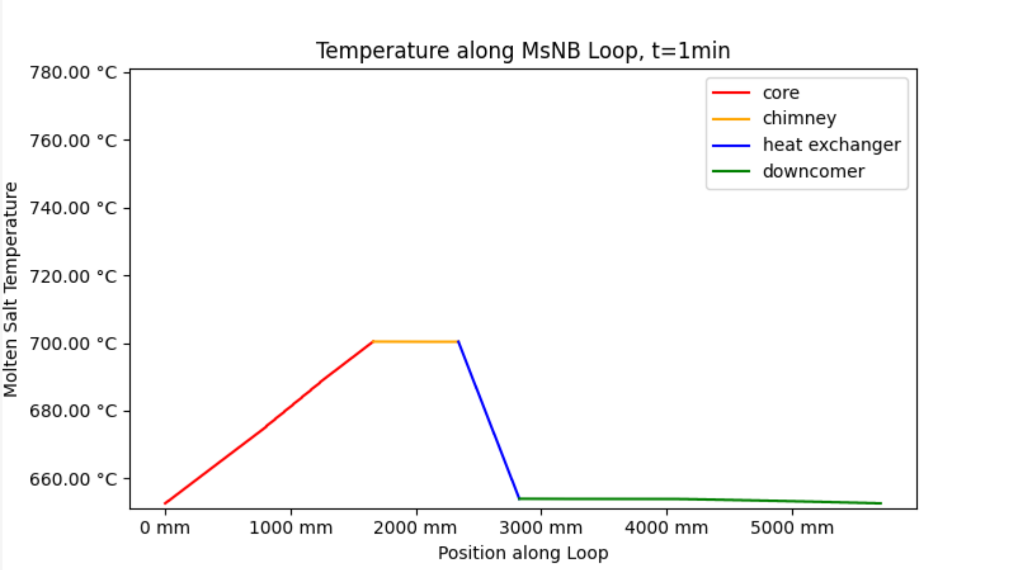

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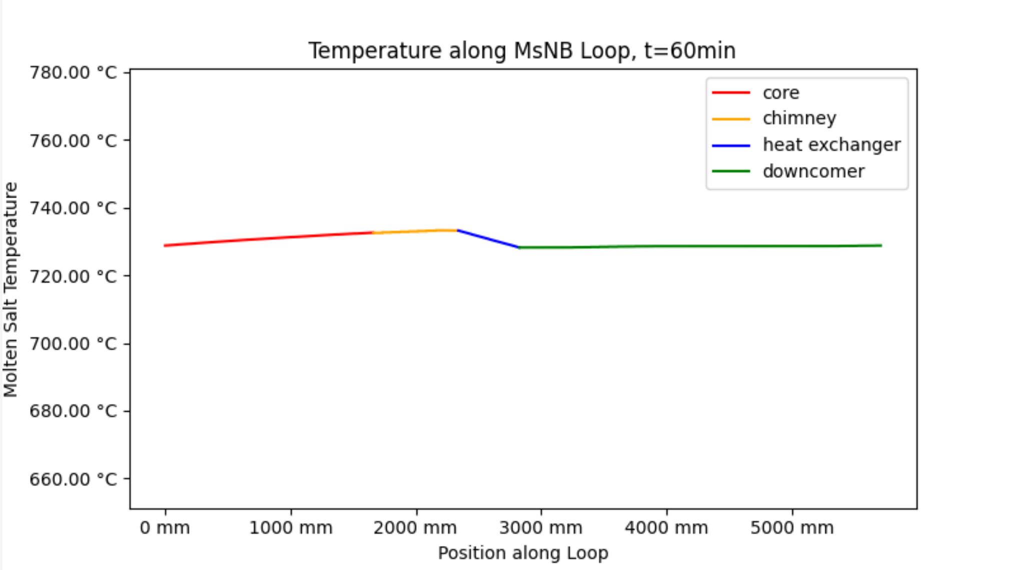

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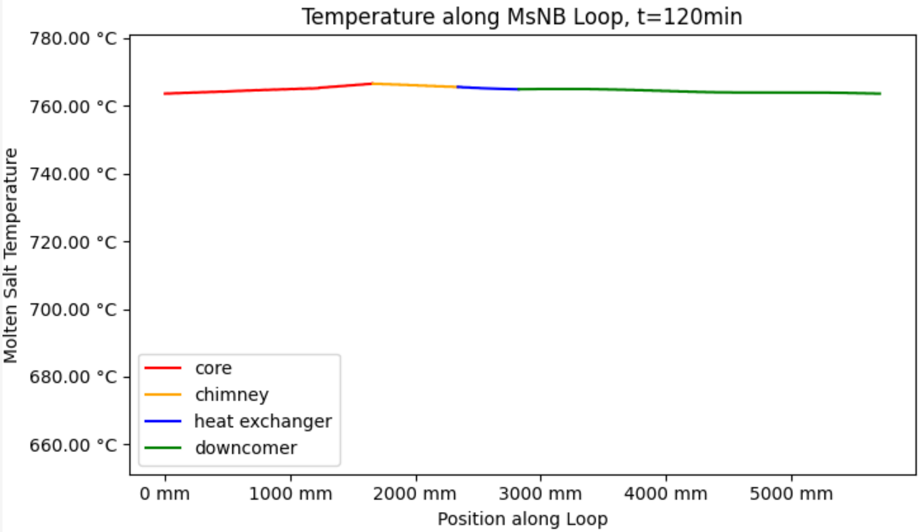

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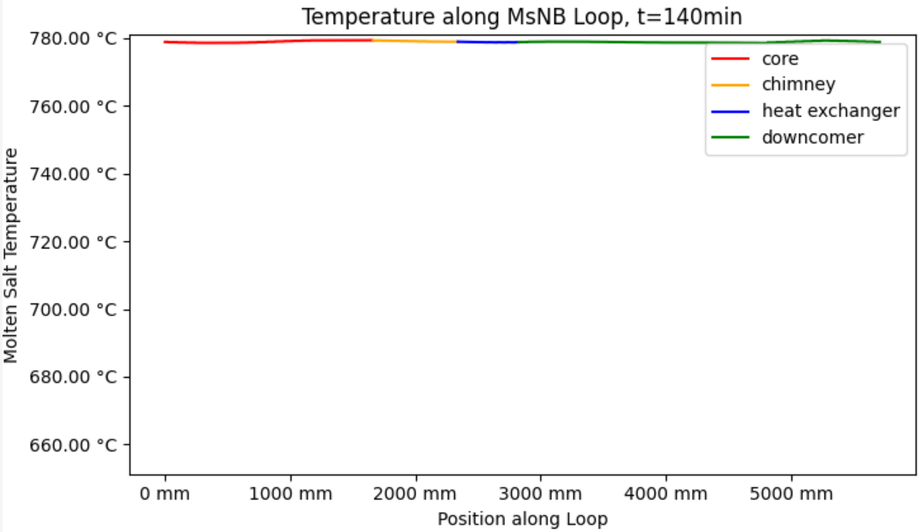

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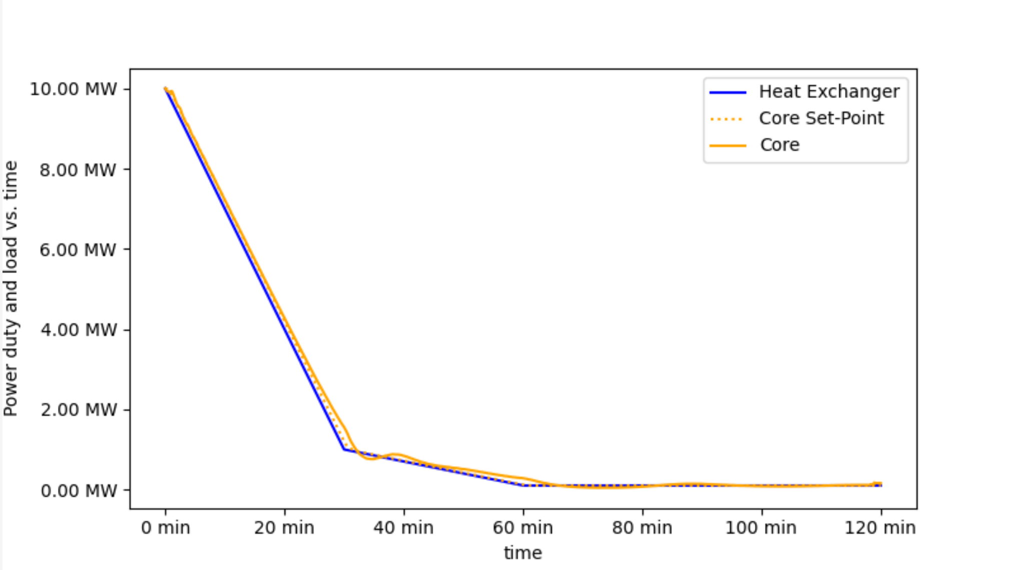

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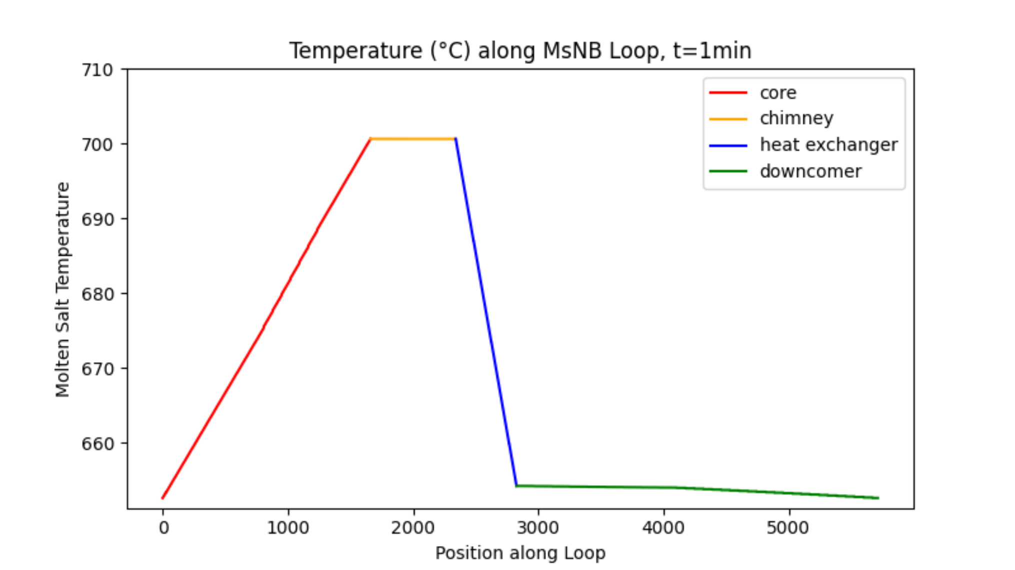

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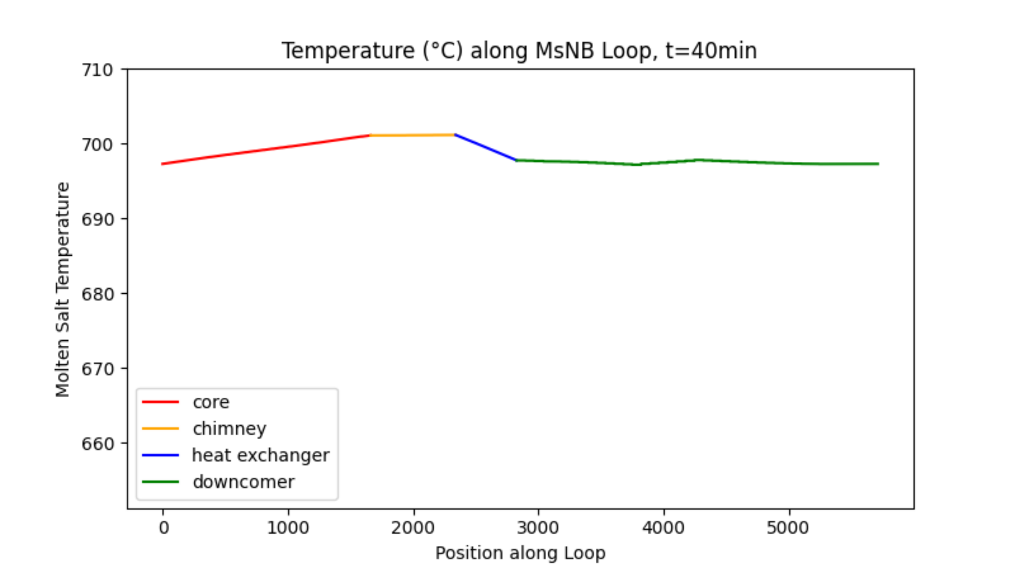

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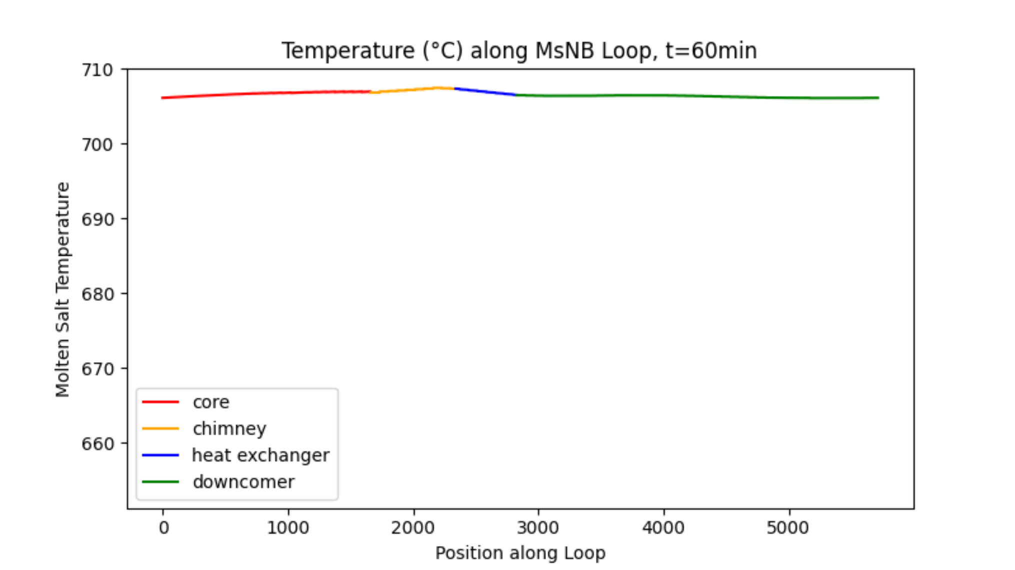

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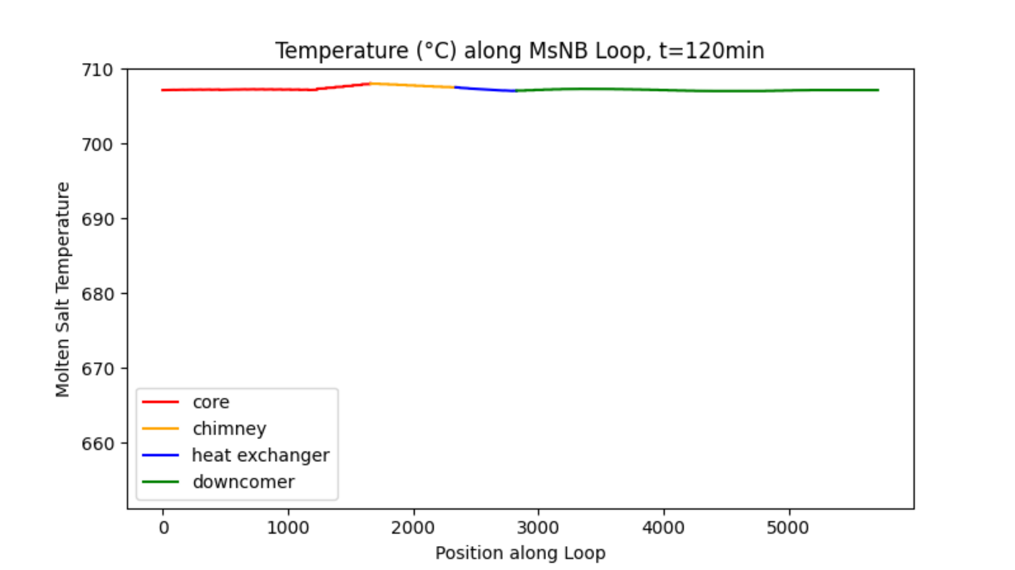
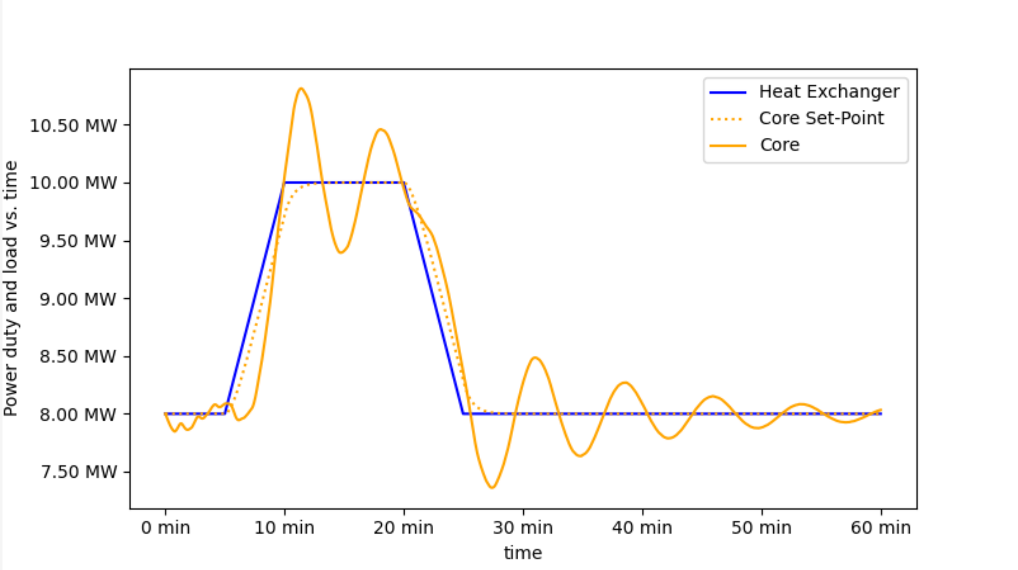
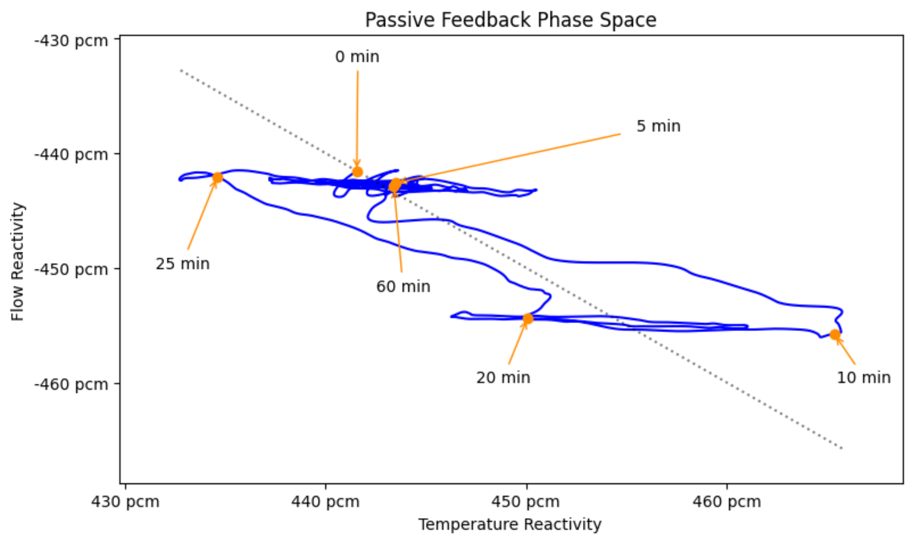


Demand-Response

Autonomous Response



Autonomous Response



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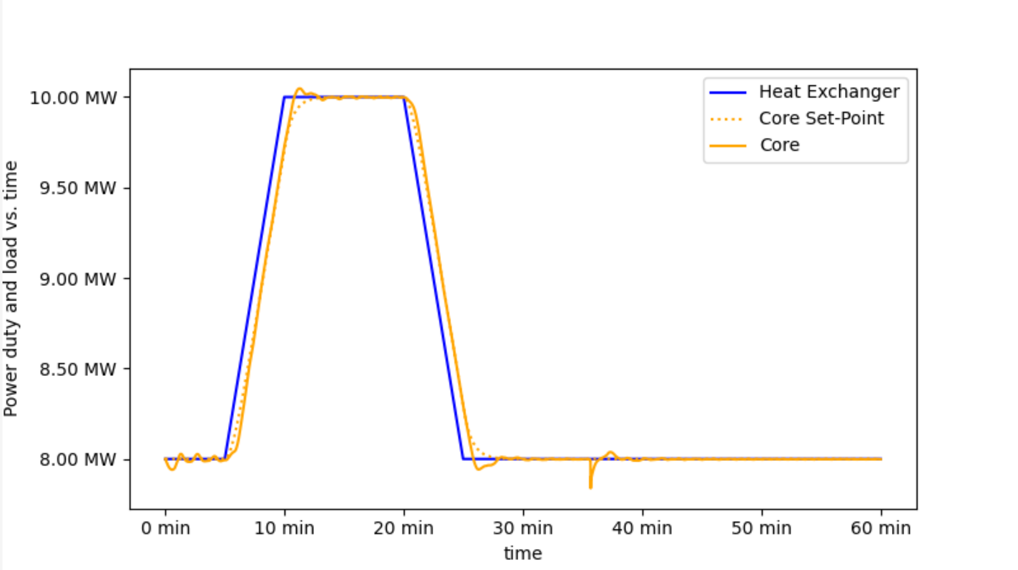
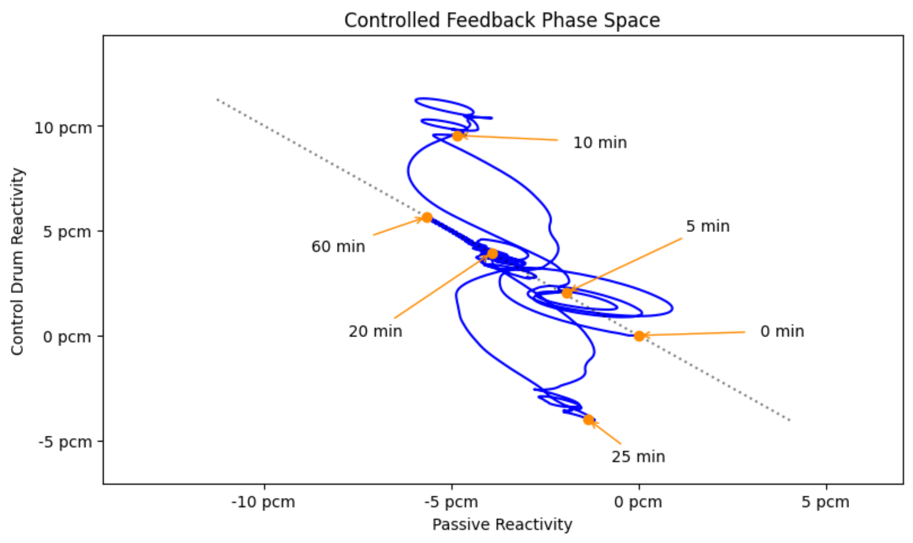


Controlled Response



Conclusions

Summary of Models Completed

- Alternating criticality and burn-up models were developed in Serpent 2 to study the evolution of the control-reactivity curve over the life of the MSNB
- Mass and energy conservation were coupled to reactor point kinetics in a Python 3.10 code to predict the flow rate and power of the MSNB
- Time and spatial advancement routine simulates heat and mass advection according to uniform-state uniform-flow
- A pre-filter reshapes the heat exchanger demand
- A PI controller compliments the passive feedback mechanisms inherent to the MSNB

Results In-Brief

Conclusions

Summary of Models Completed

Results In-Brief

- The MSNB design studied in this work has an excess reactivity of 4.834% at hot-standby
- After 8 full-power years, the MSNB fuel is depleted enough to no longer provide enough excess reactivity for effective operation
- The autonomous response is stable, but significantly under-damped for 20% step functions and ramp functions of up to 400 kW/min
- The PI controller improves the settling time by an order of magnitude for step functions, and essentially eliminates overshoot for ramp functions
- With a robust controller, the MSNB is suitable for load-following

Acknowledgements

This work and my coursework is being completed under a Graduate Fellowship funded by Nuclear Regulatory Commission (NRC).
This research made use of the resources of the High Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.

University of Idaho

Department of Nuclear Engineering and Industrial Management

References I

1. Root, S. J., et al., 2023. Thermodynamic analysis on xenon stripping to shorten restart time in molten salt microreactors. Nuclear Engineering and Design 414, 112606.
2. Root, S. J., et al., 2023. Cyber hardening of nuclear power plants with real-time nuclear reactor operation, 1. preliminary operational testing. Progress in Nuclear Energy 162, 104742.
3. Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor. Master's thesis, University of Idaho.
4. Carter, J. P., 2022. Multi-physics investigation of a natural circulation molten salt micro-reactor that utilizes an experimental in-pile device to improve core physics and system thermal-hydraulic performance. Ph.D. thesis, University of Idaho.
5. Kerlin, T. W. et al., 2019. Dynamics and Control of Nuclear Reactors. Knoxville, Tennessee: Elsevier Inc.
6. Duderstadt, J. J. et al., 1976. Nuclear Reactor Analysis. New York, NY: Wiley & Sons, first edition.
7. Lamarsh, J. R. et al., 2001. Introduction to Nuclear Engineering. Upper Sadle River, New Jersey: Pretice Hall, third edition.