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

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

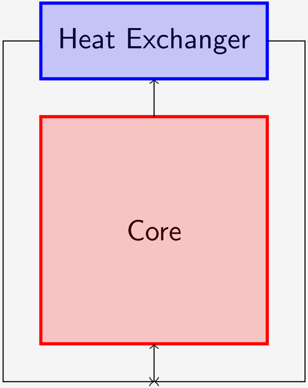
- Less than 50 MW
- Assembly line manufacturing
- Deliver/installation vs. construction

Molten Salt Nuclear Battery

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



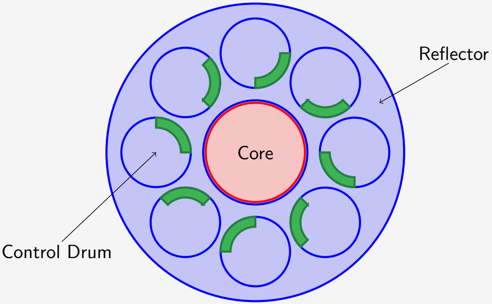
Simplified schematic drawing of an MSNB

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 [?]

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

Thermal Hydraulics [?]

Process Control

[?]
[?]

Neutronics [?]

Thermal Hydraulics [?]

- 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

[?]
[?]

Previous and Present Work

Neutronics [?]

Thermal Hydraulics [?]

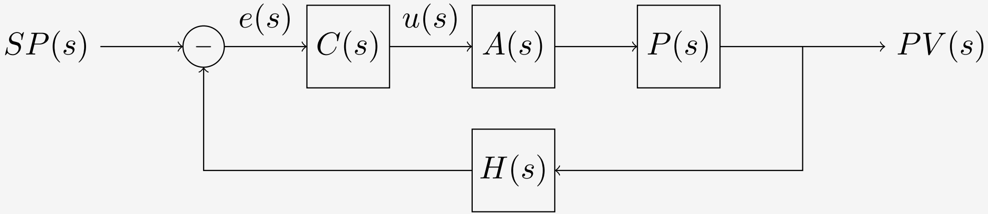
Process Control

- 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

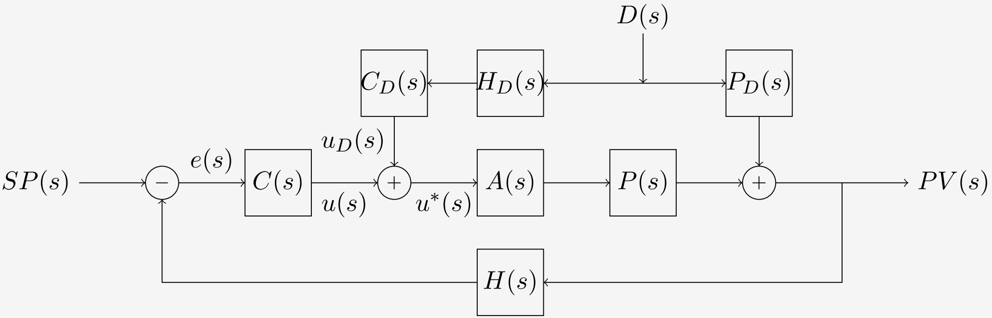
[?]
[?]

Control Theory

Feedback Control



Feedforward 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 setpoint
- 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

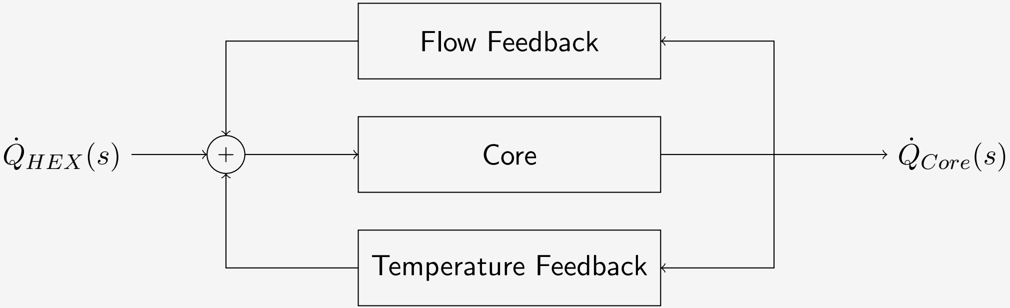
Integral

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

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

Thermal Expansion

[?]
[?]

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Doppler broadening

Thermal Expansion

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

[?]

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 [? , Ch. 6]

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

Flowing Fuel

[?]

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

[**?**]

Main Operational Control Problem - Transport Delay

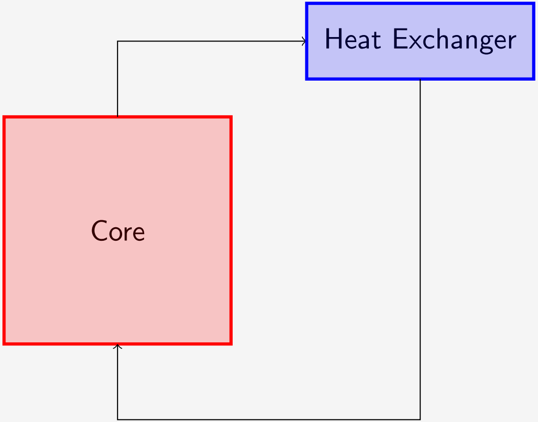
Dynamics associated with anticipated transients

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

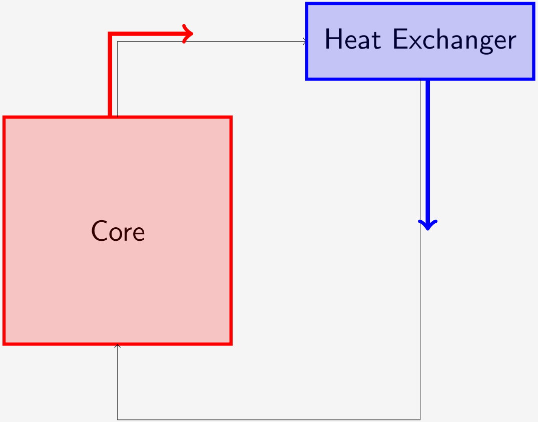
Thought Experiment

- 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

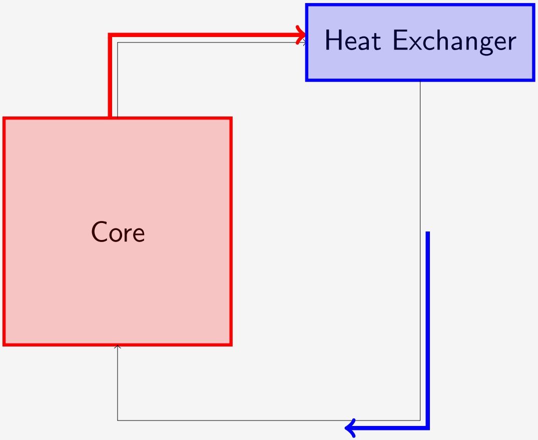
Main Operational Control Problem - Transport Delay



Simplified schematic drawing of a natural circulation MSNB

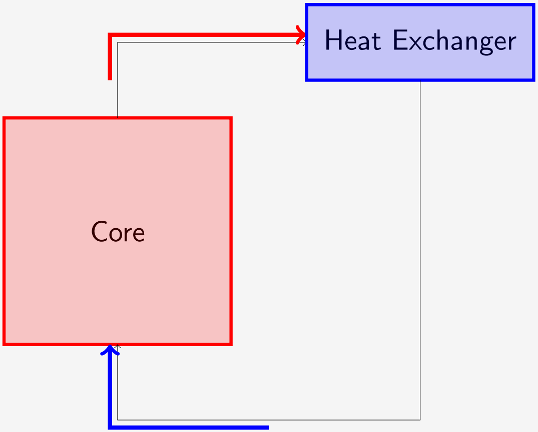


Simplified schematic drawing of a natural circulation MSNB



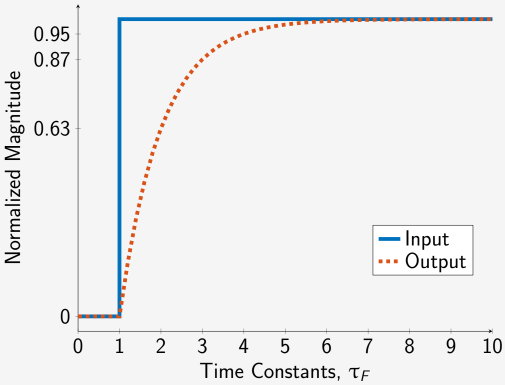
Simplified schematic drawing of a natural circulation MSNB

Main Operational Control Problem - Transport Delay
Core Perturbation

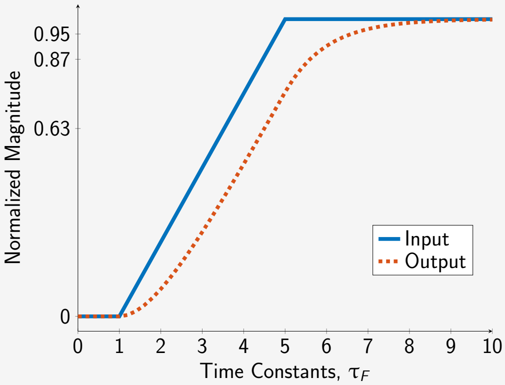


Simplified schematic drawing of a natural circulation MSNB

Pre-Filter

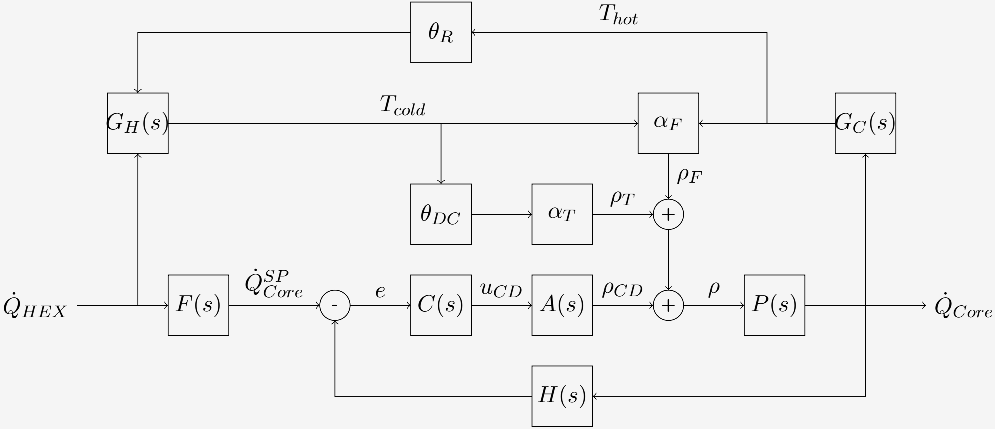


Pre-Filter on a step-function



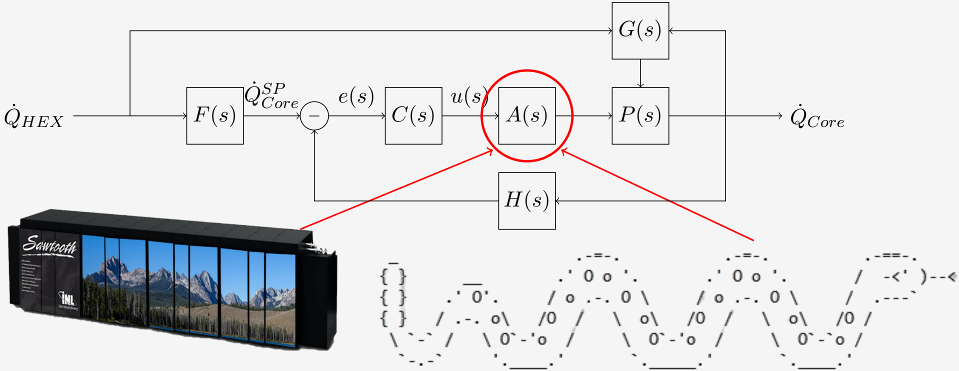
Pre-Filter on a ramp-function

MSNB Control Loop



Neutronics Modeling

Serpent Modeling



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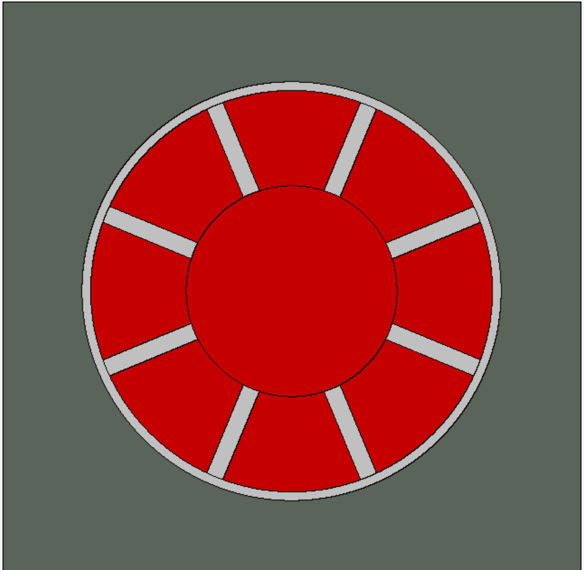

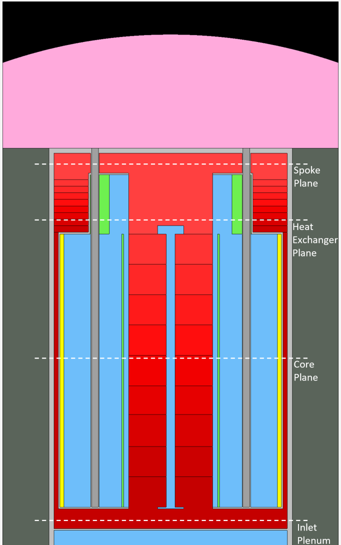

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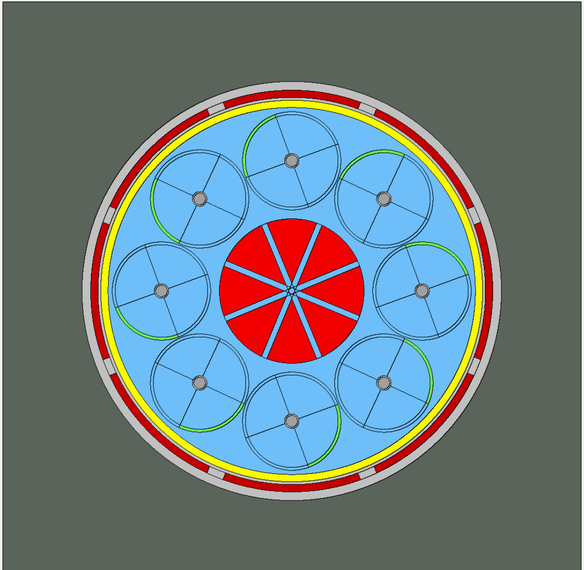

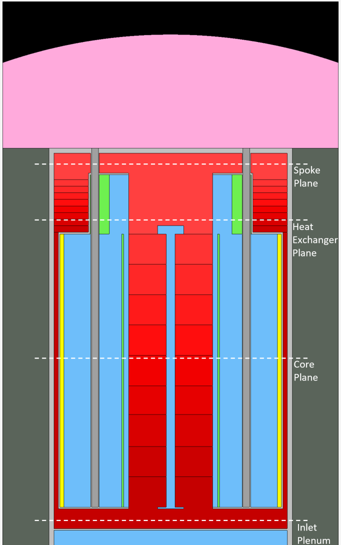

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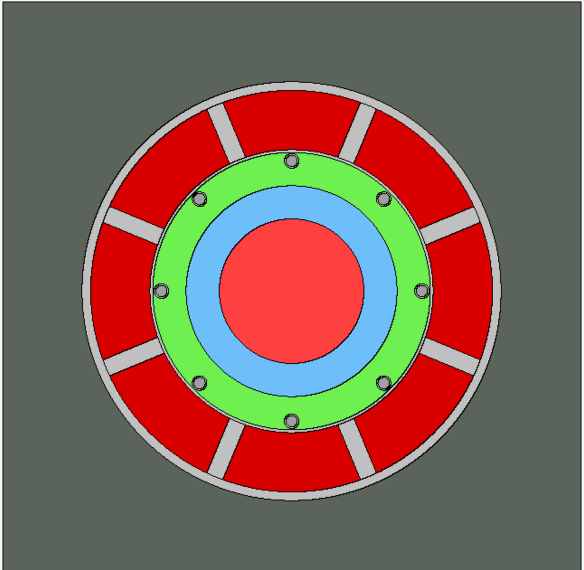

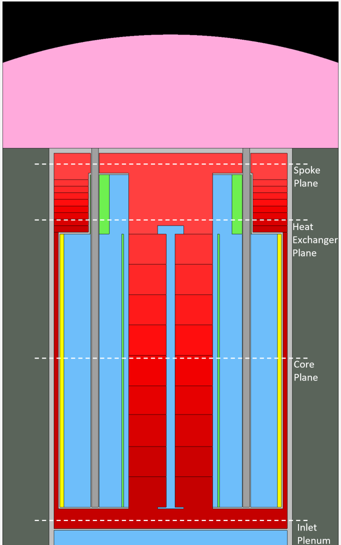

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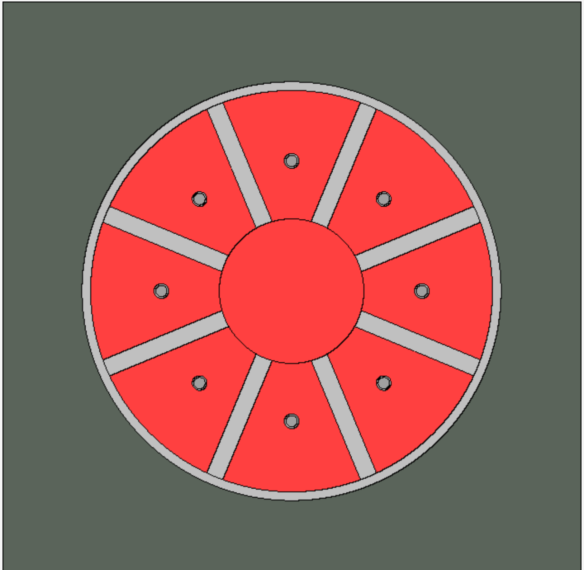

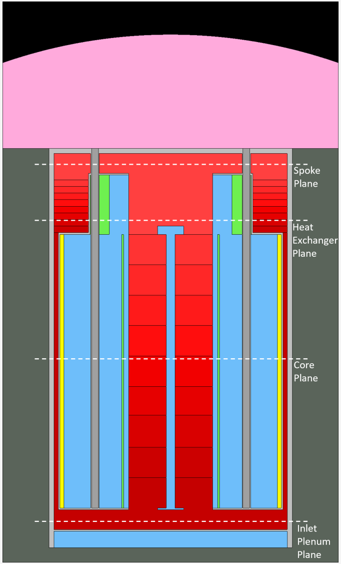

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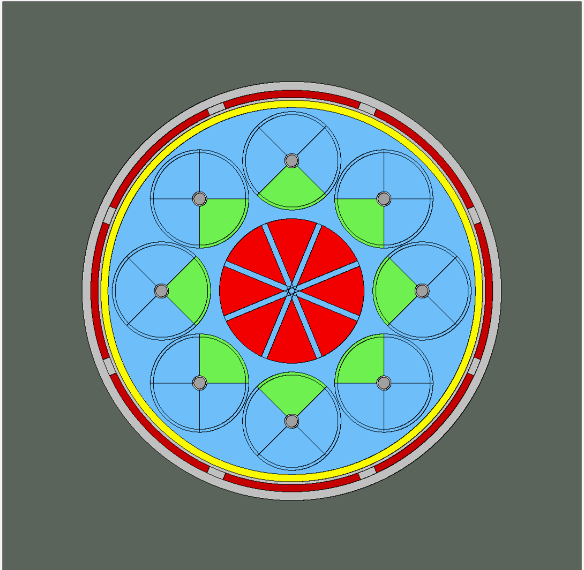

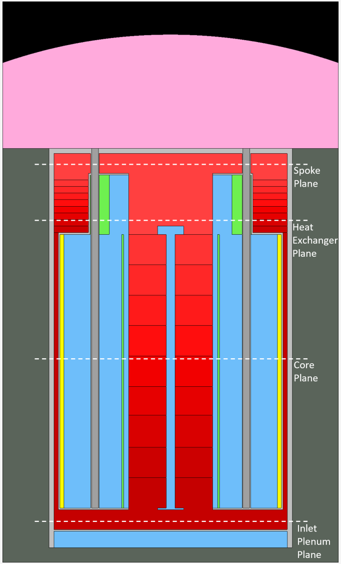

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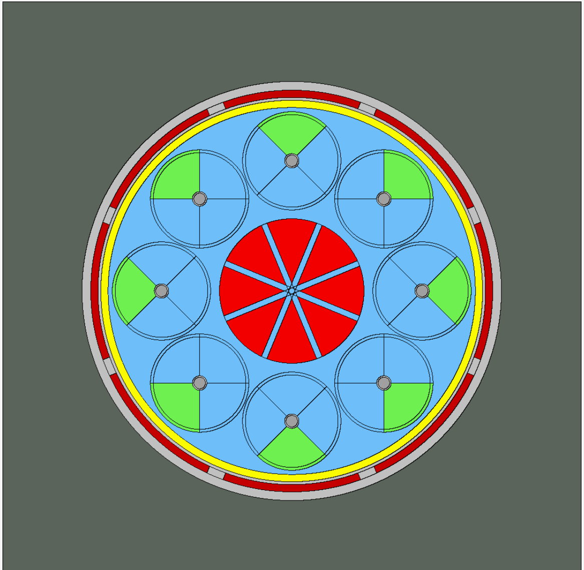

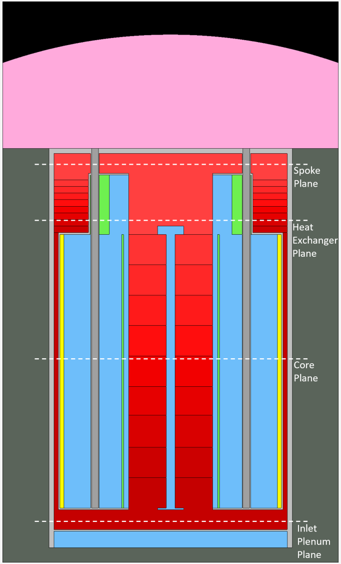

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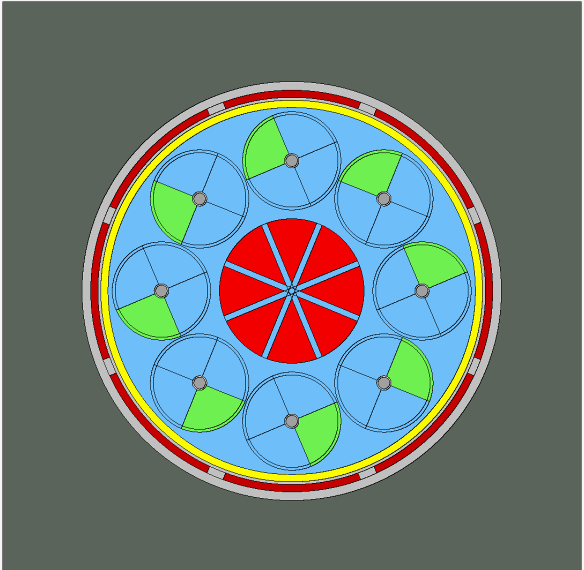

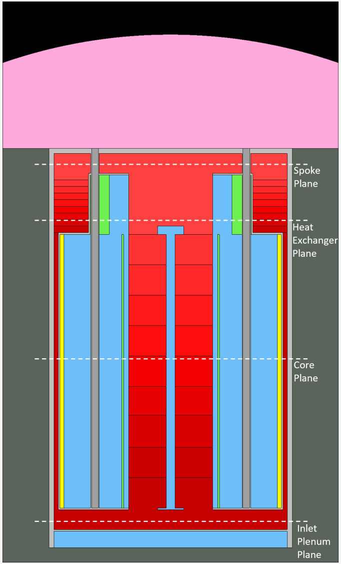

Physics Cards

Criticality

- Set Pop 1,000,000 500 100 1
- Set Power 1e7 %10MWth

Burn-Up

- Set mcvol 10,000,000
- Set nbuf
- Set printm 1 1e-10
- Set inventory "all"

Process Simulation

Control-Reactivity Curve

Controller Tuning

Demand Response

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This work and my coursework is being completed under a Graduate Fellowship funded by Nuclear Regulatory Commission (NRC).
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References I

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