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

Sam J. Root

University of Idaho ▪ Idaho Falls Center for Higher Education
Department of Nuclear Engineering and Industrial Management

December 6th, 2023

University of Idaho
Department of Nuclear Engineering
and Industrial Management

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

Introduction

Background

Gen-IV

blah

Molten Salt Reactors

Microreactors

Background

Gen-IV

Molten Salt Reactors

blah

Microreactors

Background

Gen-IV

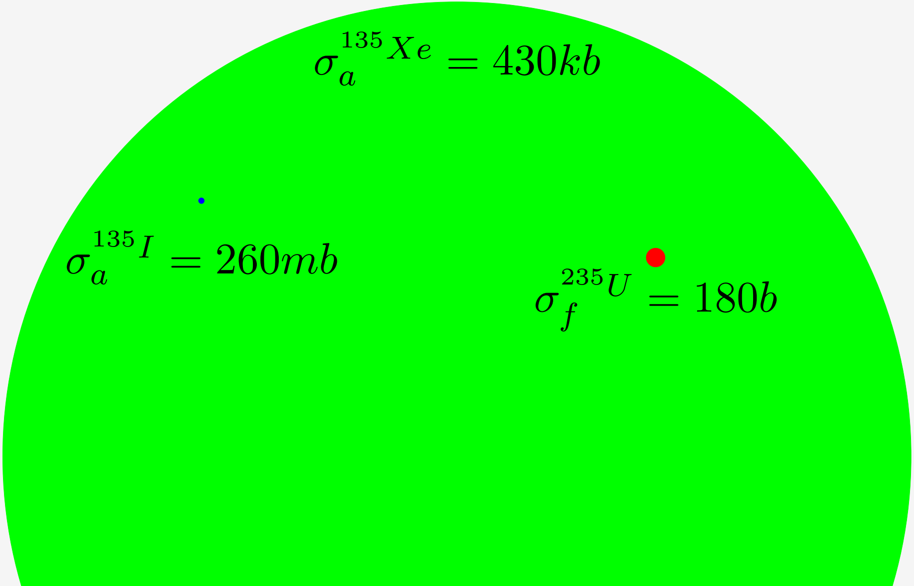
Molten Salt Reactors

Microreactors

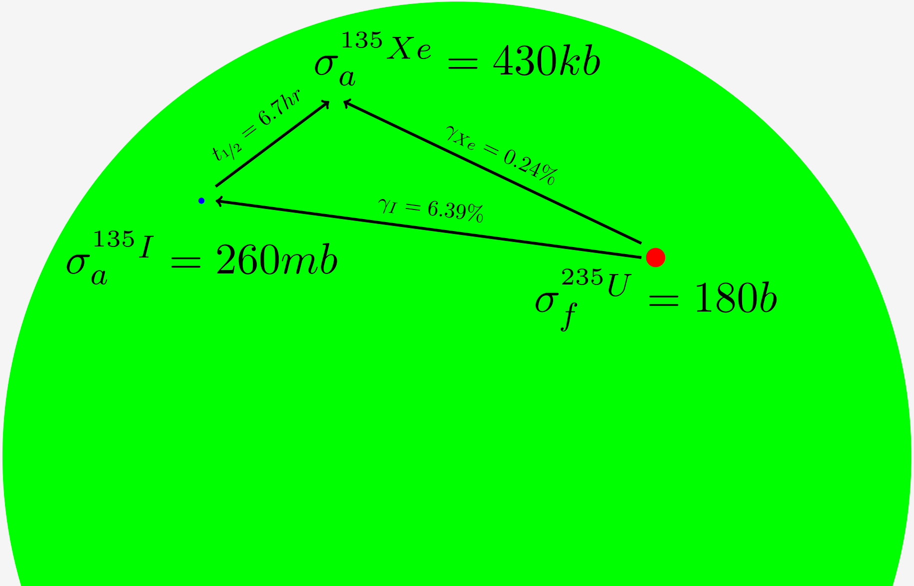
blah

Xenon-135 Stripping In-Brief

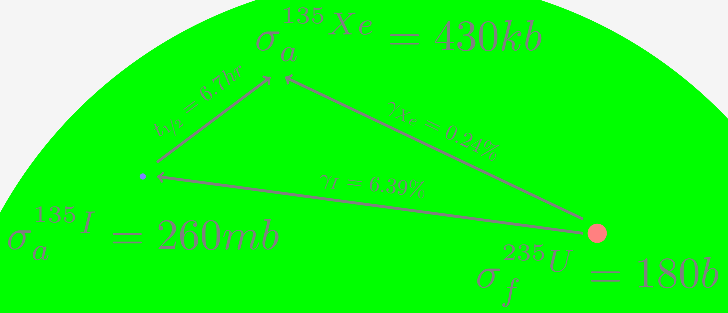
Fission Product Poisoning



Fission Product Poisoning



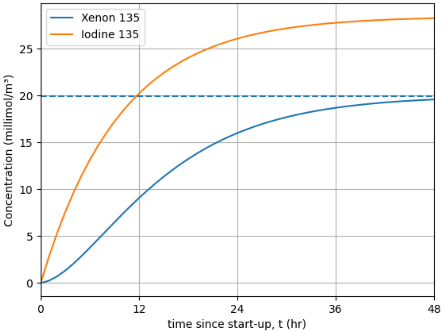
Fission Product Poisoning



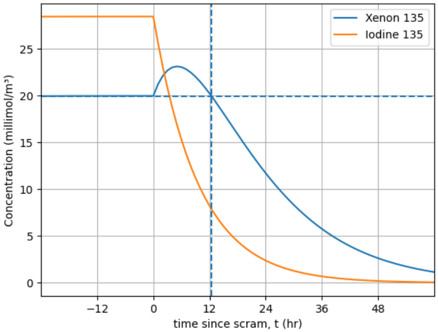
$$\frac{dI}{dt} = \underbrace{\gamma_I \Sigma_f^F \phi(t)}_{\text{Fission Yield}} - \underbrace{\lambda_I I(t)}_{\text{Beta Decay}}$$

$$\frac{dXe}{dt} = \underbrace{\lambda_I I(t)}_{\text{Precursor Decay}} + \underbrace{\gamma_{Xe} \Sigma_f^F \phi(t)}_{\text{Fission Yield}} - \underbrace{\lambda_{Xe} Xe(t)}_{\text{Beta Decay}} - \underbrace{Xe(t) \sigma_a^{Xe} \phi(t)}_{\text{Radiative Capture}}$$

Xenon Dynamics

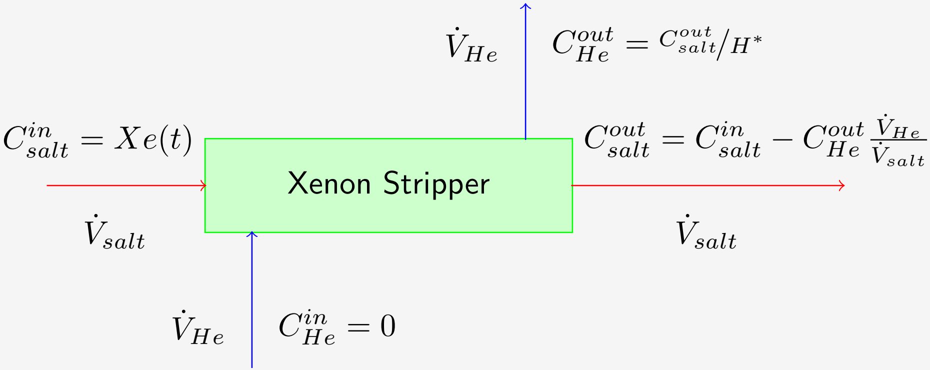


Concentration of ^{135}I and ^{135}Xe vs. time following start-up



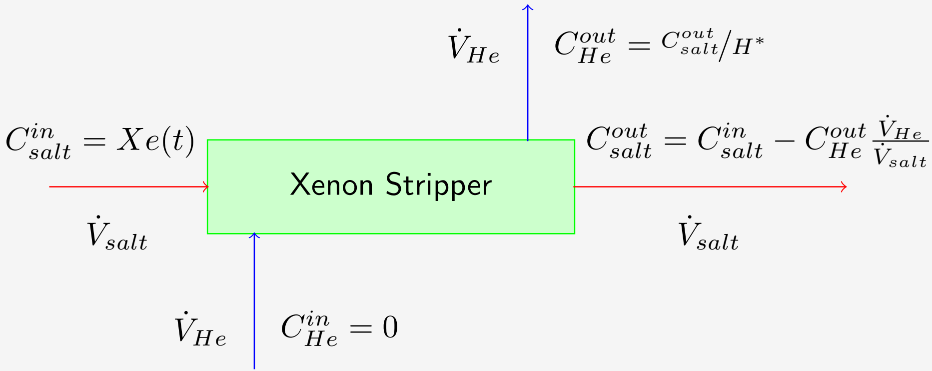
Concentration of ^{135}I and ^{135}Xe vs. time following reactor scram

Xenon Stripper



Schematic Drawing of Xenon Stripping Module

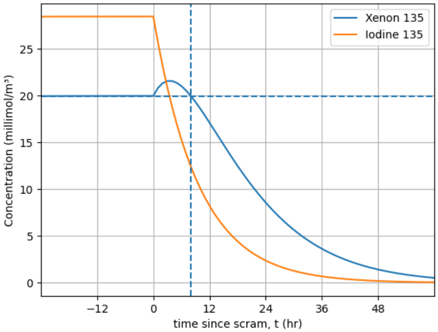
Xenon Stripper



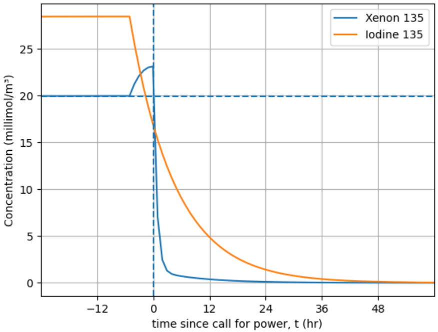
Schematic Drawing of Xenon Stripping Module

$$\frac{dXe}{dt} = \underbrace{\gamma_{Xe}\Sigma_f^F\phi(t)}_{\text{Fission Yield}} + \underbrace{\lambda_I I(t)}_{\text{Precursor Decay}} - \underbrace{\lambda_{Xe}Xe(t)}_{\text{Beta Decay}} - \underbrace{Xe(t)\sigma_a^{Xe}\phi(t)}_{\text{Radiative Capture}} - \underbrace{\frac{Xe(t)}{\tau_{salt}}\left(H^*\frac{\dot{V}_{salt}}{\dot{V}_{He}} + 1\right)^{-1}}_{\text{Stripping}}$$

Xenon Stripping Dynamics



Concentration of ^{135}I and ^{135}Xe vs. time following reactor scram - Restart Mode

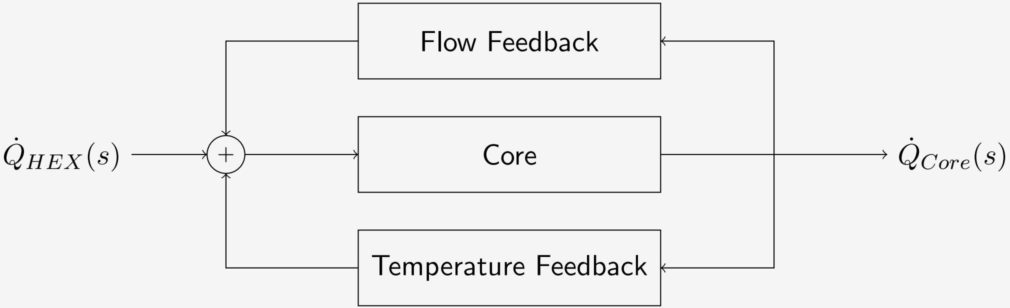


Concentration of ^{135}I and ^{135}Xe vs. time following reactor scram - Standby Mode

Control Theory

Transport Delay Problem

Passive Feedback



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

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 [3, Ch. 7]
- More epithermal neutrons absorbed by ^{238}U etc. [4, Ch. 6]

Thermal Expansion

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

[4] 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 [5]
- Similar to moderator thinning in LWRs

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

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 [6, Ch. 6]

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

Flowing Fuel

[6] 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 [3, Ch. 3]
- Larger power transport requires a higher flow rate
- Greater delayed neutron losses
- Negative feedback

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

Main Operational Control Problem - Transport Delay

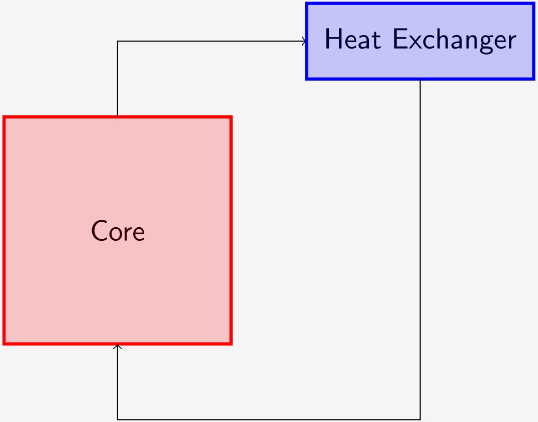
Dynamics associated with anticipated transients

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

Thought Experiment

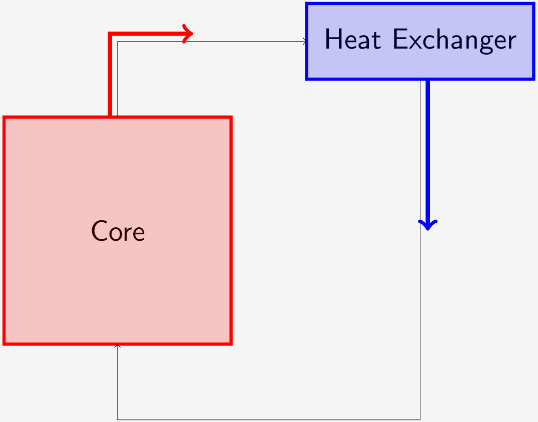
- Step increase in power demand to a steady-state critical MSNB
- Set-point is instantaneously equal to heat exchanger power consumption
- Ideal controller which produces rapid load following with minimal overshoot

Main Operational Control Problem - Transport Delay

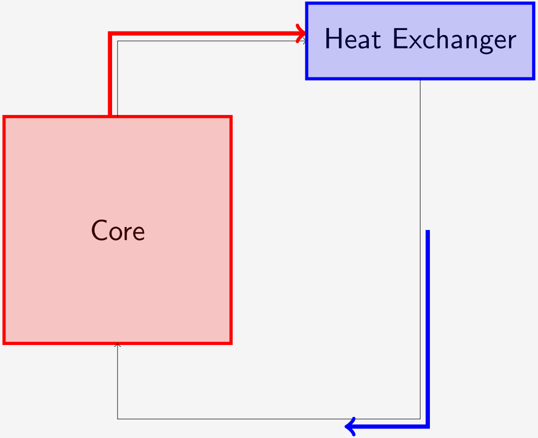


Simplified schematic drawing of a natural circulation MSNB

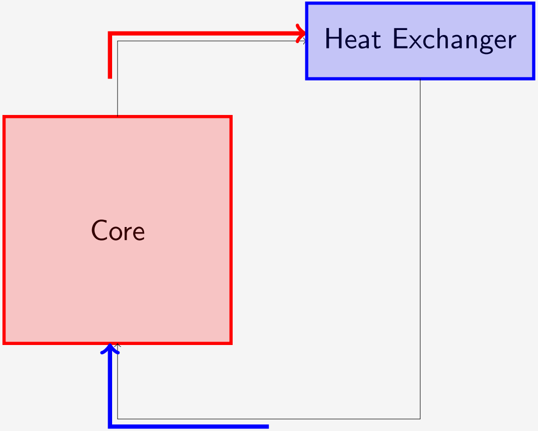
Main Operational Control Problem - Transport Delay
Immediate Response



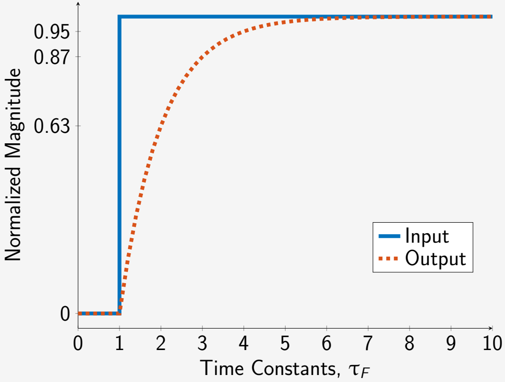
Simplified schematic drawing of a natural circulation MSNB



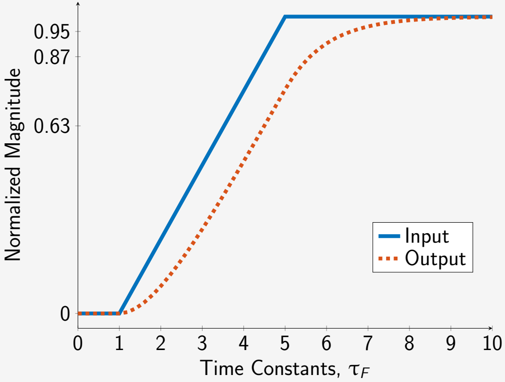
Simplified schematic drawing of a natural circulation MSNB



Simplified schematic drawing of a natural circulation MSNB



Pre-Filter on a step-function



Pre-Filter on a ramp-function

Neutronics Modeling

Process Simulation

Control-Reactivity Curve

Controller Tuning

Demand Response

1 The Molten Salt Nuclear Battery

2 Process Control Engineering

3 Reactor Characterization

4 Results and Analysis

5 Conclusions

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

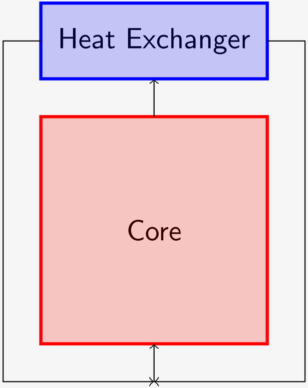
1. Root, S. J., et al., 2023. Thermodynamic analysis on xenon stripping to shorten restart time in molten salt microreactors. Nuclear Engineering and Design 414, 112606.
2. Root, S. J., et al., 2023. Cyber hardening of nuclear power plants with real-time nuclear reactor operation, 1. preliminary operational testing. Progress in Nuclear Energy 162, 104742.
3. Kerlin, T. W. et al., 2019. Dynamics and Control of Nuclear Reactors. Knoxville, Tennessee: Elsevier Inc.
4. Duderstadt, J. J. et al., 1976. Nuclear Reactor Analysis. New York, NY: Wiley & Sons, first edition.
5. Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor. Master's thesis, University of Idaho.
6. Lamarsh, J. R. et al., 2001. Introduction to Nuclear Engineering. Upper Sadle River, New Jersey: Pretice Hall, third edition.
7. 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.
8. Bequette, B. W., 2003. Process Control: Modeling Design and Simulation. Upper Sadle River, New Jersey: Pretice Hall.

References II

9. Gahinet, P. M. et al., 2013. Automated tuning of gain-scheduled control systems. IEEE Conference on Decision and Control .
10. Al Rashdan, A. et al., 2019. A frequency domain control perspective on xenon resistance for load following of thermal nuclear reactors. IEEE Transactions on Nuclear Science 66(9), 2034.
11. Wang, S., et al., 2019. A passive decay heat removal system for emergency draining tanks of MSRs. Nuclear Engineering and Design 341, 423.

Molten Salt Nuclear Battery (MSNB)

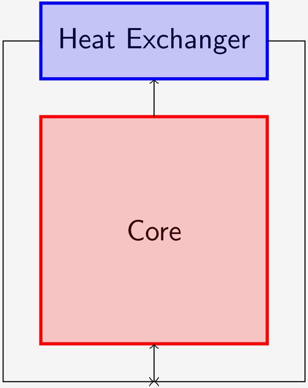
- Self-Contained liquid fueled molten salt micro-reactor - 10 year design
- 1 MW design using HALEU UF_4dissolved in $FLiNaK$
- Criticality is manipulated using axial control drums
  - Neutron absorber plate covering cylinders of neutron reflector
  - Drums are rotated to point more absorber towards the core to insert negative control reactivity



Simplified schematic drawing of an MSNB

Molten Salt Nuclear Battery (MSNB)

- Self-Contained liquid fueled molten salt micro-reactor - 10 year design
- 1 MW design using HALEU UF_4dissolved in $FLiNaK$
- 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

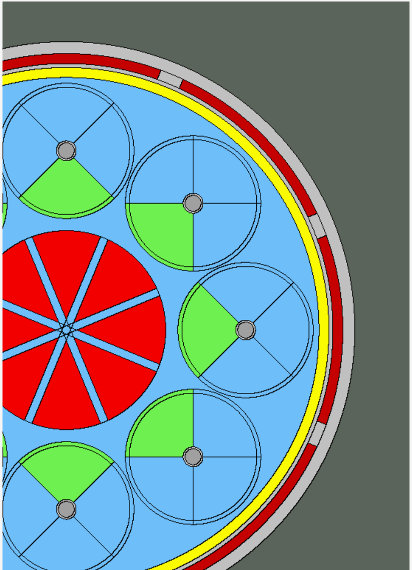


Simplified schematic drawing of an MSNB

Molten Salt Nuclear Battery (MSNB)

University of Idaho

- Self-Contained liquid fueled molten salt micro-reactor - 10 year design
- 1 MW design using HALEU UF_4dissolved in $FLiNaK$
- 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



Background on MSNB

Neutronics [5]

- Control drums give a uniform axial and radial flux profile for all reactivity insertions
- Fission product poisoning is the biggest challenge to reach the desired 10-year lifespan
- Control drum vs. reactivity curve is sinusoidal

Thermal Hydraulics [7]

Process Control

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

[7] 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

Background on MSNB

University of Idaho

Neutronics [5]

Thermal Hydraulics [7]

- The counteracting passive feedback effects of temperature reactivity and flow reactivity produce stable autonomous load following for relatively small ramp function power demand transients
- An in-core helix device can be used to manipulate temperature and power profiles in the core, as well as minimize advective loss of delayed-neutron precursors

Process Control

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

[7] 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

Background on MSNB

University of Idaho

Neutronics [5]

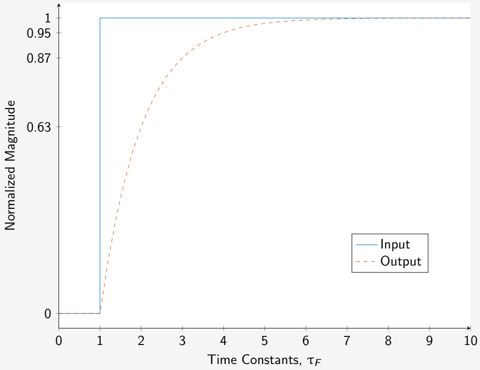
Thermal Hydraulics [7]

Process Control

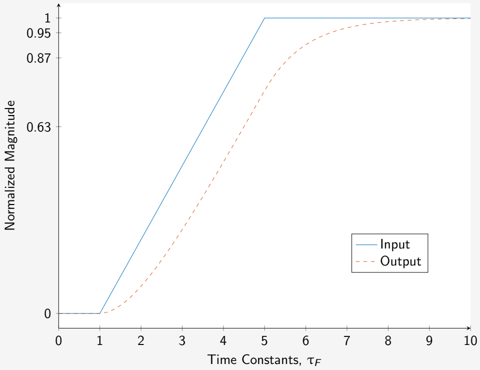
- Design controller *compliment* the autonomous capabilities provided by the passive feedback mechanisms
- Allow larger faster, more aggressive power changes
- Additional focus on time periods with a high degree of time variance (start-up, shut-down, re-start)

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

[7] 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



Pre-Filter on a step-function



Pre-Filter on a ramp-function

- Minor perturbations will cause power fluctuations
- Fine grain and constant control actuation would burn out servos prematurely
- When the error is small, allow the passive feedback mechanisms to fine tune

- Disturbances, particularly temperature reactivity, are extremely high frequency - On order of mean neutron lifetime [6, Ch. 7]
- Control actuation is similarly quick
- Time delays on the order of dozens of seconds to minutes
- Inserting control reactivity to counteract temperature reactivity at the exact right moment would be difficult or impossible, so it is unlikely that a disturbance feedforward controller could reject the disturbance before it causes error [8, Ch. 10]
- Disturbance rejection best left to feedback PID controller

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

[8] Bequette, B. W., 2003. Process Control: Modeling Design and Simulation. Upper Sadle River, New Jersey: Pretice Hall

- Sinusoidal control drum angle vs. reactivity curve - non-linear reactivity actuation - Taylor Series approximation to linearize around the operating point [8, Ch. 2]
- Fissile depletion changes the amount of control reactivity required to make the core critical - time-variant controller bias - Bias and gain schedule [9]
- Control drums manipulate *criticality*, not power directly - highly time-dependent control actuation

[9] Gahinet, P. M. et al., 2013. Automated tuning of gain-scheduled control systems. IEEE Conference on Decision and Control

[8] Bequette, B. W., 2003. Process Control: Modeling Design and Simulation. Upper Sadle River, New Jersey: Pretice Hall

- Equilibrium Poisoning
  - Poisons like ^{135}Xe and ^{149}Sa build-up after the reactor starts - this causes a negative reactivity insertion
  - Reach equilibrium over the first $\tilde{1}00$ hours
  - Gain/Bias schedule may be used
  - Alternatively, a burnable poison with appropriate *effective* half-life could be selected - ^{157}Gd shows promise to counteract ^{135}Xe build-up
- Restart Poisoning
  - ^{135}Xe levels increase following shut-down because its beta-precursor (^{135}I) decays faster
  - Requires a lot of excess control reactivity and very good control to counteract the positive reactivity insertion of poison burn-out after restart
  - Low-flux burn-out instead of full shut-down
  - Stripping ^{135}Xe and other fission gasses before re-start

Control Drum Characterization
MCNP

- Use KCODE to develop control drum vs. reactivity curve at various points in the core lifespan
- Use Burn-up routine to study how the core criticality at different conditions effects the control drum vs. reactivity
    - Cold/clean start-up
    - Burnable poison start-up
    - Equilibrium poisoning
    - Long-term depletion of fissile isotopes
- Develop bias/unity point schedule
- Will to use HPC or Falcon

- 1D+time finite element model that accounts for passive feedback mechanisms during unsteady state subcritical, critical, and supercritical modes to calculate the core power and flow loop temperature profile over time
- Simulate system response to:
    - Control actuation
    - Heat exchanger transients
- Empirical fitting of reactor transfer function
- Studies can be conducted locally or with cluster resources

- Model control loop in Simulink
- Investigate system stability using frequency response tests
- Use built-in numerical methods to implement a PID controller tuning method
- Repeat for different core conditions to develop gain-schedule and/or look-up table for the controller parameters

- Implement control drum reactivity, pre-filter, and PID controller into the process simulation
- Test autonomous response to heat exchanger power demand transients
- Repeat with controller active
- Quantitatively compare response using settling time, dampening ratio, peak overshoot ratio etc.

Timeline

Table: Timeframe for Execution of Project

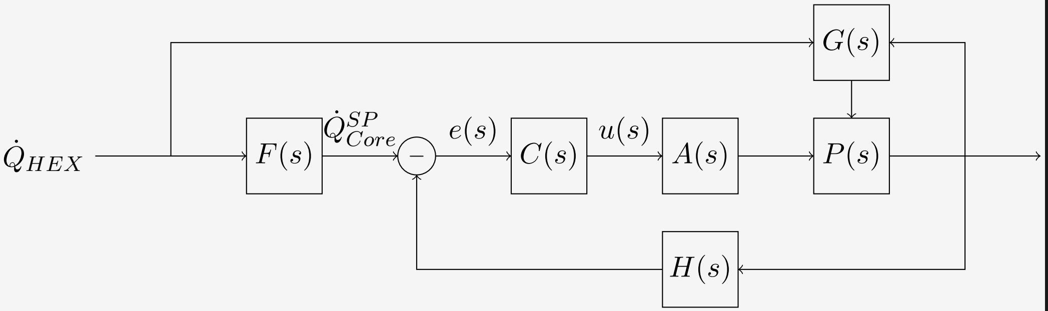
Tasks	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Control Drums	**X**	**X**	**X**				
Process Simulation		**X**	**X**	**X**			
Controller Tuning				**X**	**X**		
Implementation					**X**	**X**	
Cross-Cutting						**X**	**X**
Defend							**X**

Other Considerations

- Poison perturbations following power transients [10]
- Melting of *in-situ* frozen salt
- SCRAM system must be passive
- Decay heat system [11]
- Flow rate control

[10] Al Rashdan, A. et al., 2019. A frequency domain control perspective on xenon resistance for load following of thermal nuclear reactors. IEEE Transactions on Nuclear Science 66(9), 2034

[11] Wang, S., et al., 2019. A passive decay heat removal system for emergency draining tanks of MSRs. Nuclear Engineering and Design 341, 423



Simplified control loop of a natural circulation MSNB