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

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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

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

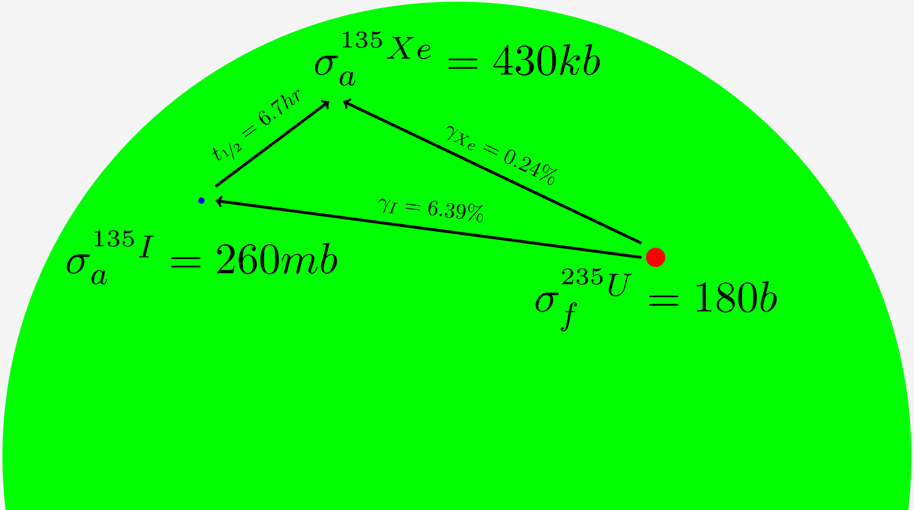
Fission Product Poisoning

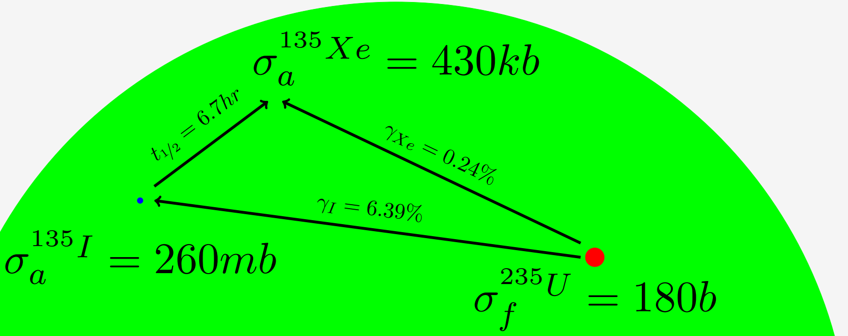
$$\sigma_a^{135}Xe = 430kb$$

$$\sigma_a^{135}I = 260mb$$

$$\sigma_f^{235}U = 180b$$

Fission Product Poisoning





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

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

Control Theory

Transport Delay Problem

Neutronics Modeling

Process Simulation

1 The Molten Salt Nuclear Battery

2 Process Control Engineering

3 Reactor Characterization

4 Results and Analysis

- Control-Reactivity Curve
- Controller Tuning
- Demand Response

5 Conclusions

Control-Reactivity Curve

Controller Tuning

Demand Response

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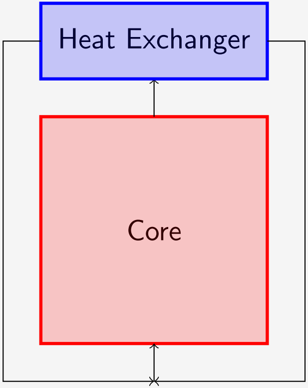
References I

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)

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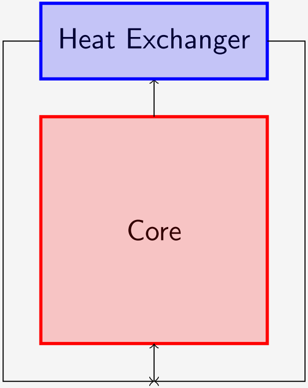

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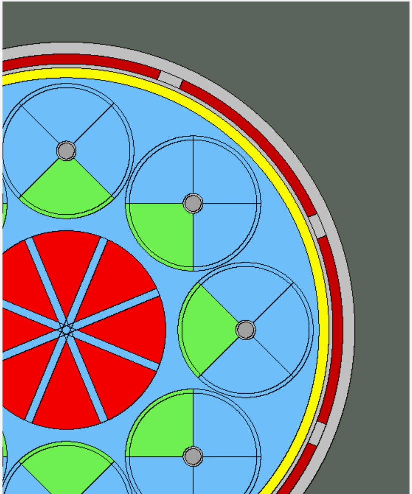

Neutronics [?]

- 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 [?]

Process Control

[?]
[?]

Background on MSNB

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Neutronics [?]

Thermal Hydraulics [?]

- 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

[?]
[?]

Neutronics [?]

Thermal Hydraulics [?]

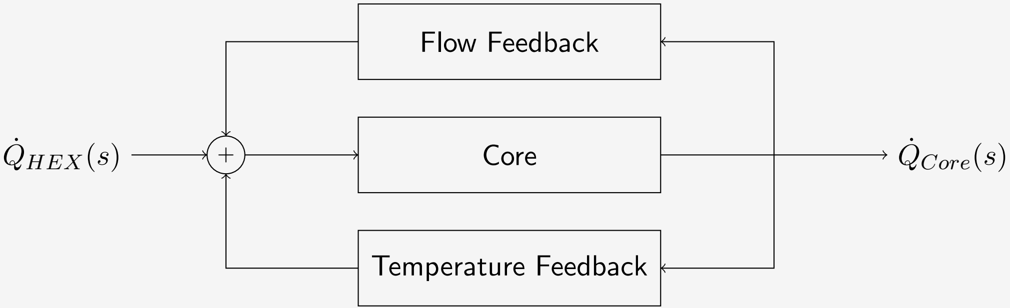
Process Control

- 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)

[?]

[?]

Passive Feedback



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

- Doppler broadening of resonance peaks results in more epithermal neutrons absorbed by ^{238}U etc. [? , Ch. 6]
- Molten salt fuels have high thermal expansion coefficient [?]
- Increased temperature leads to lower heavy metal density and smaller macroscopic fission cross-section at high temperature
- Similar to moderator thinning in LWRs
- These two effects combine to result in less power production at higher temperature

[?]

[?]

Passive Feedback

Flow Reactivity

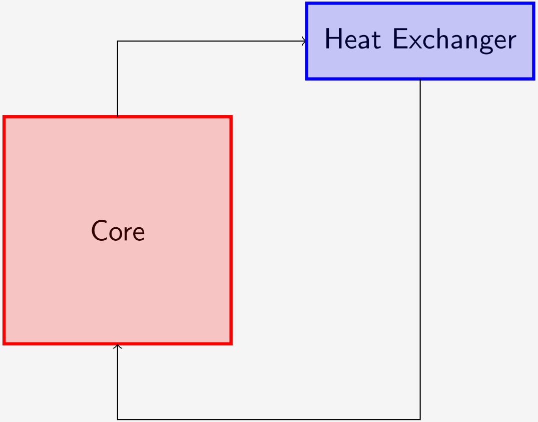
- Driven by advection of delayed neutron precursors [? , Ch. 3]
  - Most fission events release daughter neutrons *promptly*
  - Sometimes, unstable nuclides which decay by neutron emission are produced instead
  - $t_{1/2}$ from less than a second to over a minute [? , Ch. 6]
- Precursors produced near the core exit and long lived precursors may emit their neutrons outside of the core, so they are effectively *lost* from the fission chain reaction
- In natural circulation, larger power transport requires a higher flow rate, and greater delayed neutron losses

[?]
[?]

Main Operational Control Problem - Transport Delay

- Start design process by discussing 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

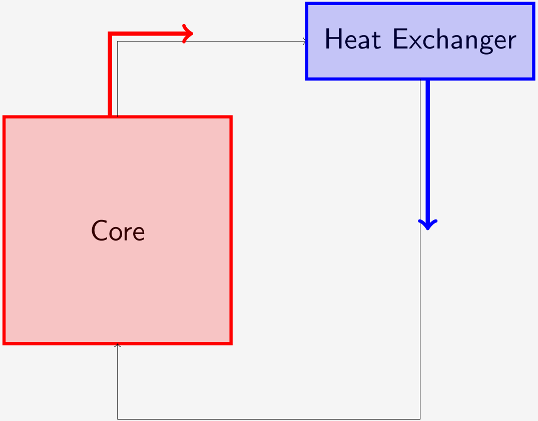
Main Operational Control Problem - Transport Delay



Simplified schematic drawing of a natural circulation MSNB

Main Operational Control Problem - Transport Delay

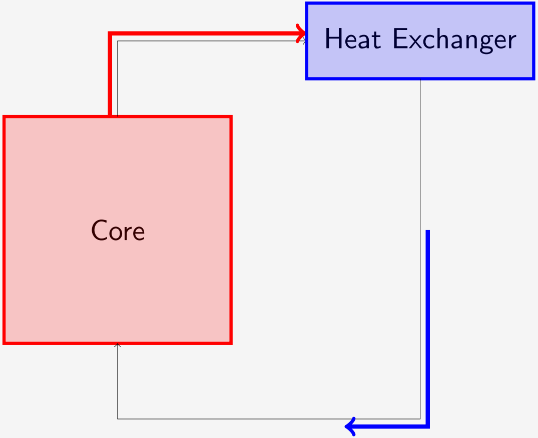
Immediate Response



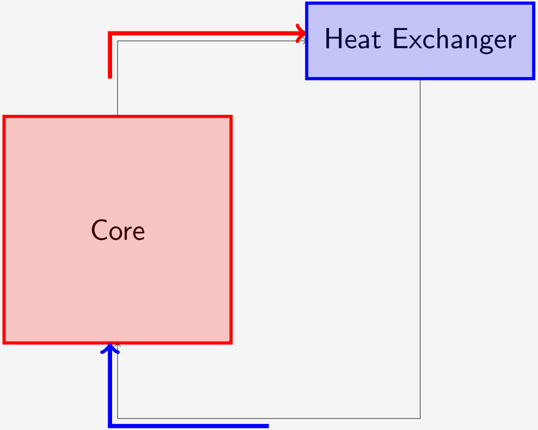
Simplified schematic drawing of a natural circulation MSNB

Main Operational Control Problem - Transport Delay

Heat Exchanger Perturbation



Simplified schematic drawing of a natural circulation MSNB



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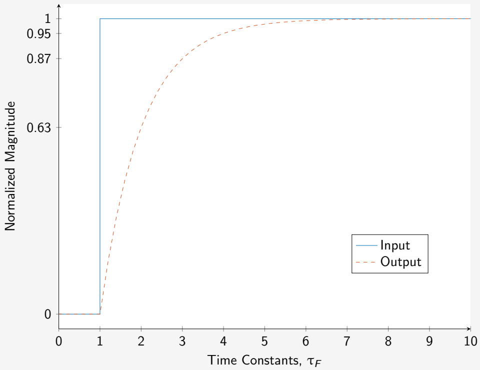
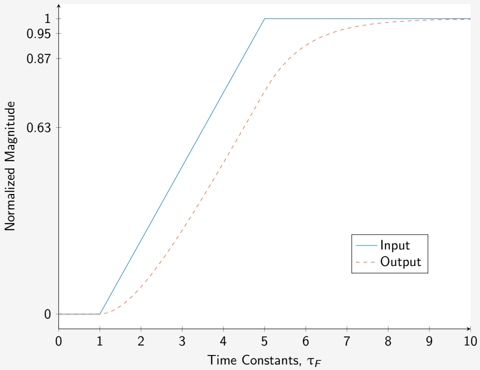


Pre-Filter on a step-function



Pre-Filter on a ramp-function

Design Decisions

Dead-band

- 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 [**?** , 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 [**?** , Ch. 10]
- Disturbance rejection best left to feedback PID controller

[**?**]
[**?**]

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

[?]
[?]

Time-Variance and Non-Linearity

Special Cases

- 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

- 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

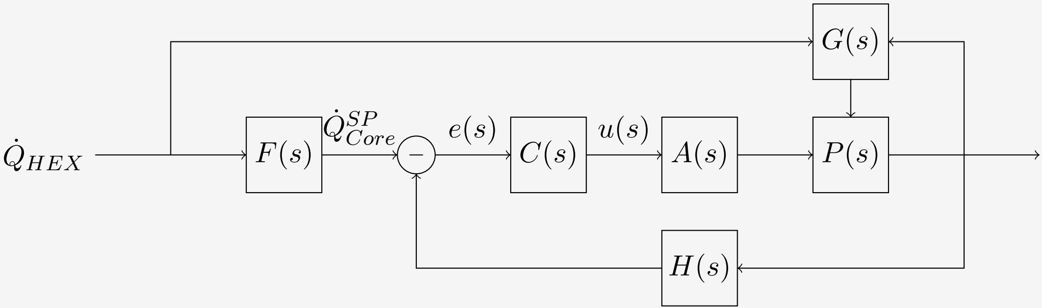
Table: Timeframe for Execution of Project

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 [?]
- Melting of *in-situ* frozen salt
- SCRAM system must be passive
- Decay heat system [?]
- Flow rate control

[?]
[?]



Simplified control loop of a natural circulation MSNB