Nuclear Energy University Program
U.S. Department of Energy

Evaluation of Semi-Autonomous Passive Control Systems for HTGR Type Special Purpose Reactors

Prof. Brendan Kochunas
Co-PIs: Victor Petrov, Nicolas Stauff, Changho Lee, Claudio Filippone

Microreactor Program Winter Review 3/06/2024

COLLEGE OF ENGINEERING
NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

HolosGen™

Argonne NATIONAL LABORATORY

Outline

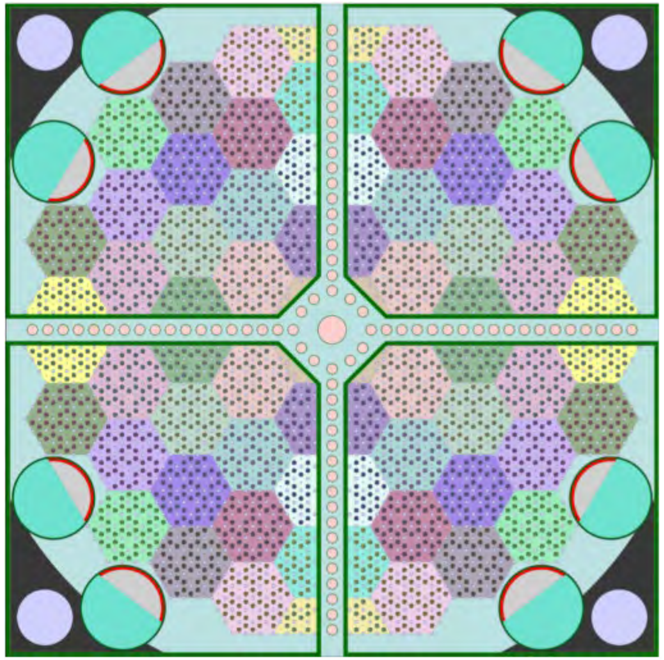
- Project Overview
- Project Highlights
- Project Metrics
- Summary and Questions

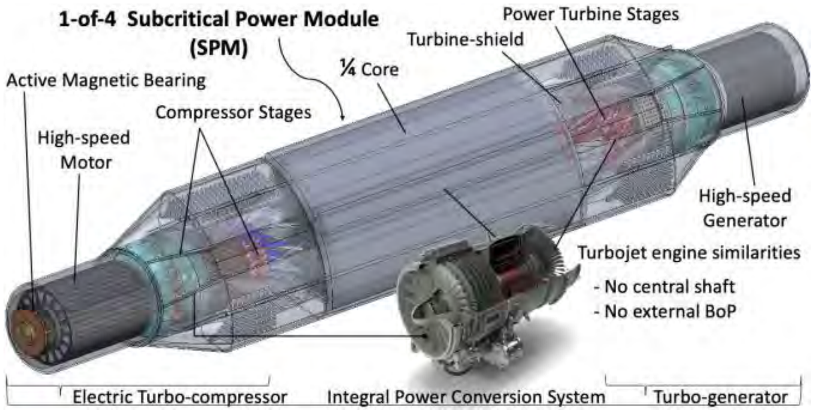
Project Overview

Objectives

- “The objective of the proposed work here is to ***develop and evaluate new passive autonomous control systems for high temperature gas reactor (HTGR)*** type SPR concepts.”
- Investigating Passive Variable Flow Controllers
- Comparing with Control Algorithms for Control Drums
  - Contributed several new methods/capabilities here.
- The value of passive autonomous control systems will be evaluated against transient response to load following.

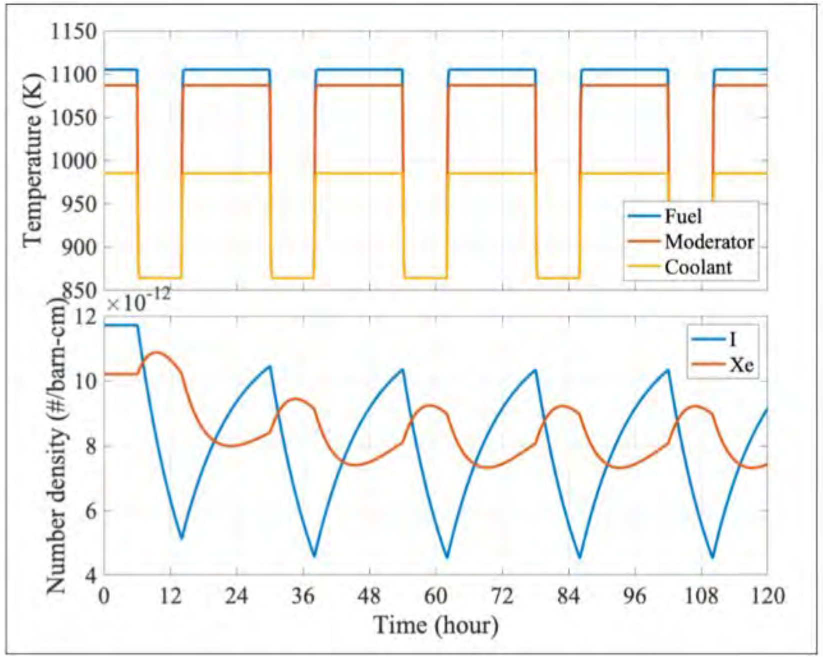
Cross Section of Core

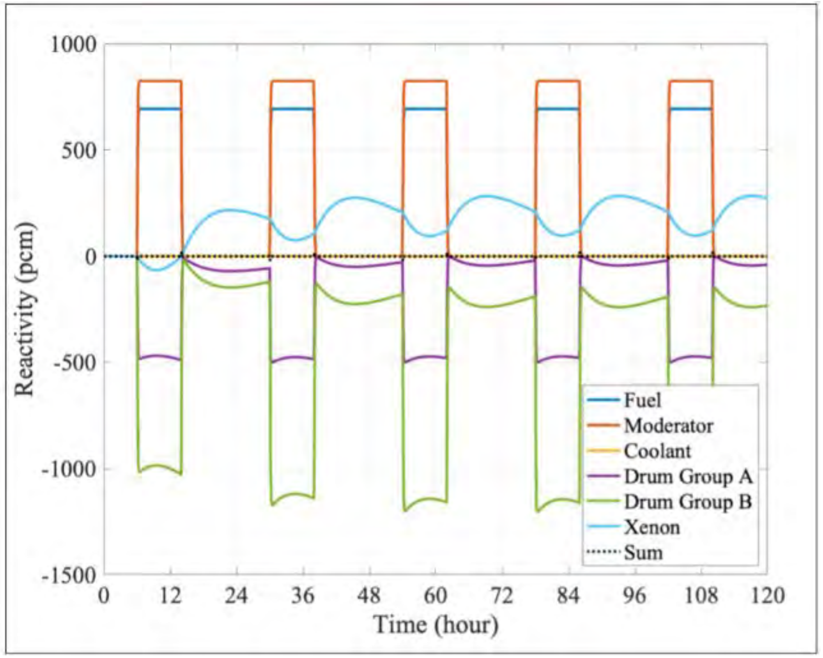




Motivating Application: Autonomous Load Follow

- Daily load following example
  - Xenon model in both MPC and system
  - Control using two inputs: Group A – 1 drum , Group B – 4 drums
  - Power ramp rate = ±20%P_r/min





Automated Control

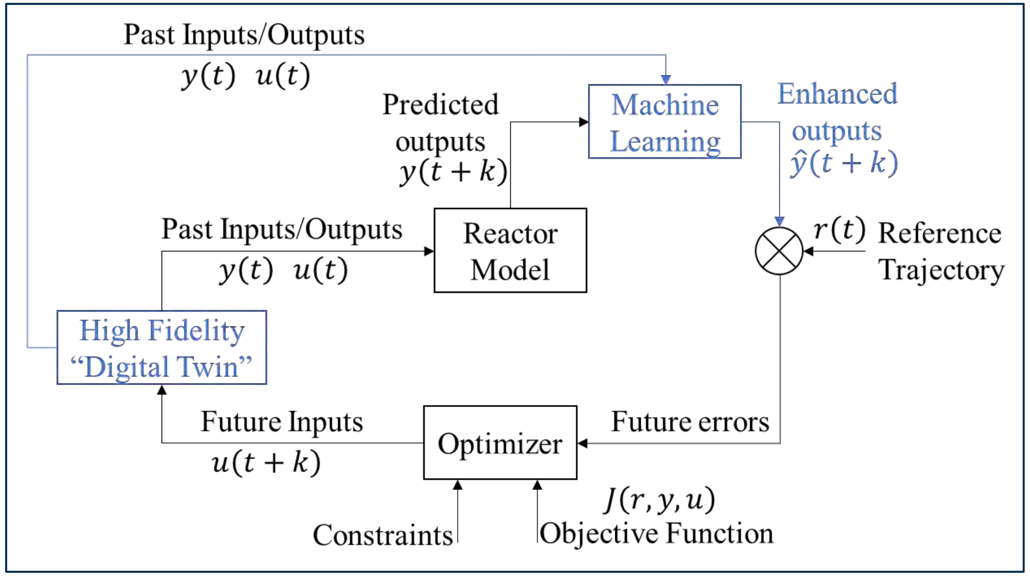
Can reactor components be designed to give a certain dynamic response?

- Reactor Dynamics are well known
  - Point Kinetics and two or three temperature equations
  - Spatial kinetics & high-fidelity

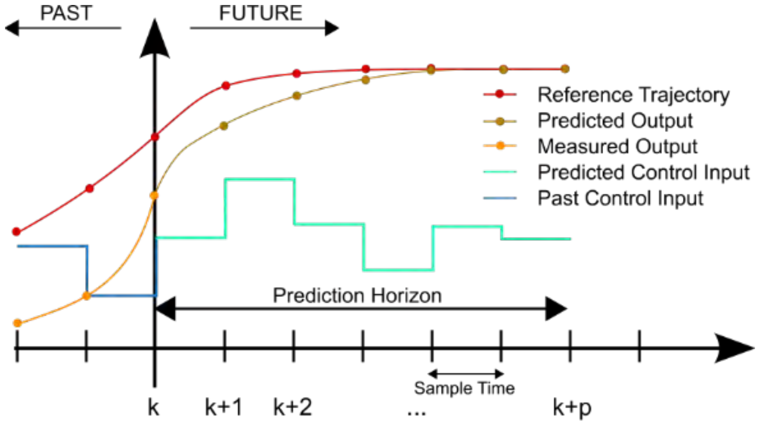
$$\delta\rho(t) = \delta\rho_{cr}(t) + \delta\rho_{T_{inlet}}(t) + \delta\rho_{\dot{m}}(t) + \delta\rho_{Xe}(t) + \alpha_f\left(T_f(t) - T_{f0}\right) + \alpha_m\left(T_m(t) - T_{m0}\right)$$

- Demand More Power
→ ? → increase reactivity
- Demand Less power
→ ? → decrease reactivity

How good do model-based controllers have to be, and can they learn?

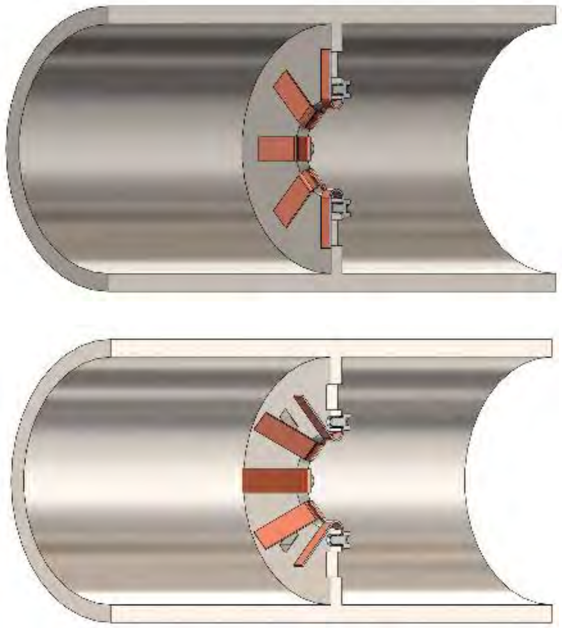


Model Predictive Control



Passive Variable Flow Controllers

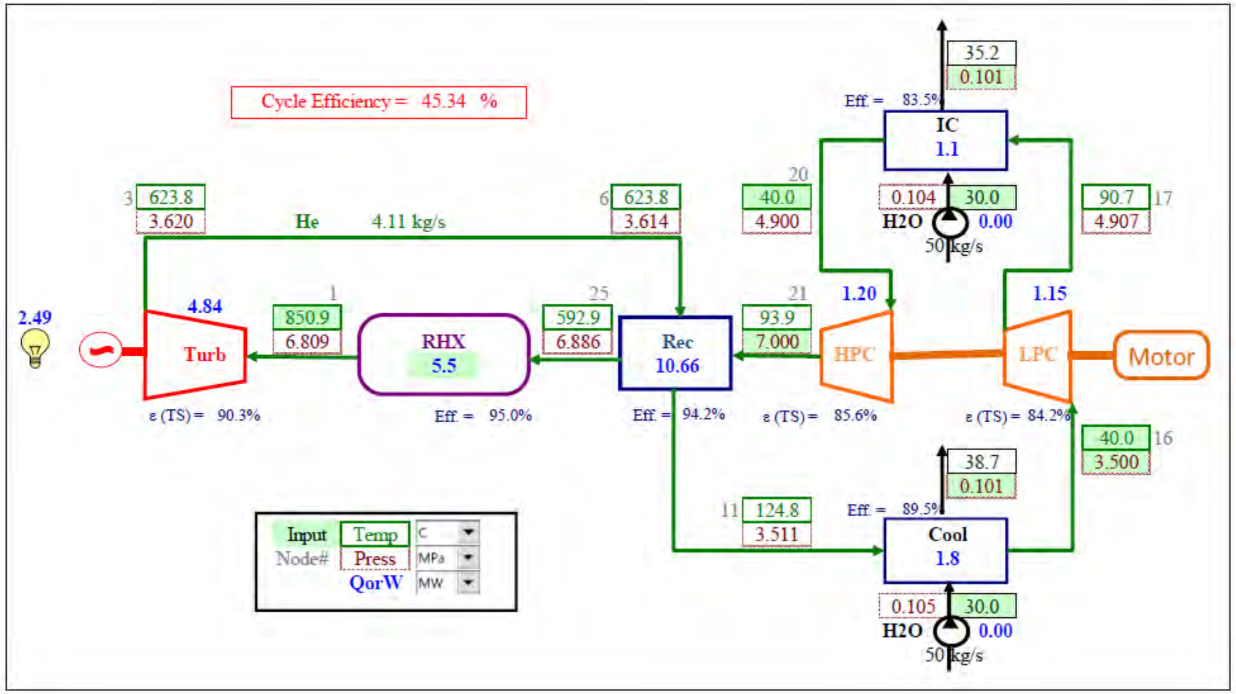
- Use bimetallic valve based on thermal expansion
- Temperature increases—flow area increases
- Temperature decreases—flow area decreases



Closed

Open

Conceptual Illustration



Analogous to turbine throttling
Concept could be implemented for valves for turbine bypass, compressor throttling, maybe inventory control

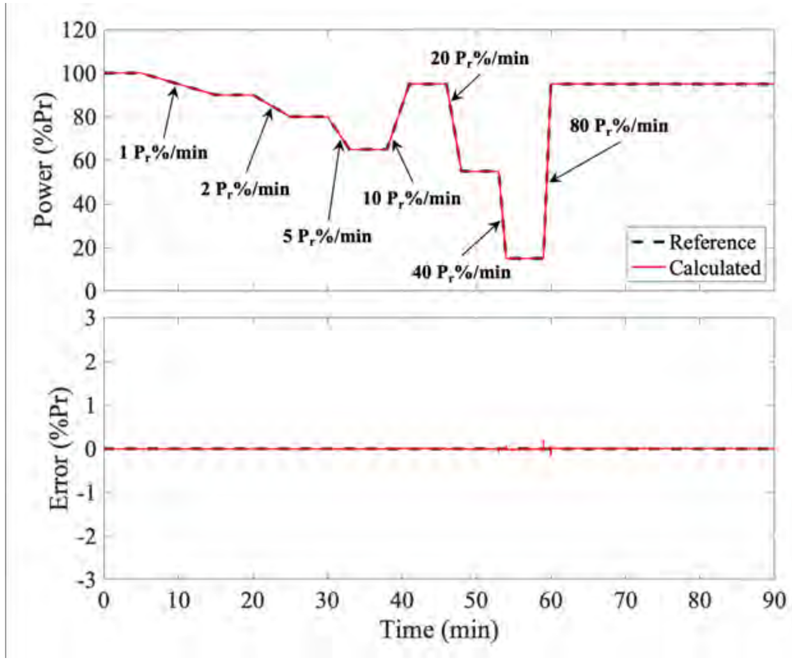
Project Highlights

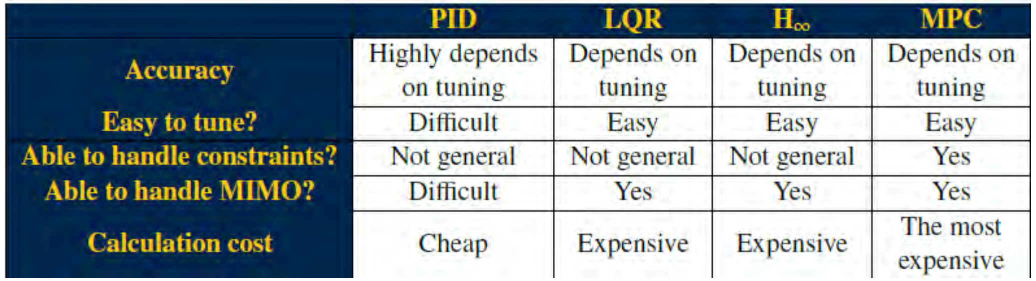
Model Predictive Control

- ***Problem***
  - Conventional PID control is model-free, and controllers for each component operate independently.
- ***Our Solution***
  - Use state-of-the-art model-based controller

$$\boxed{\begin{gathered} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) \end{gathered}}$$

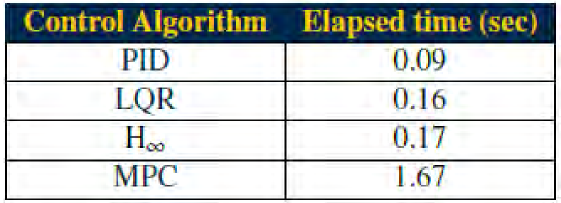
- ***Result***
  - Works great. Pretty insensitive to model parameters, can be made arbitrarily accurate.
- ***Value***
  - Not much for just reactivity control. Value is in potential to extend to whole system, and ability to incorporate notions of component health. MIMO Control





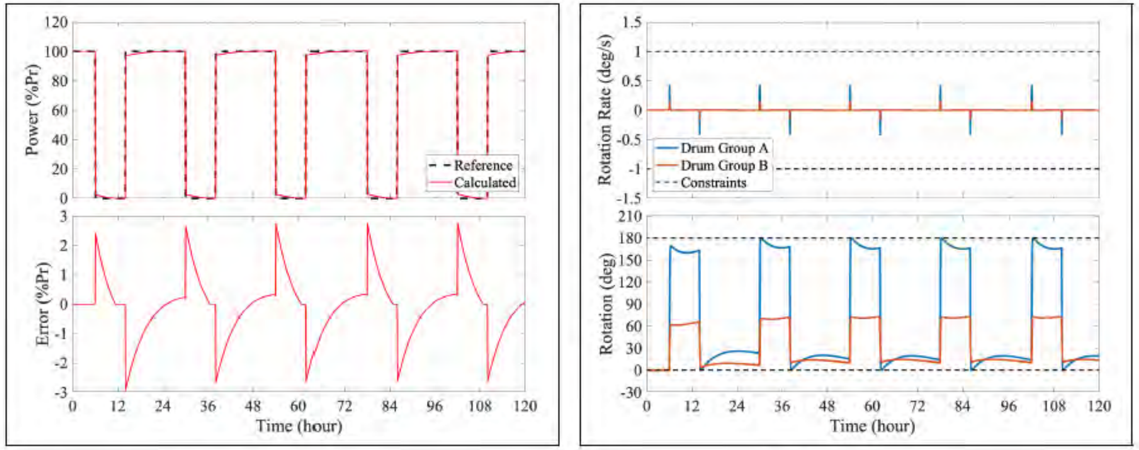
	PID	LQR	H_∞	MPC
Accuracy	Highly depends on tuning	Depends on tuning	Depends on tuning	Depends on tuning
Easy to tune?	Difficult	Easy	Easy	Easy
Able to handle constraints?	Not general	Not general	Not general	Yes
Able to handle MIMO?	Difficult	Yes	Yes	Yes
Calculation cost	Cheap	Expensive	Expensive	The most expensive

Time to simulate 4000s with 10ms time step



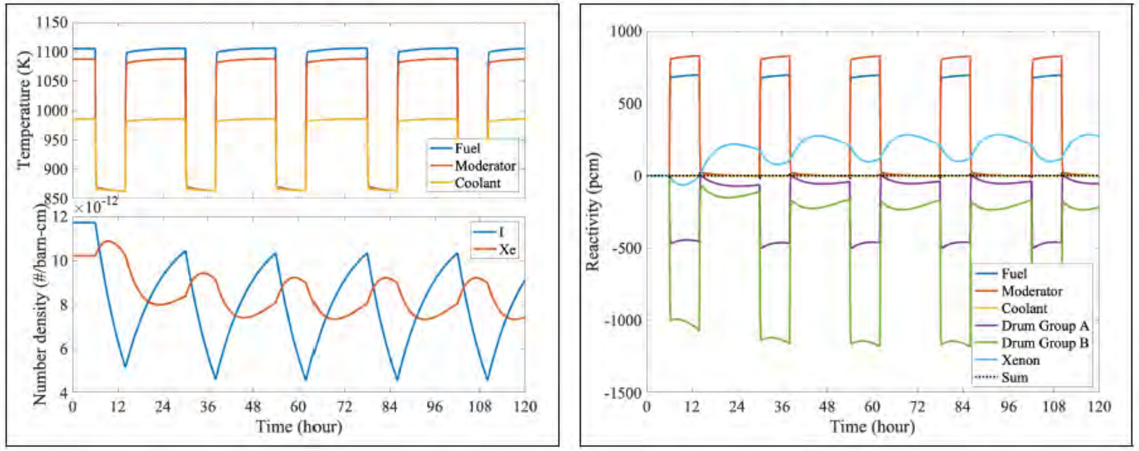
Control Algorithm	Elapsed time (sec)
PID	0.09
LQR	0.16
H_∞	0.17
MPC	1.67

Model Predictive Control Sensitivities



(a) Power and error

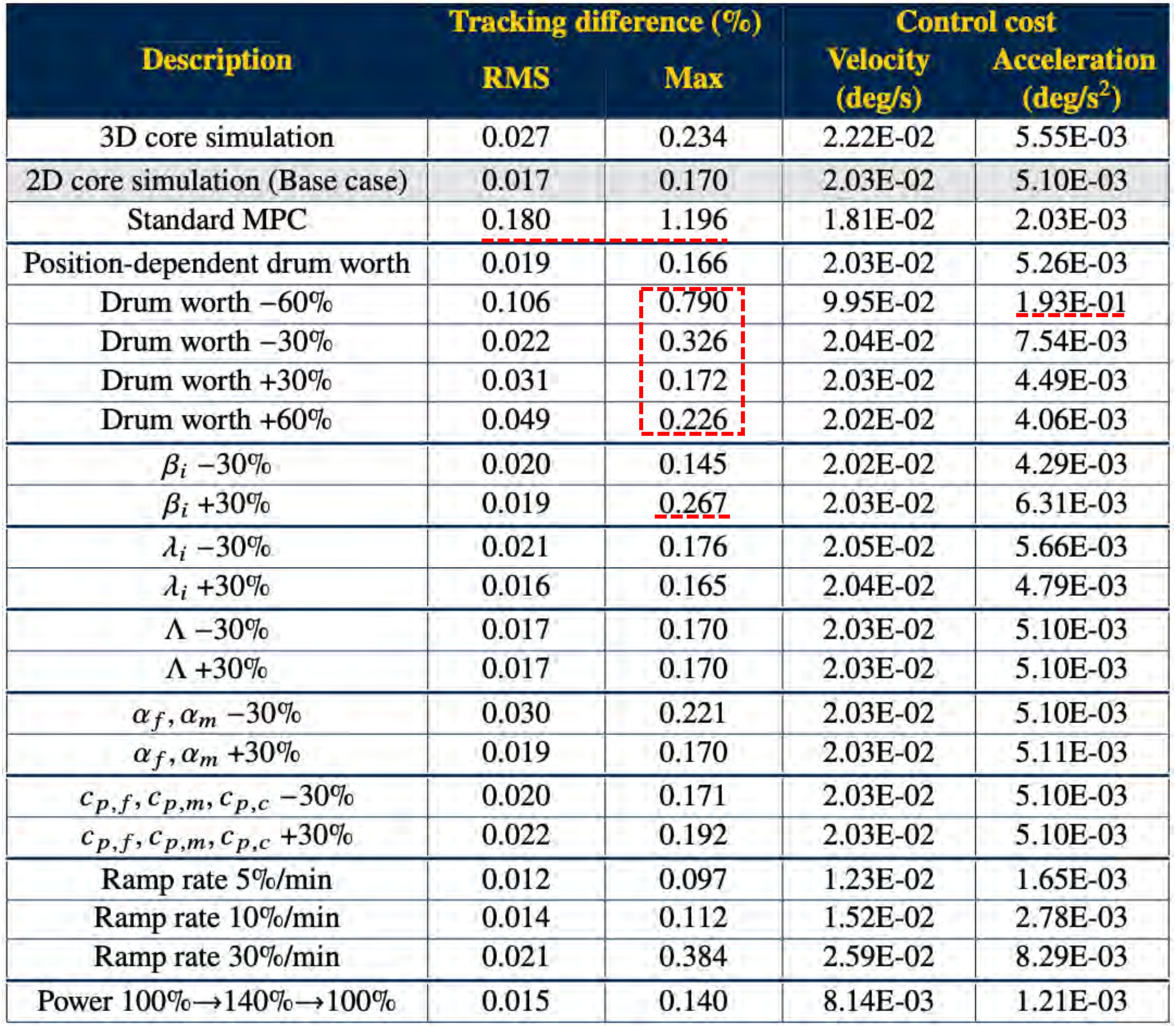
(b) Control inputs



(c) Temperature and density

(d) Reactivity change

Figure 28. Simulation results for peaking power plant scenario with mismatch model



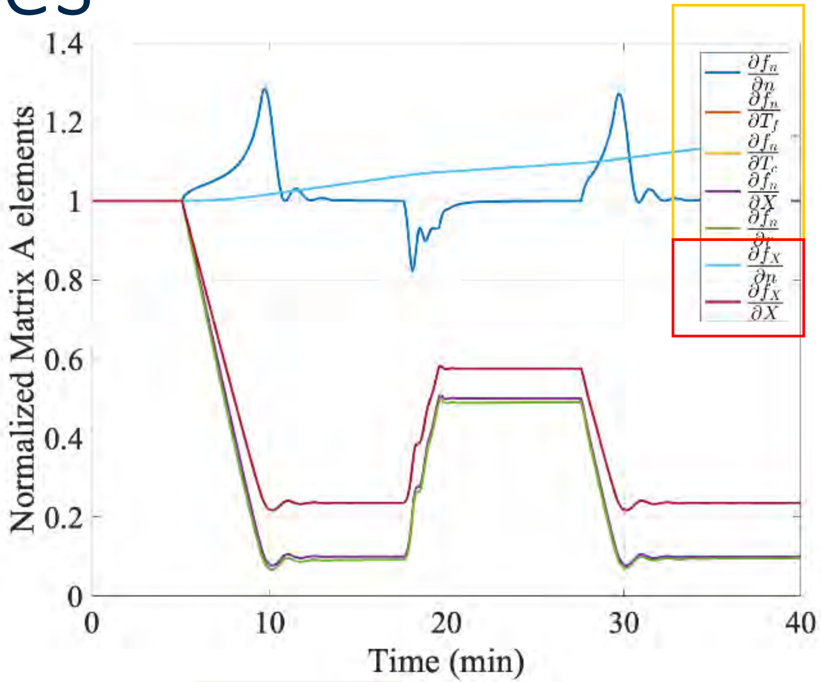
Description	Tracking difference (%) RMS	Tracking difference (%) Max	Control cost Velocity (deg/s)	Control cost Acceleration (deg/s^2)
3D core simulation	0.027	0.234	2.22E-02	5.55E-03
2D core simulation (Base case)	0.017	0.170	2.03E-02	5.10E-03
Standard MPC	0.180	1.196	1.81E-02	2.03E-03
Position-dependent drum worth	0.019	0.166	2.03E-02	5.26E-03
Drum worth −60%	0.106	0.790	9.95E-02	1.93E-01
Drum worth −30%	0.022	0.326	2.04E-02	7.54E-03
Drum worth +30%	0.031	0.172	2.03E-02	4.49E-03
Drum worth +60%	0.049	0.226	2.02E-02	4.06E-03
β_i −30%	0.020	0.145	2.02E-02	4.29E-03
β_i +30%	0.019	0.267	2.03E-02	6.31E-03
λ_i −30%	0.021	0.176	2.05E-02	5.66E-03
λ_i +30%	0.016	0.165	2.04E-02	4.79E-03
Λ −30%	0.017	0.170	2.03E-02	5.10E-03
Λ +30%	0.017	0.170	2.03E-02	5.10E-03
α_f, α_m −30%	0.030	0.221	2.03E-02	5.10E-03
α_f, α_m +30%	0.019	0.170	2.03E-02	5.11E-03
$c_{p,f}, c_{p,m}, c_{p,c}$ −30%	0.020	0.171	2.03E-02	5.10E-03
$c_{p,f}, c_{p,m}, c_{p,c}$ +30%	0.022	0.192	2.03E-02	5.10E-03
Ramp rate 5%/min	0.012	0.097	1.23E-02	1.65E-03
Ramp rate 10%/min	0.014	0.112	1.52E-02	2.78E-03
Ramp rate 30%/min	0.021	0.384	2.59E-02	8.29E-03
Power 100%→140%→100%	0.015	0.140	8.14E-03	1.21E-03

Model Predictive Control with Gaussian Process Regression for learning nonlinearities

- ***Problem***
  - MPC uses a linear state-space model, nonlinear variants are
- ***Our Solution***
  - Use GPR to learn variation in state-space representation
- ***Result***
  - It works, but you have to solve the problem to obtain the solution.
- ***Value***
  - None. ML is dumb. Use your equations and math. Adaptive MPC is perfectly adequate.

$$\frac{dN_I(t)}{dt} = \gamma_i \Sigma_f v n(t) - \lambda_I N_I(t)$$

$$\frac{dN_{Xe}(t)}{dt} = \gamma_{Xe} \Sigma_f v n(t) + \lambda_I N_I(t) - \lambda_{Xe} N_{Xe}(t) - \boxed{\sigma_{Xe} v n(t) N_{Xe}(t)}$$



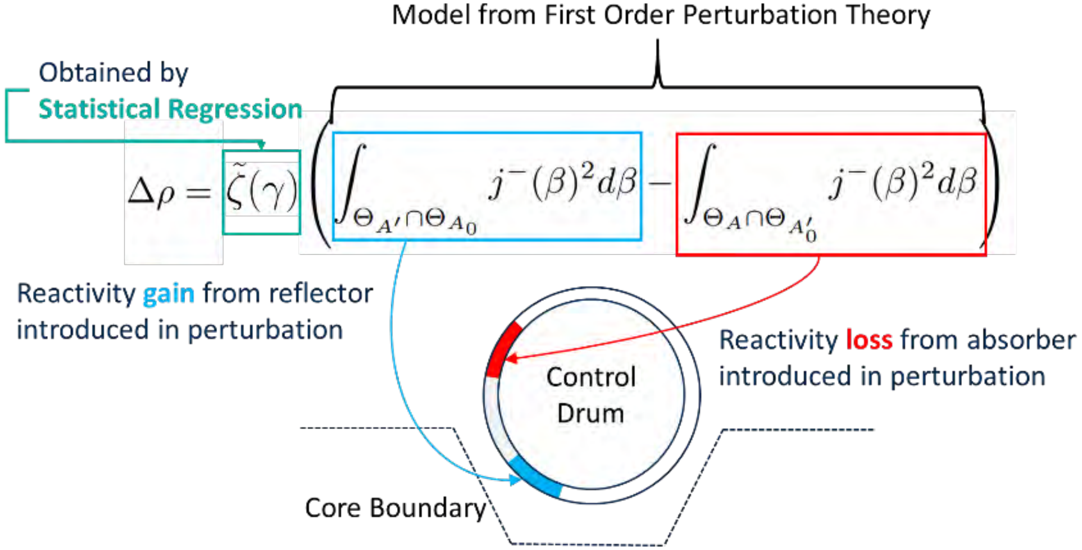
$$\frac{dn(t)}{dt} = \boxed{\frac{\rho(t) - \beta}{\Lambda}} n(t) + \sum_i \lambda_i C_i(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t)$$

$$\rho(t) = \alpha_f \left(T_f(t) - T_f(0)\right) + \alpha_c\left(T_c(t) - T_c(0)\right) + \alpha_m\left(T_m(t) - T_m(t)\right) - \frac{\sigma_{Xe}}{v\Sigma_f}\left(N_{Xe}(t) - N_{Xe}(0)\right) + \rho_{ext}(t)$$

Hybrid Machine Learning and Perturbation Theory Method for Microreactor Control Drums

- ***Problem***
  - For real time control how do I accurately estimate the reactivity of my control system for an arbitrary configuration of drums?
- ***Our Solution***
  - Use analytic first order perturbation theory to get first order physics effects
    - Who remembers undergraduate nuclear engineering?
  - Use (a somewhat complex) linear regression to correct for inherent assumptions of analytical model
- ***Result***
  - Run 70 whole-core Monte Carlo calculations to train model
  - Calculate core reactivity to within 50 pcm of Monte Carlo in milliseconds
- ***Value***
  - Efficiency: Over 1,000 Monte Carlo calculations cases are needed to tabulate all possibilities
  - Quick calculations for optimization, sensitivity or UQ.



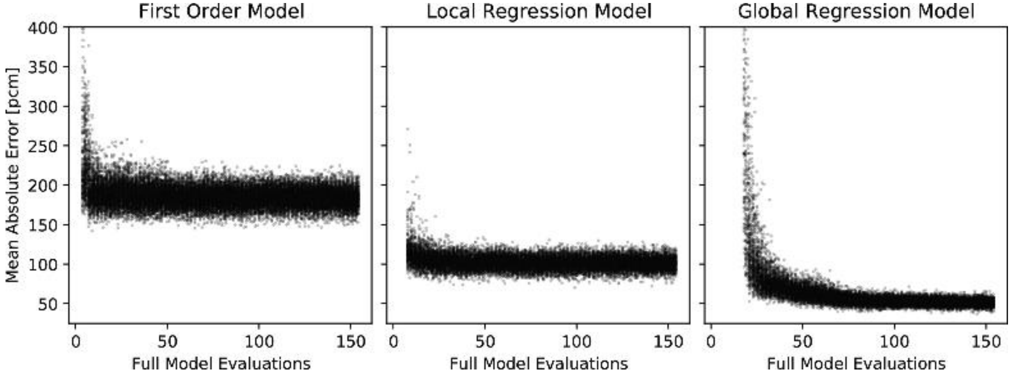
Model from First Order Perturbation Theory

Obtained by **Statistical Regression**

$$\Delta\rho = \boxed{\tilde{\zeta}(\gamma)}\overbrace{\left(\boxed{\int_{\Theta_{A'}\cap\Theta_{A_0}} j^-(\beta)^2 d\beta} - \boxed{\int_{\Theta_A\cap\Theta_{A_0'}} j^-(\beta)^2 d\beta}\right)}$$

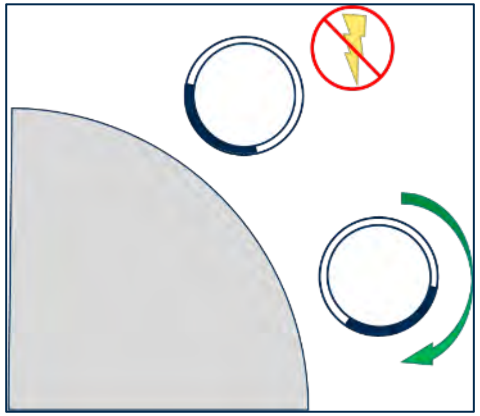
Reactivity **gain** from reflector introduced in perturbation

Reactivity **loss** from absorber introduced in perturbation



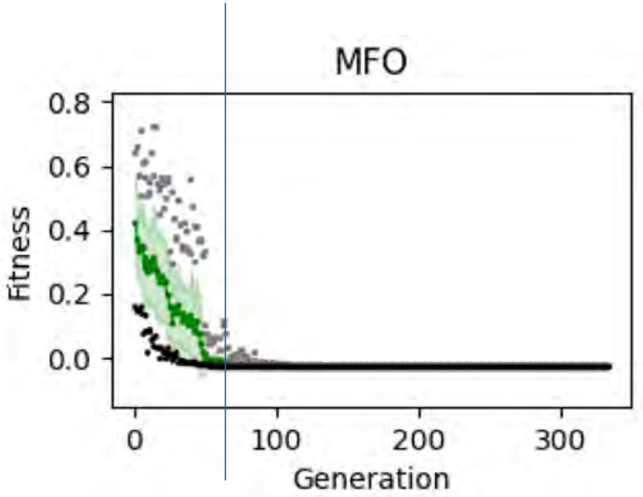
Multi-Objective Optimization of Microreactor Control Drum Operation

- ***Problem***
  - For real time control how do I accurately determine an optimal control drum configuration to meet reactivity requirements, peaking requirements, and do so robustly?
- ***Our Solution***
  - Multi-objective optimization with scalarization and moth flame optimization
- ***Result***
  - Capable of configuring 8 drums to match a desired reactivity, while satisfying quadrant power tilt ratio, even when you have a struck drum
- ***Value***
  - Near real-time method for robust reactivity control of microreactors



Works with Stuck Drums

Optimal Control Drum Positioning Reached

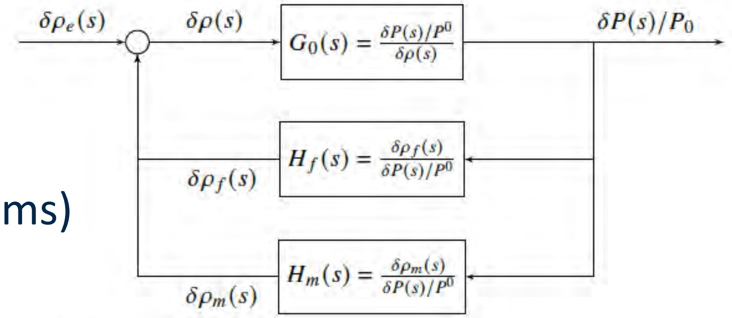


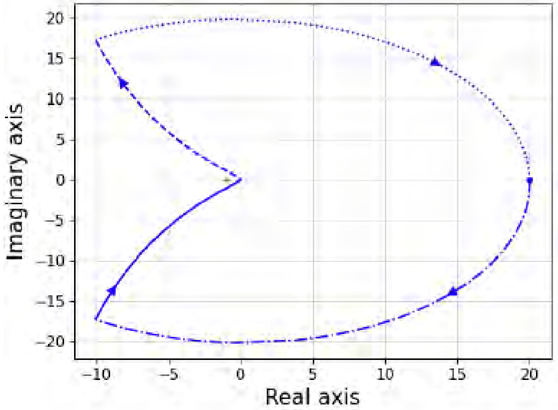
Optimal solution solved with high-fidelity Monte Carlo (~50 pcm off critical QPTR within 0.001)

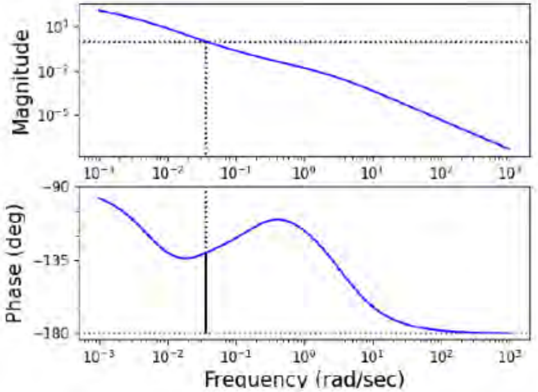
Analytic Stability Analysis

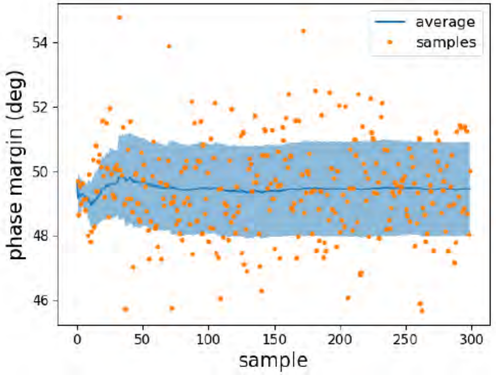
- ***Problem***
  - How do we know the physics of the reactor is unconditionally stable over all possible inputs?
- ***Our Solution***
  - Standard analytic methods of stability analysis: linear stability analysis, Nyquist plots, Bode Diagrams
- ***Result***
  - HTGR-like MNRs are very inherently safe in terms of dynamics—primarily due to doppler feedback
- ***Value***
  - Mostly pedagogical beyond answering very specific question above.

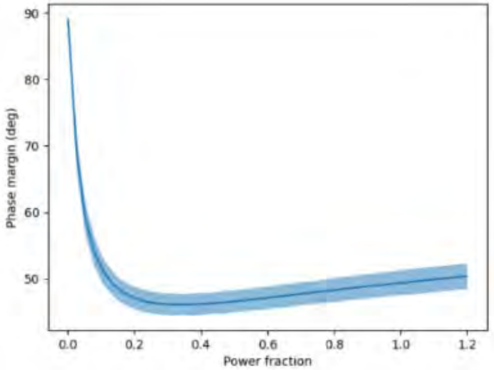
Open-Loop
Block Diagram
(Laplace Transforms)



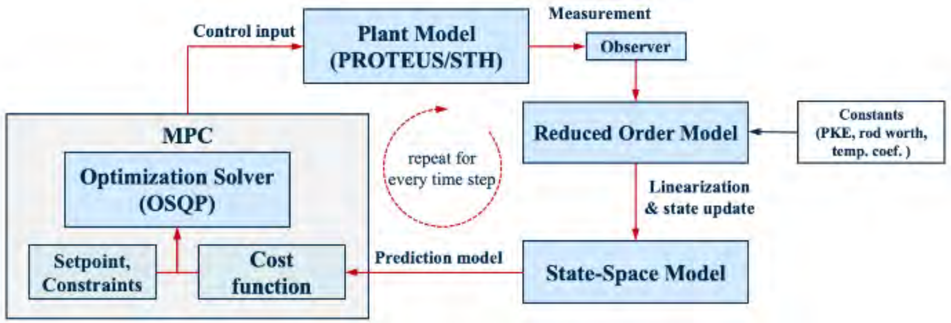


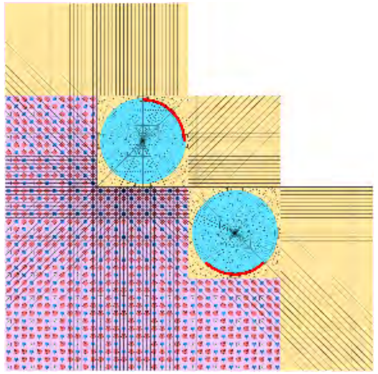




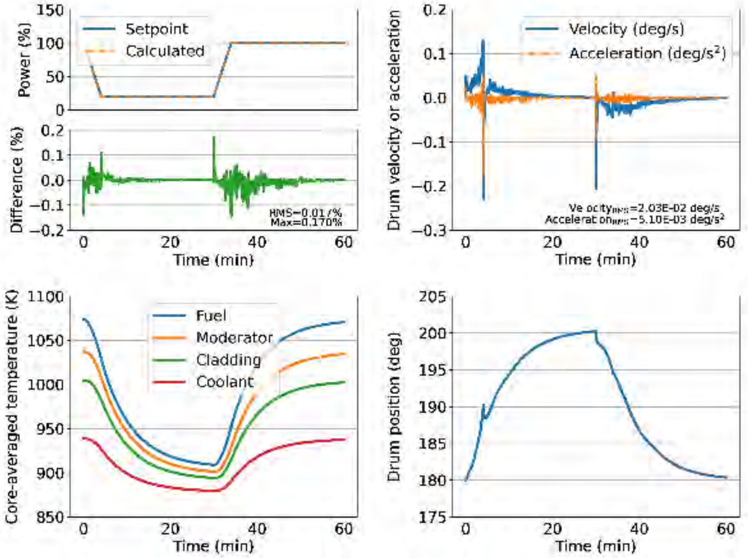


Integrated High-Fidelity Simulation with Model Predictive Control



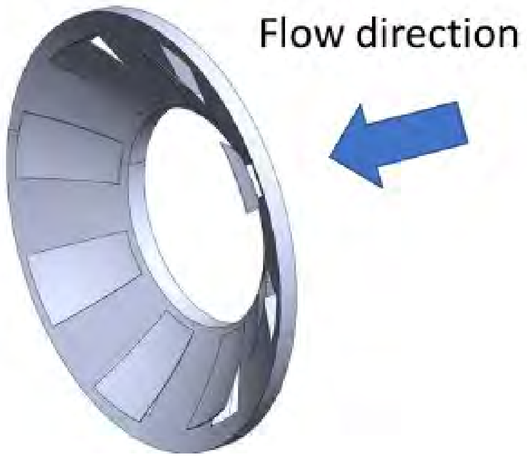


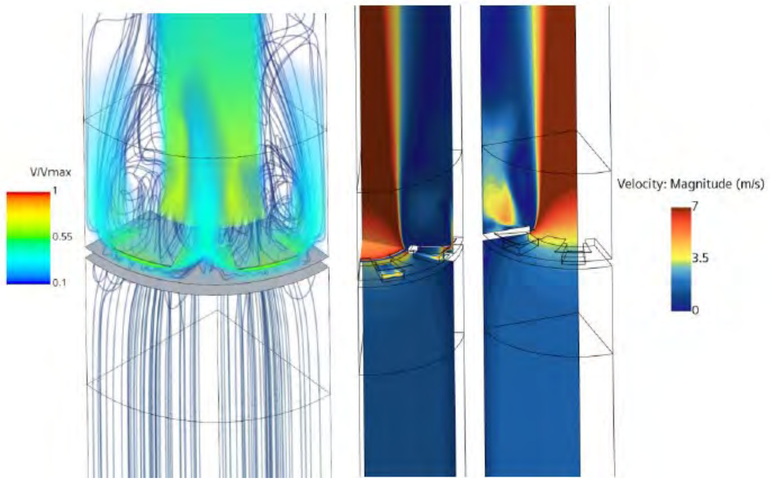
- ***Problem***
  - High-fidelity multiphysics simulation has some benefit to reactor design, most control system designs use point models. Can we extend simulation capability to incorporate control algorithms?
- ***Our Solution***
  - Couple MPC simulations with multiphysics transient HTGR simulation. Developed a simplified TH solver as well.
- ***Result***
  - Successfully demonstrated capability, but still a long way to go.
- ***Value***
  - Initial step for broader capabilities to co-design I&C systems with the rest of the reactor.

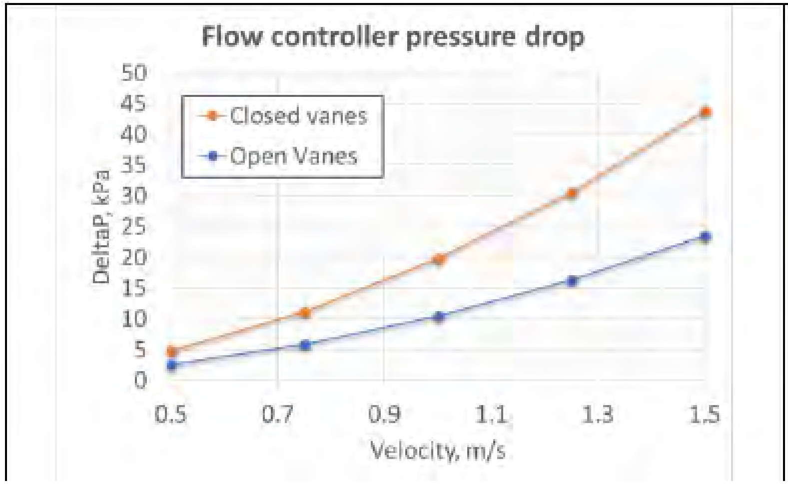


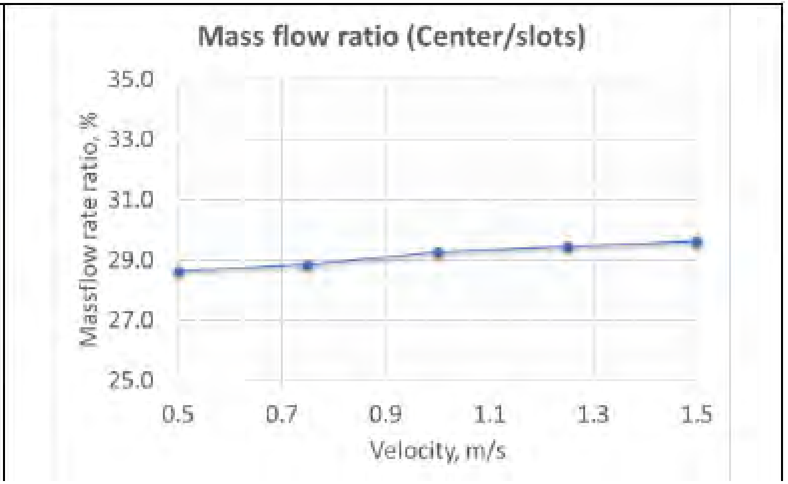
Passive Variable Flow Controller

- ***Problem***
  - Can we devise a component that facilitates load following that uses concepts from inherently and passively safe components?
- ***Our Solution***
  - Design a valve that uses bimetallic vanes
  - Use conventional CAE tools and explore pre-conceptual design space for materials and geometry.
- ***Result***
  - Candidate material selection. Evolution of geometry. Reasonable control for pressure drop and flow rate.
- ***Value***
  - Proof-of-principle simulation motivates continued research.





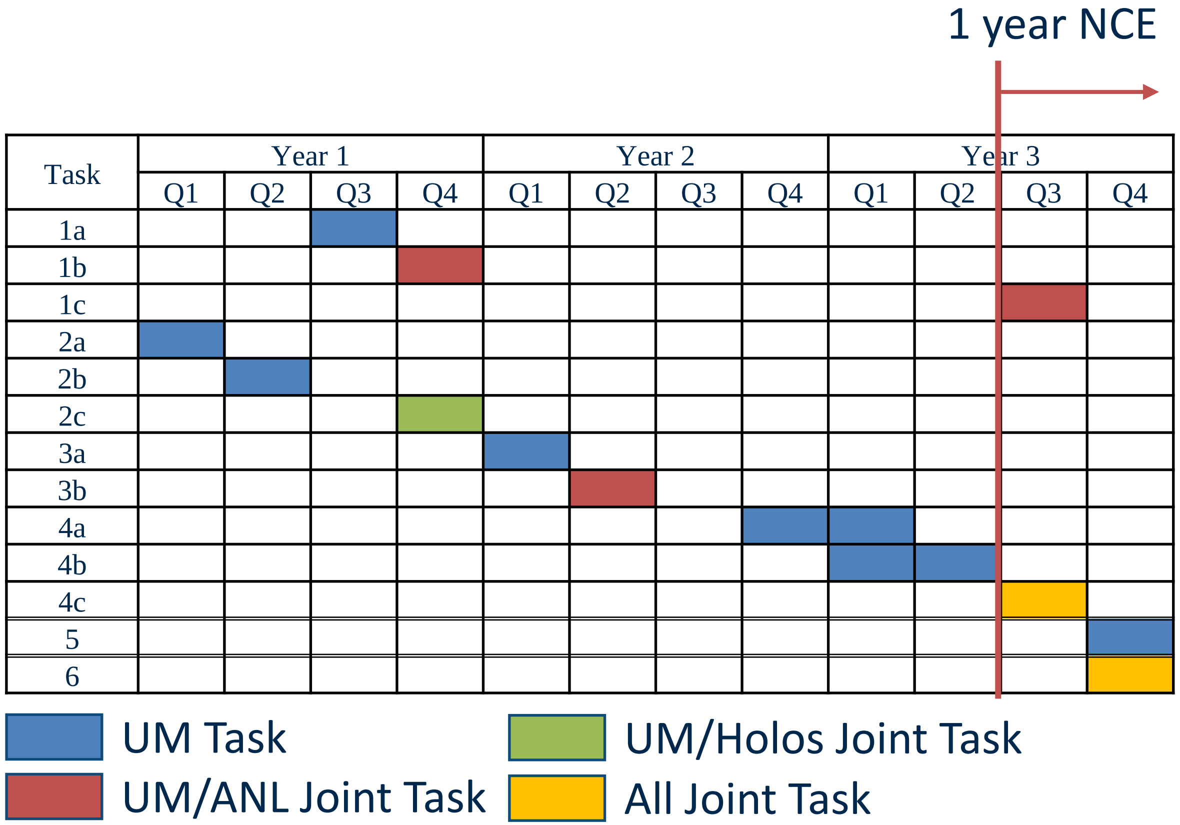




Project Metrics

Milestones

Task #	Description
2a	Assessment of local temperature reactivity response
2b	Assessment of variable reflector reactivity envelope
2c	Global and Local Reactivity Assessments for Passive Control Systems
1a	Point Kinetics Model Development with MPC
3	Passive Feedback Model Development and Integration
4b	High Fidelity Transient Simulations of the Multi-module HTGR Special Purpose Reactor
4c	Comparison of Passive Feedback Control versus Idealized Control of Multi-Module HTGR Special Purpose Reactor
5	CFD and FEM Analysis of Passive Variable Flow Controller
6	Final Project Report



1 year NCE

Task	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1a			🟦									
1b				🟥								
1c											🟥	
2a	🟦											
2b		🟦										
2c				🟩								
3a					🟦							
3b						🟥						
4a								🟦	🟦			
4b									🟦	🟦		
4c											🟨	
5												🟦
6												🟨

🟦	UM Task	🟩	UM/Holos Joint Task
🟥	UM/ANL Joint Task	🟨	All Joint Task

8 Milestone Reports + Final report

Milestone Reports

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

Assessment of Local
Temperature Reactivity
Response in Multi-Module H
Special Purpose React

Volkan Seker, University of Michigan
Brendan Kochunas, University of Michigan

04/30/2020

NEUP
U.S. Department

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

Assessment of Variable
Reflector Reactivity
Envelope in Multi-Module
HTGR Special Purpose
Reactor

Brendan Kochunas, Kaitlyn Barr, and Shai
Kinast

University of Michigan

07/31/2020

NEUP
U.S. Department of

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

Global and Local
Reactivity Assessments
for Passive Control
Systems of Multi-module
HTGR Special Purpose
Reactors

Brendan Kochunas, Kaitlyn Barr, Shai
Kinast, and Sooyoung Choi

University of Michigan

09/30/2020

NEUP
U.S. Department of

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

Point Kinetics Model
Development with
Predictive Control for
Multi-Module HTGR
Special Purpose Reactor

Sooyoung Choi, Shai Kinast, and Brendan
Kochunas

University of Michigan

12/29/2020

NEUP
U.S. Department of

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

Preliminary Passive
Feedback Model
Development and
Integration

Qicang Shen[1] and Brendan Kochunas[1]

[1]University of Michigan

06/30/2021

NEUP
U.S. Department of

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

High Fidelity Transient
Simulations of the
Multi-module HTGR
Special Purpose Reactor

Sooyoung Choi[1], Qicang Shen[1], Chang-ho
Lee[2], and Brendan Kochunas[1]

[1]University of Michigan
[2]Argonne National Laboratory

09/14/2023

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

CFD and FEM Analysis of
Passive Variable Flow
Controller

Yucan Ding[1], Victor Petrov[1], and Brendan
Kochunas[1]

[1]University of Michigan

09/15/2023

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES

Nuclear Reactor
Analysis & Methods
Group
NuRAM

NURAM-2023-008-00

Comparison of Passive
Feedback Control versus
Idealized Control of
Multi-Module HTGR SPR

Sooyoung Choi[1], Qicang Shen[1], and Brendan
Kochunas[1]

[1]University of Michigan

09/28/2023

Publications and Personnel

- Personnel
  - 5 students
  - 2 research staff
  - 1 visiting scholar
- ~5 journal (2 published, 1 submitted, 2 in draft)
  - D. Price, S. Kinast, K. Barr, *et al.*, "A perturbation-based hybrid methodology for control drum worth prediction applied to the holos-quad microreactor concept," *Annals of Nuclear Energy*, vol. 168, p. 108 903, 2022.
  - D. Price, M. I. Radaideh, and B. Kochunas, "Multiobjective optimization of nuclear microreactor reactivity control system operation with swarm and evolutionary algorithms," *Nuclear Engineering and Design*, vol. 393, p. 111 776, 2022.
- 9 peer reviewed conference papers

- S. Kinast, D. Price, D. Sivan, *et al.*, "Sensitivity study of stability margins of htr-type microreactor," *M&C2023*.
- S. Choi, Q. Shen, C. H. Lee, *et al.*, "Preliminary results of load follow simulation for holos-quad microreactor using proteus and model predictive control," *M&C 2023.*
- V. Petrov and Y. Ding, "Passive temperature-sensitive flow-controlling device based on bimetallic membrane deflection, fem, and cfd feasibility study," in *NURETH-20*, 2023.
- D. Price, S. Kinast, and B. Kochunas, "Error analysis of a hybrid control drum worth model," in *PHYSOR 2022*
- S. Kinast, C. Filippone, and B. Kochunas, "Stability Margin Analysis of the Holos-Quad Microreactor Design," in *PHYSOR 2022*
- S. Choi, S. Kinast, C. Filippone, *et al.*, "Comparative Study for Load-FollowOperations of the Holos Microreactor," in *M&C2021*
- S. Kinast, D. Sivan, S. Choi, *et al.*, "Frequency Domain Analysis of HTR-like Microreactors," in *M&C 2021*
- S. Choi, S. Kinast, V. Seker, *et al.*, "Preliminary Study of Model Predictive Control for Load Follow Operation of Holos Reactor," *Trans. Am. Nucl. Soc.*, **122**, 2020.
- D. Sivan, S. Kinast, S. Choi, *et al.*, "Linear stability analysis of htr-like micro-reactors," *Trans. Am. Nucl. Soc.*, **122**, 2020.

Summary

- 3 (+1) year $400,000 project.
    - 8 milestone reports and final report
    - 14 peer-reviewed publications
    - 5 students and 3 staff (one visitor).
- Key scientific advancements
    - Rigorous demonstration and analysis of Model Predictive Control.
        - Its all physics based, no AI needed! (Some ML math methods can help)
        - Several possible extensions not demonstrated in this project.
    - Advanced control algorithms can be incorporated into state of the art high-fidelity multiphysics simulation tools for co-design and verification of I&C systems.
    - Advancements in algorithms for real-time controllers.
    - Proof-of-principle simulation analysis on passive variable flow controller.

Questions

Thank you!