Design of a PID Controller for a Molten Salt Microreactor

Master's Plan

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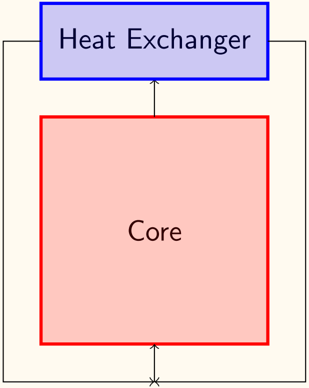
Outline

Scope

Molten Salt Nuclear Battery (MSNB)

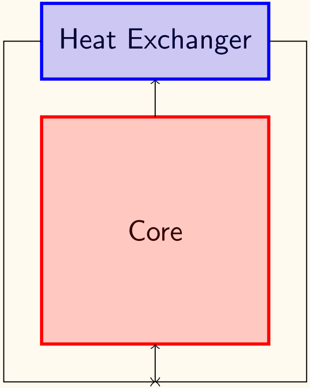
- Self-Contained liquid fueled molten salt micro-reactor - 10 year design



Simplified schematic drawing of an MSNB

Molten Salt Nuclear Battery (MSNB)

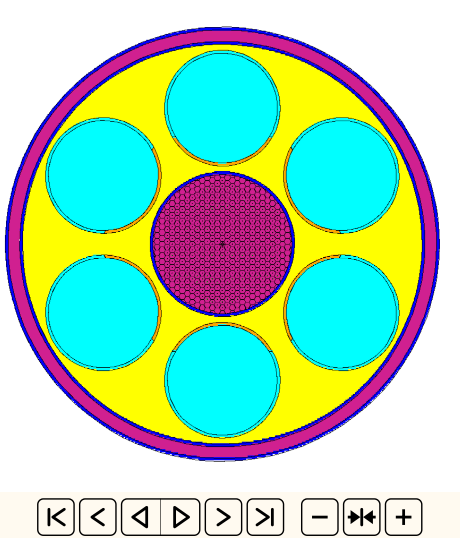
- Self-Contained liquid fueled molten salt micro-reactor - 10 year design
- 1 MW design using HALEU UF_4dissolved in *FLiNaK*



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



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

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

[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.
Ph.D. thesis, Univesity of Idaho

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

Process Control

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

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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)

[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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Applied Literature Review

Passive Feedback

Main Operational Control Problem - Transport Delay

Time-Variance and Non-Linearity

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

Implementation and Testing

Python

- 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 [3]
- Melting of *in-situ* frozen salt
- Decay heat system [4]
- Flow rate control

[3] 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

[4] 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

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References

1. Peterson, J., 8 2019. An analysis of the nuclear characteristics of a molten salt microreactor. Master's thesis, University of Idaho.
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. Ph.D. thesis, Univesity of Idaho.
3. 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.
4. 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`