Design of a PID Controller for a Molten Salt Microreactor

Master's Plan

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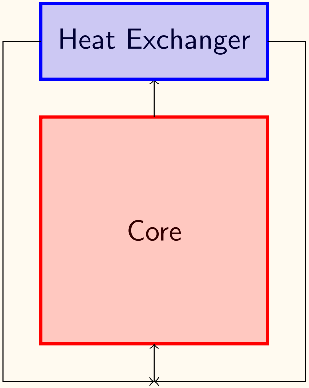
Outline

Scope

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

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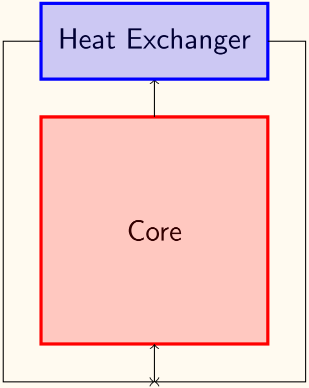

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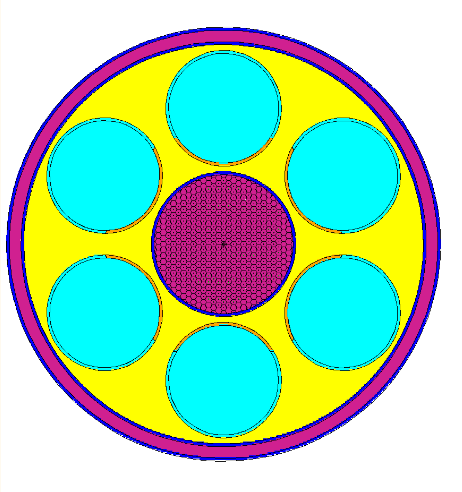

MsNB Control Drums

Background on MSNB

Neutronics [1]

- 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 [2]

Process Control

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[1] Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor.
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[2] 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.
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Background on MSNB

Neutronics [1]

Thermal Hydraulics [2]

- 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

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Background on MSNB

Neutronics [1]

Thermal Hydraulics [2]

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)

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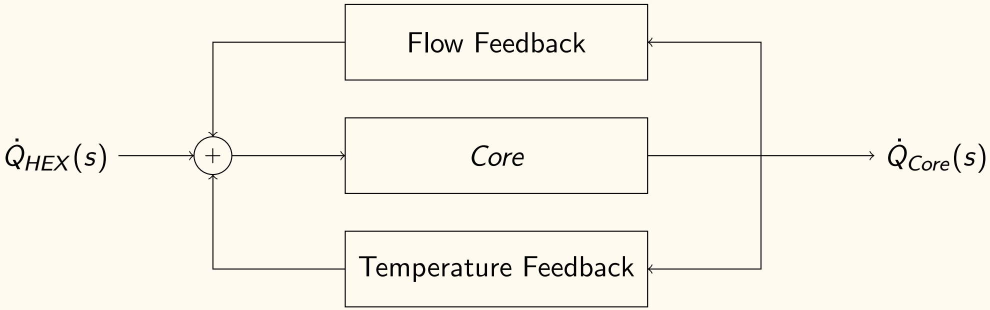
Applied Literature Review

Passive Feedback



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

Passive Feedback

Temperature Reactivity

- Doppler broadening of resonance peaks results in more epithermal neutrons absorbed by ^{238}U etc. [3, Ch. 6]
- Molten salt fuels have high thermal expansion coefficient [1]
- 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

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

[1] 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

- Driven by advection of delayed neutron precursors [4, 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 [5, 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

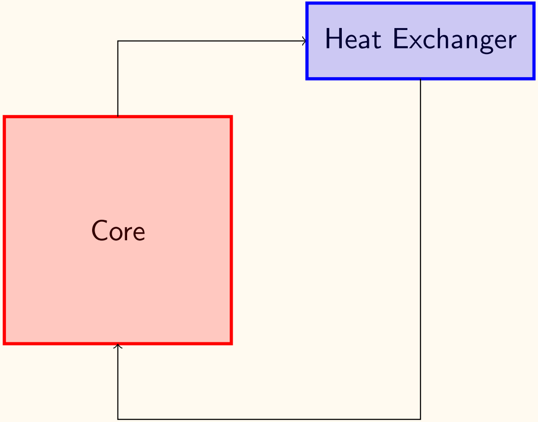
[4] Kerlin, T. W. et al., 2019. Dynamics and Control of Nuclear Reactors. Knoxville, Tennessee: Elsevier Inc

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

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

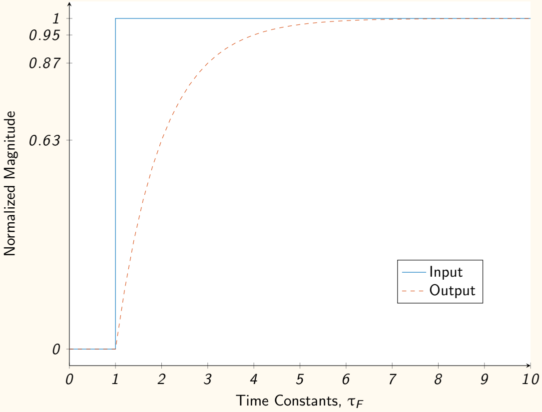
Main Operational Control Problem - Transport Delay



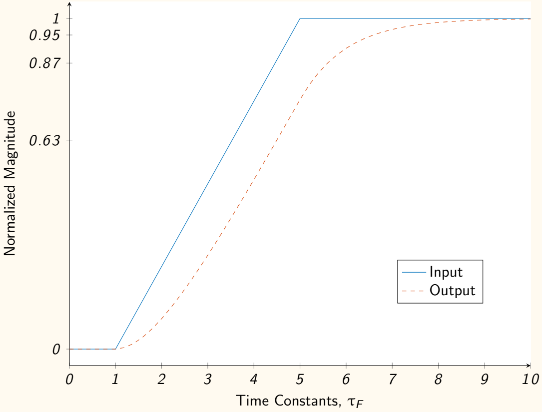
Simplified schematic drawing of a natural circulation MSNB

Design Decisions

Pre-Filter



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

Design Decisions

Disturbance Feedforward

- Disturbances, particularly temperature reactivity, are extremely high frequency - On order of mean neutron lifetime [5, 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 [6, Ch. 10]
- Disturbance rejection best left to feedback PID controller

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

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

Time-Variance and Non-Linearity

- Sinusoidal control drum angle vs. reactivity curve - non-linear reactivity actuation - Taylor Series approximation to linearize around the operating point [6, Ch. 2]
- Fissile depletion changes the amount of control reactivity required to make the core critical - time-variant controller bias - Bias and gain schedule [7]
- Control drums manipulate *criticality*, not power directly - highly time-dependent control actuation

[7] Gahinet, P. M. et al., 2013. Automated tuning of gain-scheduled control systems.
IEEE Conference on Decision and Control.
URL https://ieeexplore.ieee.org/document/6760297

[6] Bequette, B. W., 2003. Process Control: Modeling Design and Simulation.
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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

Future Work

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

Process Simulation

Python

- 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

Controller Tuning

MATLAB-Simulink

- 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**

Final Remarks

Other Considerations

- Poison perturbations following power transients [8]
- Melting of *in-situ* frozen salt
- SCRAM system must be passive
- Decay heat system [9]
- Flow rate control

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[8] 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. doi: 10.1109/TNS.2019.2934171

[9] Wang, S., et al., 2019. A passive decay heat removal system for emergency draining tanks of molten salt reactors. Nuclear Engineering and Design 341, 423. ISSN 0029-5493. doi: https://doi.org/10.1016/j.nucengdes.2018.11.021. URL https://www.sciencedirect.com/science/article/pii/S0029549318309567

Discussion

- Non-Linearity vs. Time-Variance
- Control Loop

Acknowledgements

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References

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   URL `https://www.sciencedirect.com/science/article/pii/S0029549318309567`