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

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

- 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

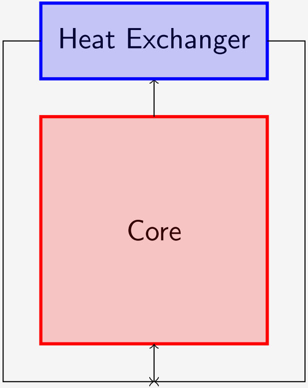
- Less than 50 MW
- Assembly line manufacturing
- Deliver/installation vs. construction

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

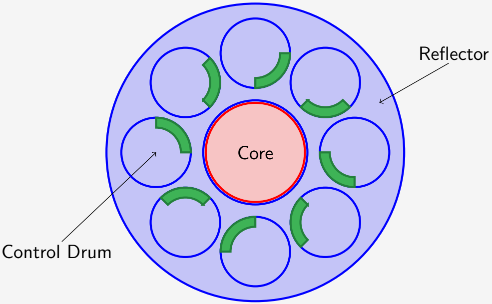


Simplified schematic drawing of an MSNB

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 [3]

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

Thermal Hydraulics [4]

Process Control

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

[4] 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

Previous and Present Work

University of Idaho

Neutronics [3]

Thermal Hydraulics [4]

- 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

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

[4] 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

Neutronics [3]

Thermal Hydraulics [4]

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

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

[4] 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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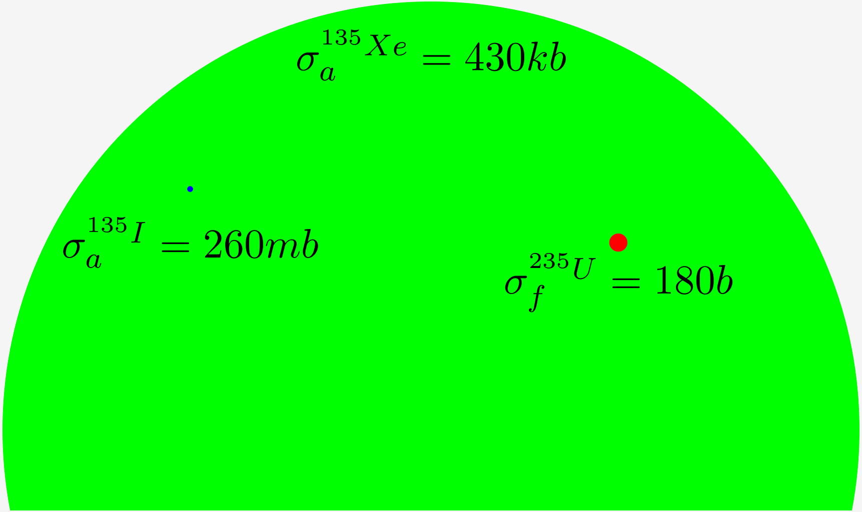
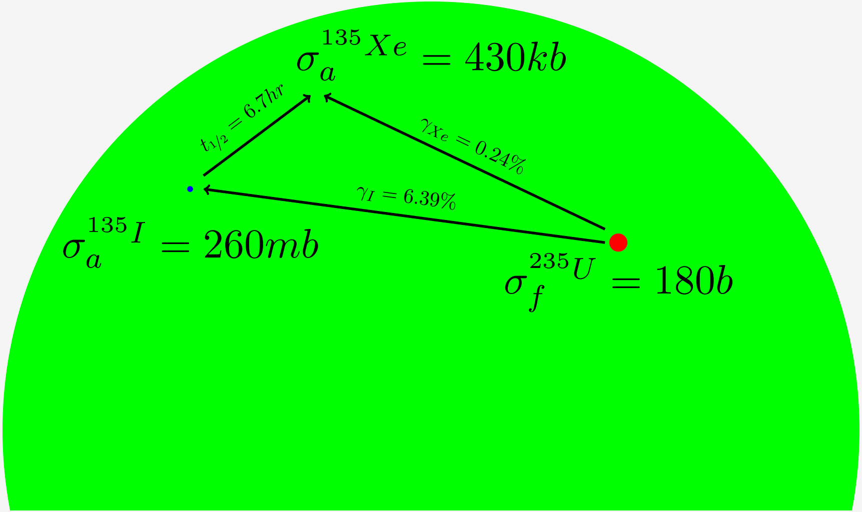
Xenon-135 Stripping In-Brief

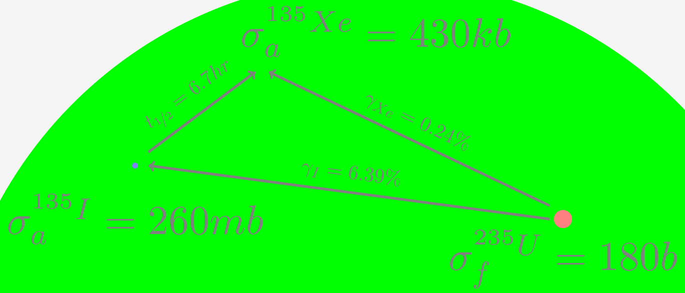
Fission Product Poisoning



Fission Product Poisoning

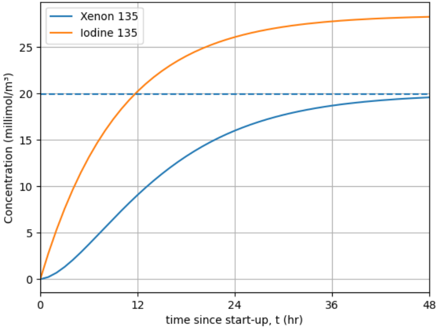


Fission Product Poisoning

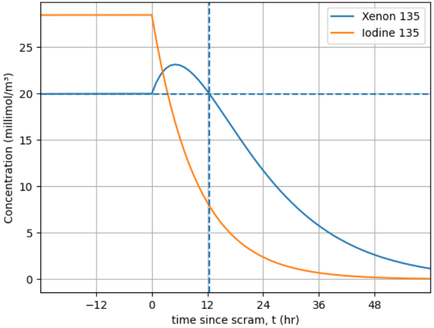


$$\frac{dI}{dt} = \underbrace{\gamma_I \Sigma_f^F \phi(t)}_{\text{Fission Yield}} - \underbrace{\lambda_I I(t)}_{\text{Beta Decay}}$$

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

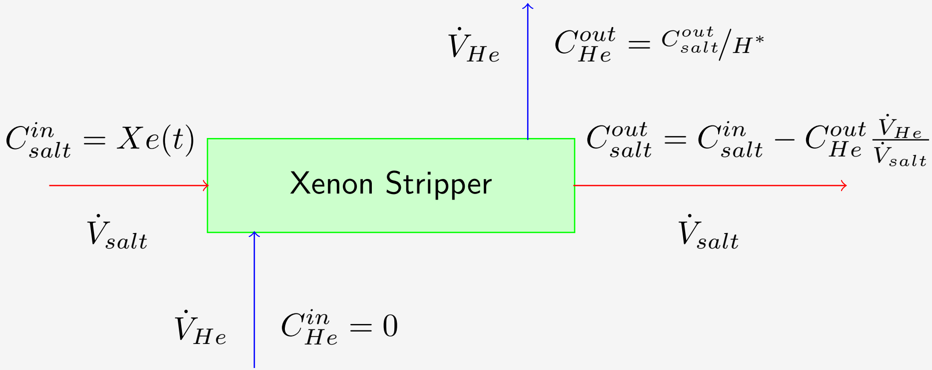


Concentration of ^{135}I and ^{135}Xe vs. time following start-up



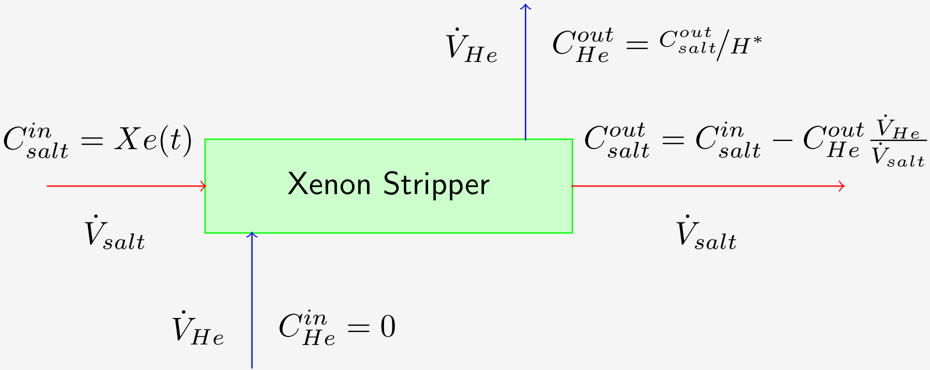
Concentration of ^{135}I and ^{135}Xe vs. time following reactor scram

Xenon Stripper



Schematic Drawing of Xenon Stripping Module

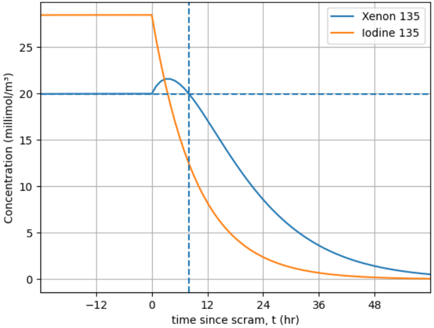
Xenon Stripper



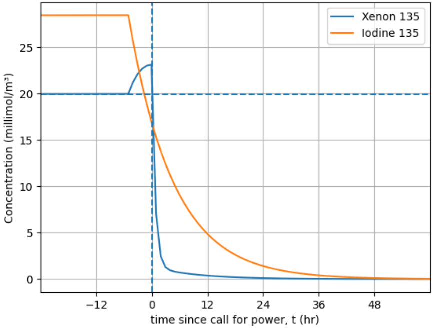
Schematic Drawing of Xenon Stripping Module

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

Xenon Stripping Dynamics



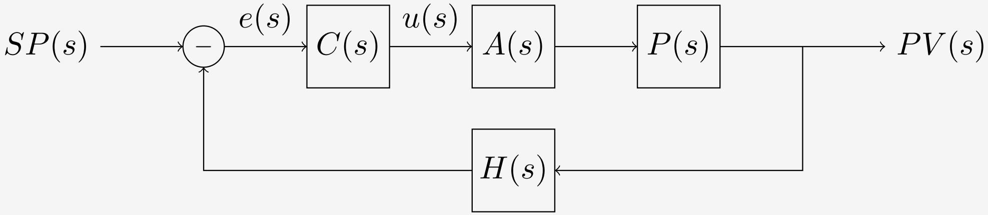
Concentration of ^{135}I and ^{135}Xe vs. time following reactor scram - Restart Mode



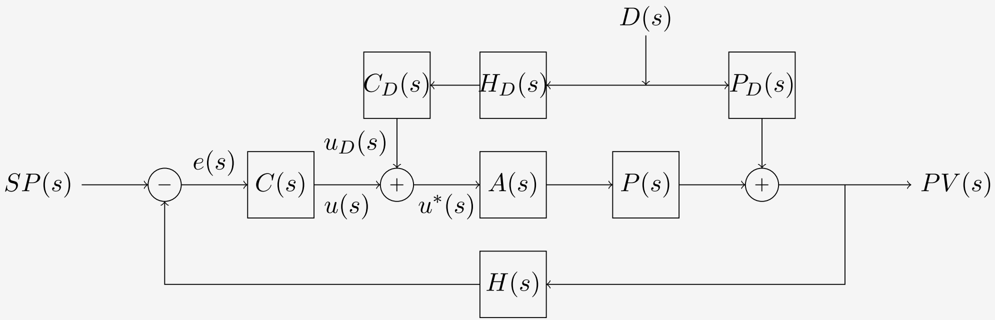
Concentration of ^{135}I and ^{135}Xe vs. time following reactor scram - Standby Mode

Control Theory

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 set-point
- 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

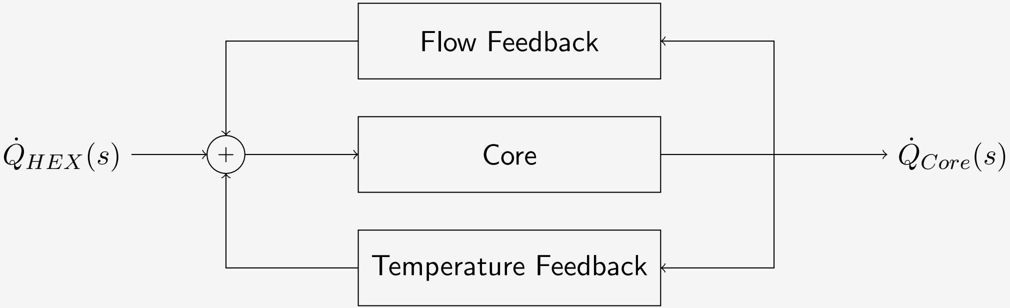
Integral

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

Thermal Expansion

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

[6] 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 [3]
- Similar to moderator thinning in LWRs

[3] 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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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 [7, Ch. 6]

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

Flowing Fuel

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

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

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

Main Operational Control Problem - Transport Delay

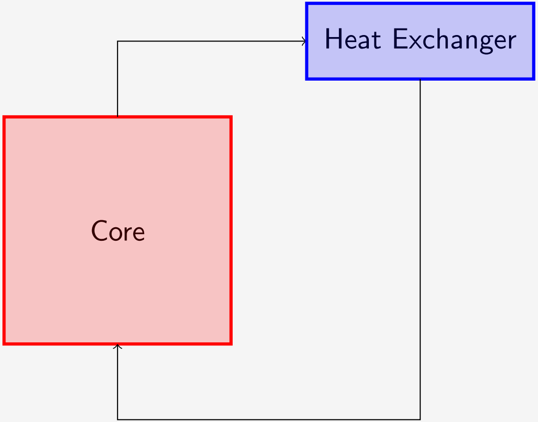
Dynamics associated with anticipated transients

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

Thought Experiment

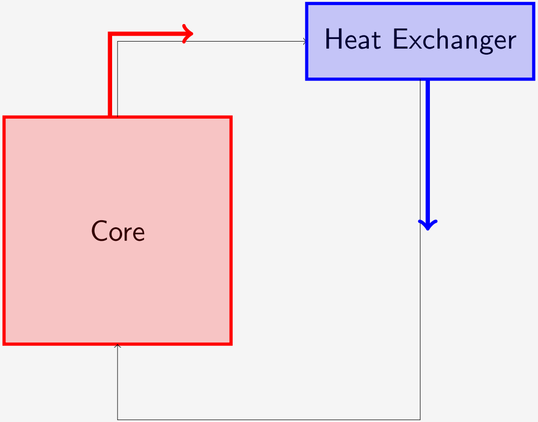
- Step increase in power demand to a steady-state critical MSNB
- Set-point is instantaneously equal to heat exchanger power consumption
- Ideal controller which produces rapid load following with minimal overshoot

Main Operational Control Problem - Transport Delay

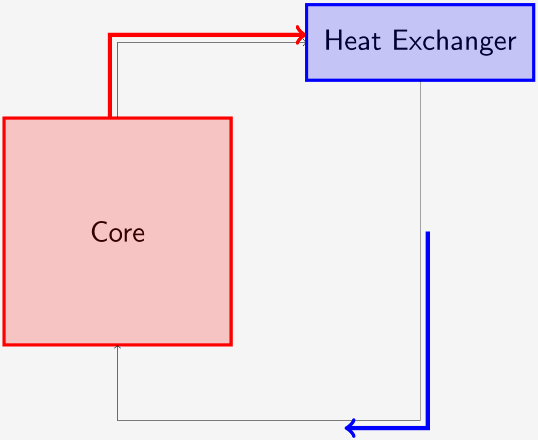


Simplified schematic drawing of a natural circulation MSNB

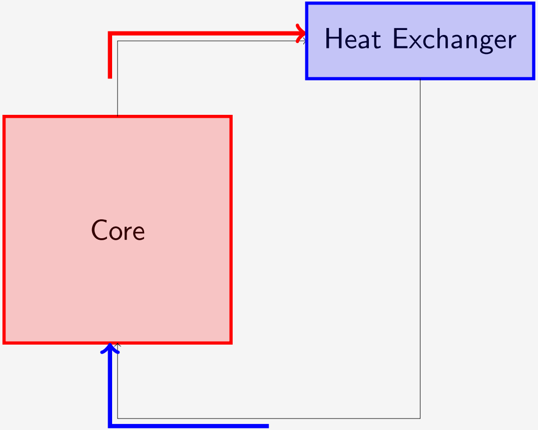
Main Operational Control Problem - Transport Delay
Immediate Response



Simplified schematic drawing of a natural circulation MSNB

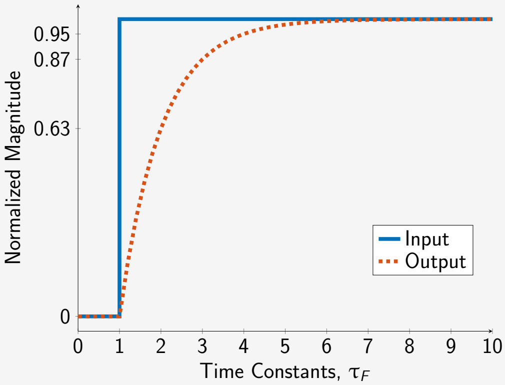


Simplified schematic drawing of a natural circulation MSNB

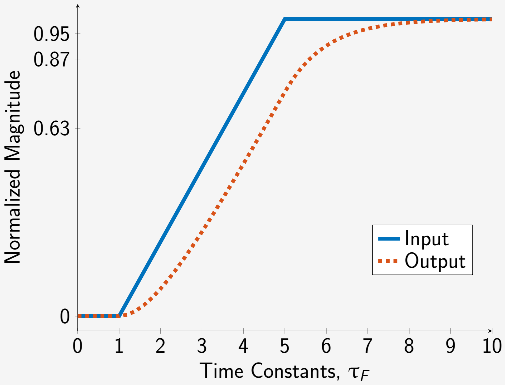


Simplified schematic drawing of a natural circulation MSNB

Pre-Filter

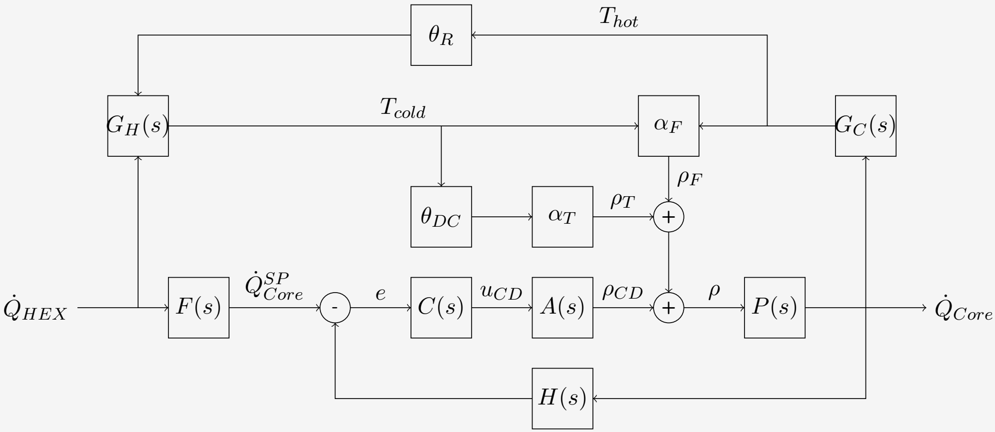


Pre-Filter on a step-function



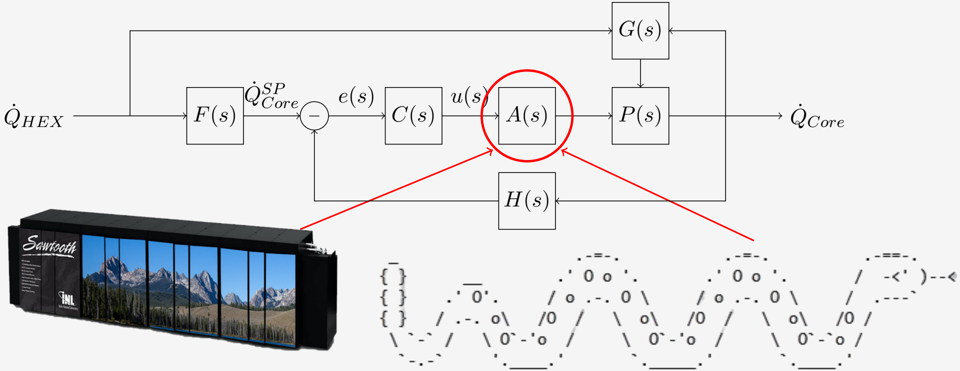
Pre-Filter on a ramp-function

MSNB Control Loop



Neutronics Modeling

Serpent Modeling



Process Simulation

Control-Reactivity Curve

Controller Tuning

Demand Response

Acknowledgements

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References I

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