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Autonomous Operation of Advanced Reactors – Initial Discussions on Technical and Market Advancements

INL/MIS-25-87788 Rev:000

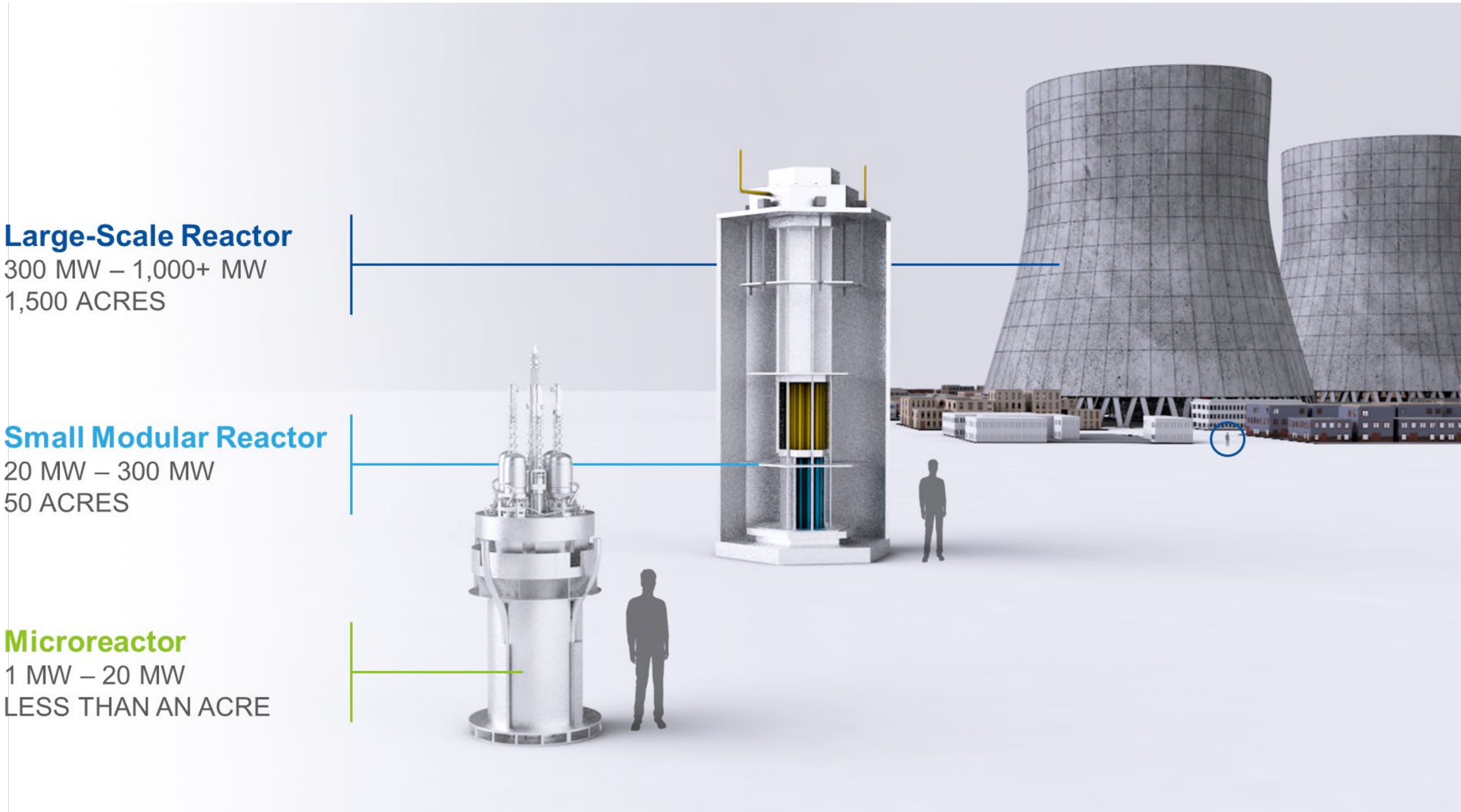
Next Generation Reactors: Multiple Sizes and Different Levels of Autonomy

Small Modular Reactors (SMRs)

- Smaller power output and footprint
- Modular fabrication and assembly
- Passive safety

Microreactors

- Transportable and very easy to install
- Cater to remote communities
- Simplified safety (low source term)
- Little to no on-site staff
- **Nuclear as a 'product' rather than 'project'**



Team

- Idaho National Laboratory
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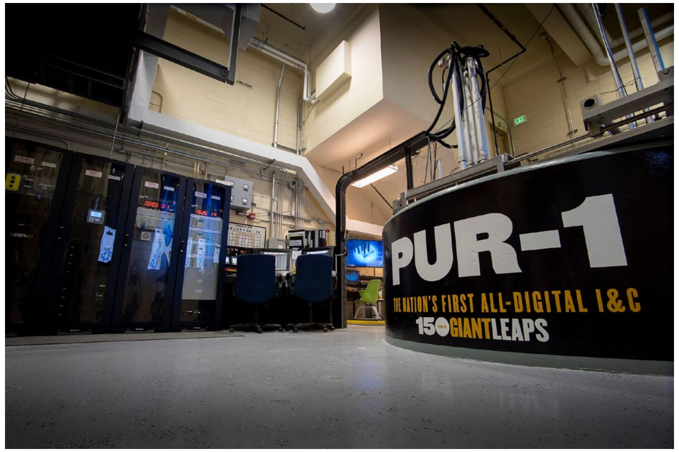
  - Linyu Lin
  - Joseph Oncken
  - Shannon Eggers

- Purdue University
  - Stylianos Chatzidakis
  - Zachery Dahm

- Curtiss-Wright (in-kind collaborator)
  - Robert England

OTC
Office of Technology Commercialization

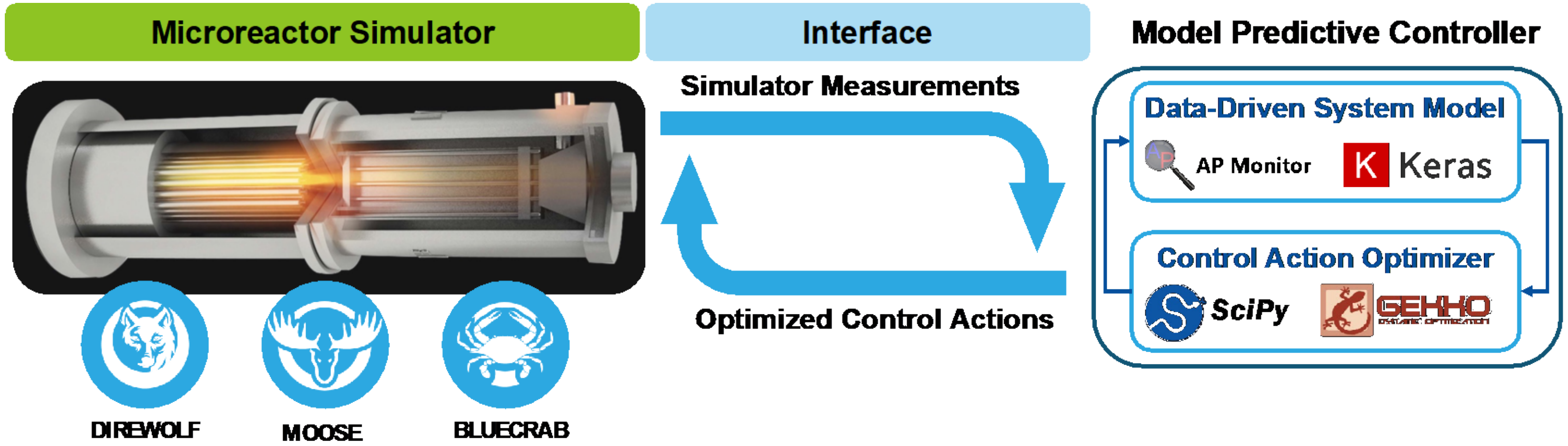
INL High Performance Computing



Purdue University Reactor One (PUR-1)

Scalable Hybrid Modeling with Anticipatory Control Strategy for Autonomous Operation of Modular and Microreactor

- First-of-a-kind anticipatory controller **Autonomous Control fOr Reactor technology (ACORN)** to achieve autonomous control of microreactors
- Leverages and expands INL's modeling and simulation capabilities like DireWolf and BlueCRAB for capturing microreactor thermal and neutronic performance
- ACORN controller provides optimal control actions for microreactor under different scenarios and external uncertainties
  - Steady state and transient operations
  - Flexible operation (load following)
  - Failure or degraded operation



ACORN advances the level of automation to address the self-regulating attribute of microreactors. This advancement also accounts for economics of operation of microreactors.

Lin, L., J. Oncken, and V. Agarwal. 2024. "Anticipatory Control for Heat-Pipe Microreactor using Data-Driven Model Predictive Control." Annals of Nuclear Energy, 200, 110399. https://doi.org/10.1016/j.anucene.2024.110399.

Project Objectives

- To advance the adoption readiness level (2 to 5) and technology readiness level (3-6) of ACORN.
- Achieve hardware-in-the-loop demonstration with PUR-1 digital control system by taking into consideration cybersecurity concerns.
- Development of user–centric visualization for situational awareness of PUR-1 with autonomous operation ability.
- Develop a training program at Purdue University for effective human machine interactions.

Seeking stakeholders' input on the autonomous concept of operations of advanced reactors

The survey will close on October 3, 2025.

Autonomous Control for Reactor Technologies

A Technology Commercialization Fund Project

Are you thinking about Automation?
How about Full Autonomy? How about AI for Full Autonomy?

We want your input

Please scan the QR code for a short survey to inform our research.
All feedback will be presented in aggregate, high-level form. No personally identifiable information (PII) or specific organizational data will be disclosed.

For project details, contact: Vivek Agarwal, Distinguished Staff Scientist • Idaho National Laboratory • vivek.agarwal@inl.gov

In Collaboration with CURTISS-WRIGHT PURDUE UNIVERSITY

25-50666

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

INL Idaho National Laboratory

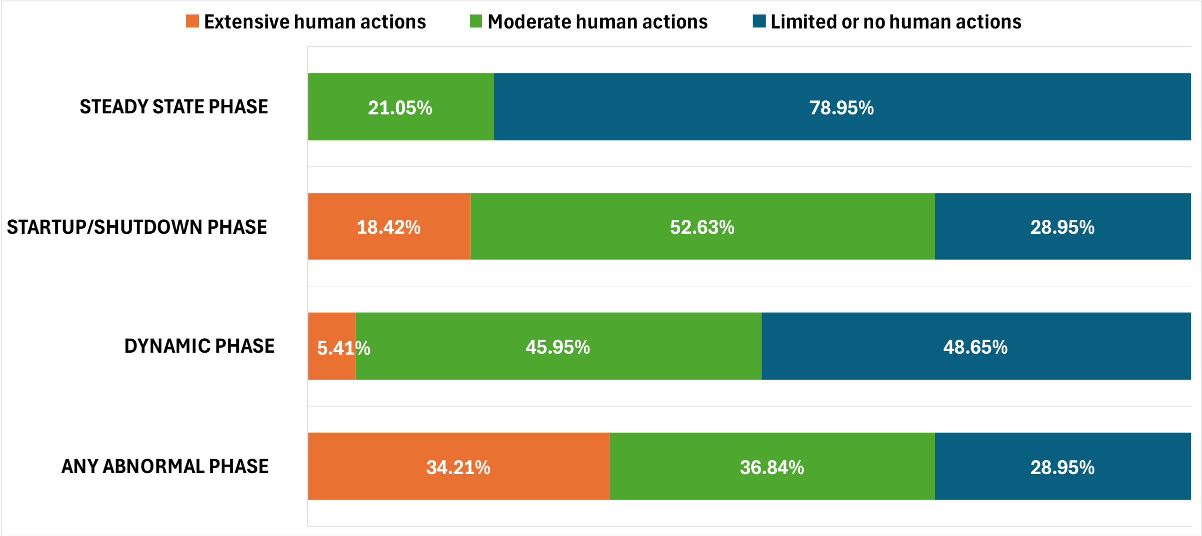
Preliminary feedback from stakeholders

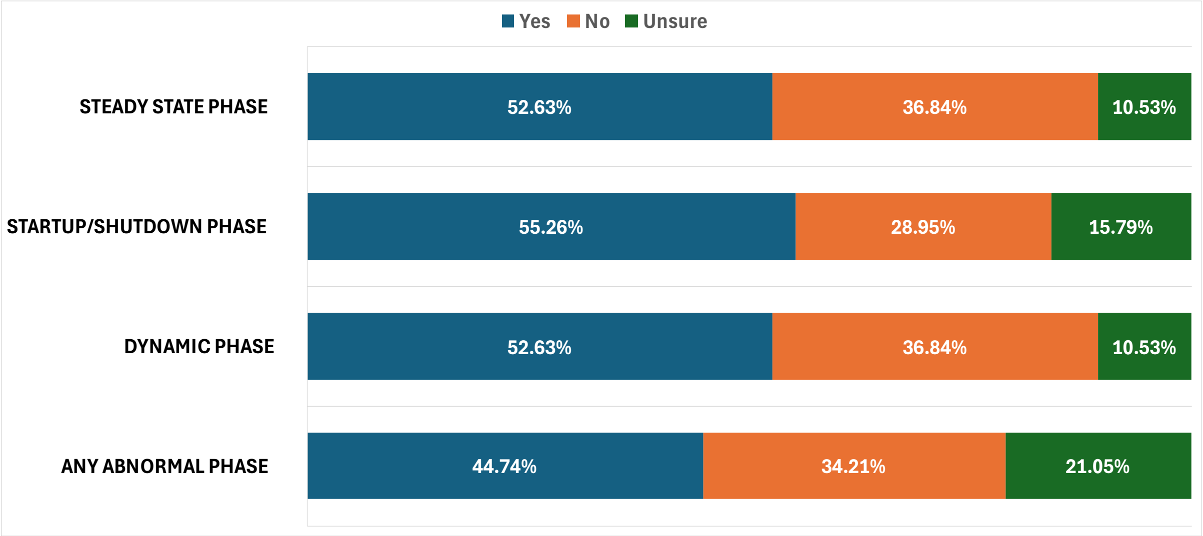
Select your concept of operations (ConOps) for the various phases of operations.

- Steady state
- Startup/Shutdown phase
- Dynamic phase
- Any abnormal phase

Select whether you expect your ConOps to change over time as you deploy more reactors.

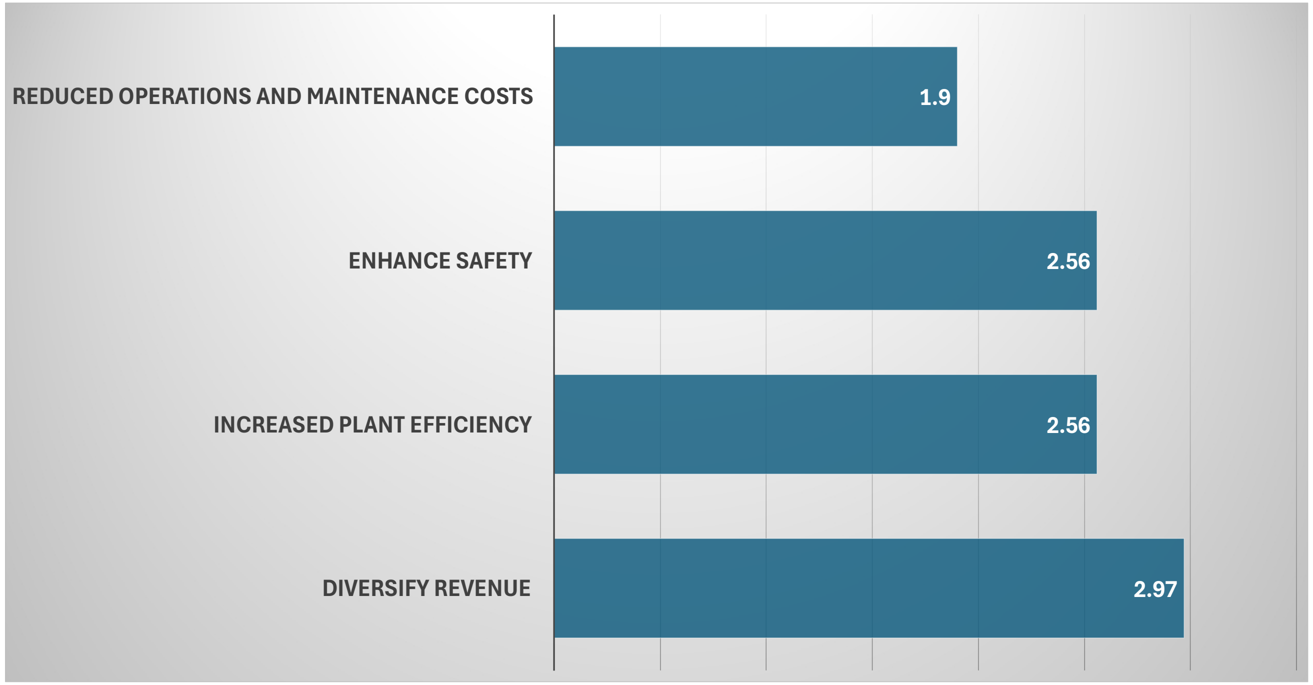
- Steady state
- Startup/Shutdown phase
- Dynamic phase
- Any abnormal phase



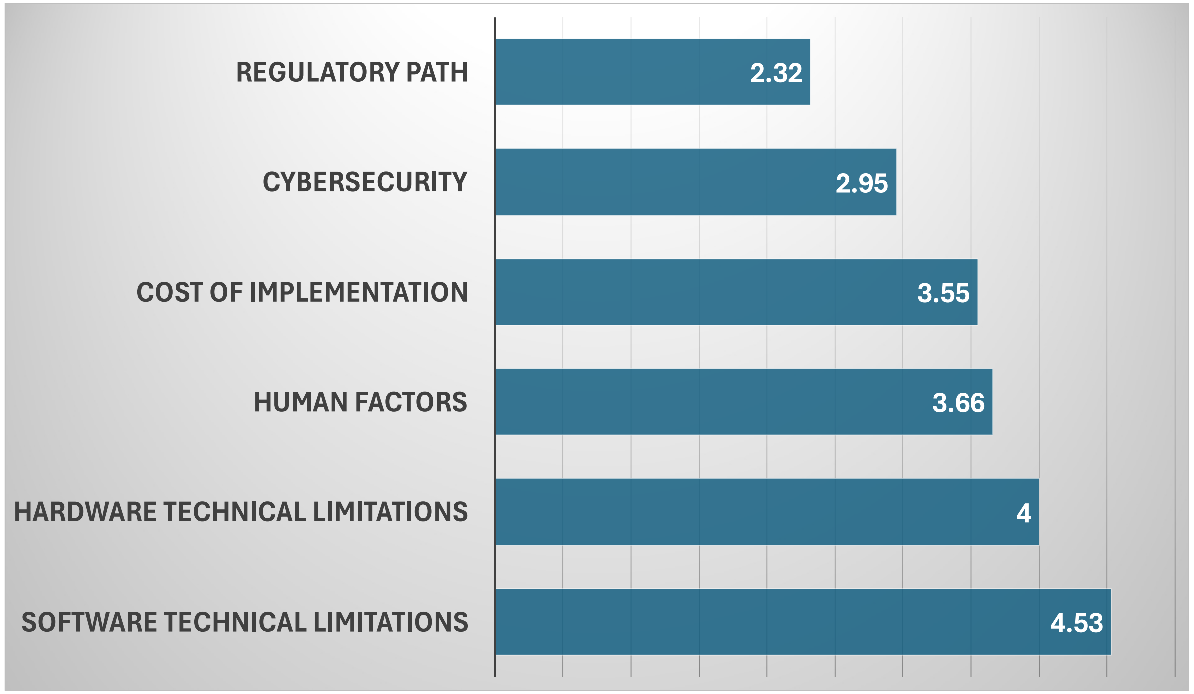


Preliminary feedback from stakeholders

Ranked benefits of using automated or autonomous operation
(Scale: 1-4 | 1=Biggest Benefit)

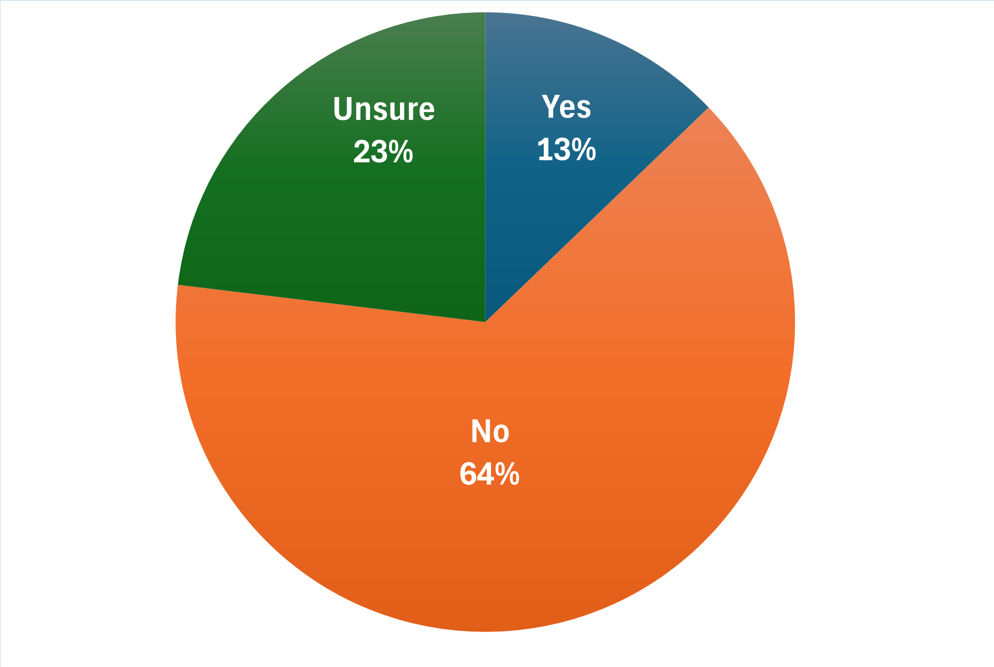


Ranked challenges with automated operation and/or autonomous control
(Scale: 1-6 | 1=Biggest Challenge)

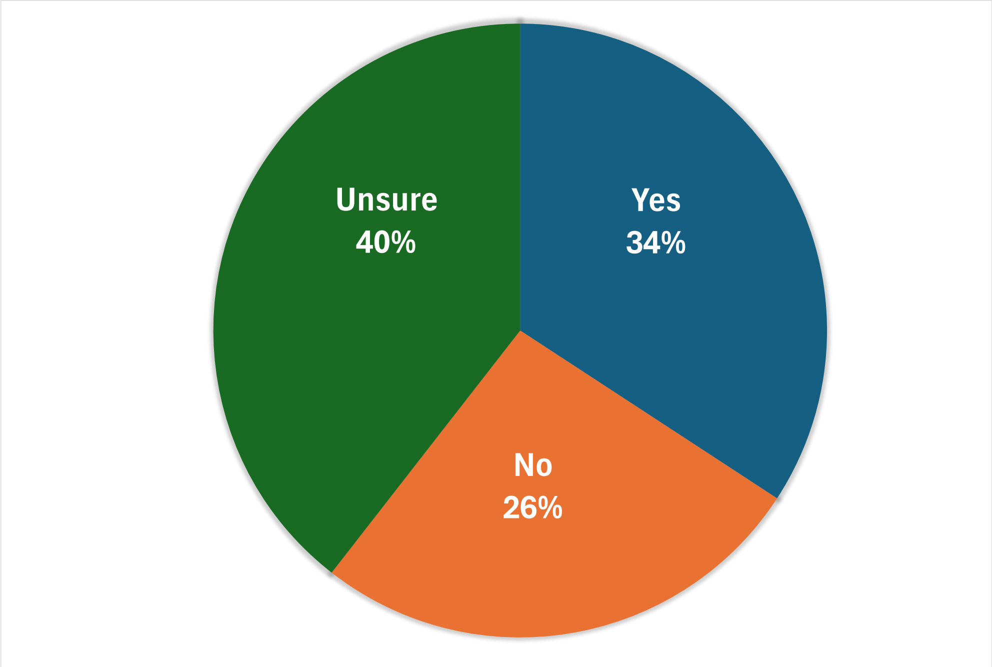


Preliminary feedback from stakeholders

Is artificial intelligence necessary to achieve autonomous control?

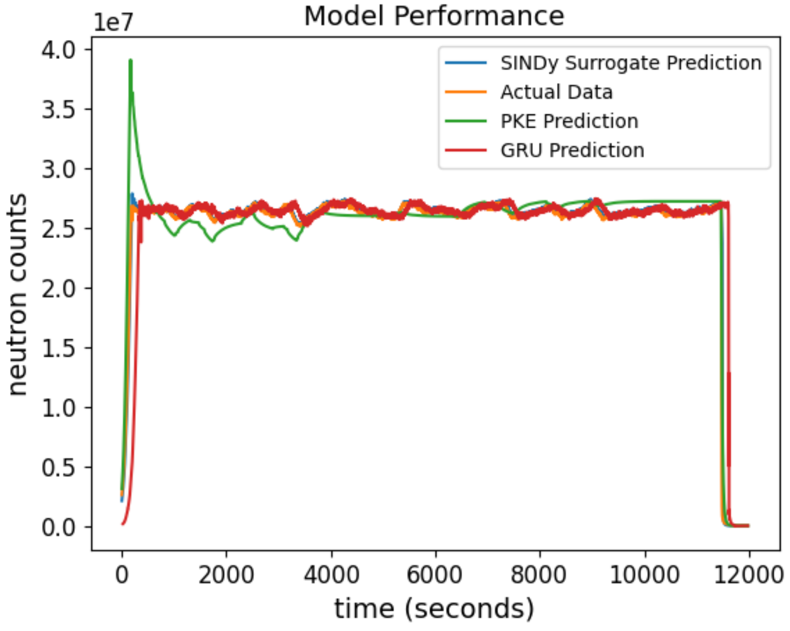


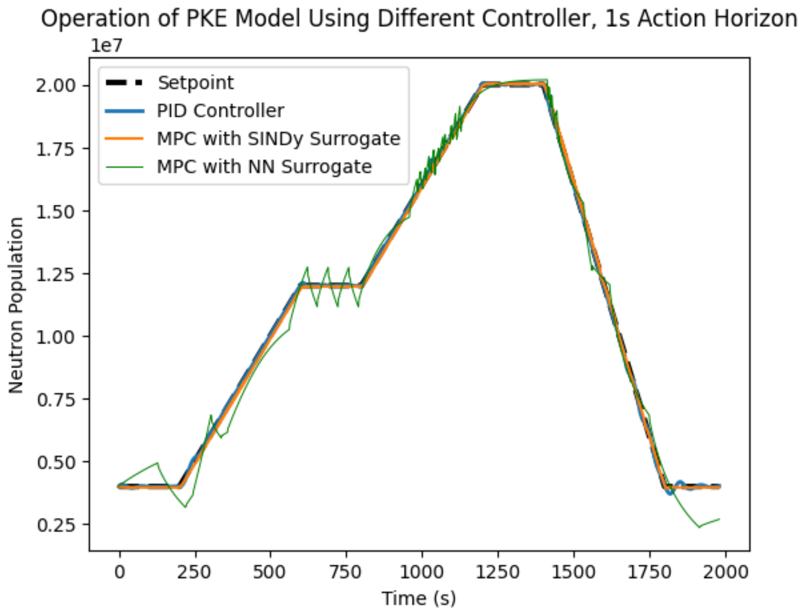
Are you comfortable with artificial intelligence being a part of an autonomous control system of a nuclear plant?



Ongoing Research

- Adapt ACORN to PUR-1 using operational data
- Test ACORN using physics-based models, i.e., Point Kinetic (PKE) model with 6 delayed neutron groups and power feedback
- Predictors using sparse identification of nonlinear dynamics (SINDy) and neural networks
- Optimizers using line search and quadratic programming
- Control rod positions are converted to reactivity using experimentally determined rod worth curves
- Controller will adjust either:
  - Reactivity
  - Control rod positions
- Data in model and operational data is generated at 1Hz.





Effect of action frequency on performance and stability

- MPC is better suited for slow transient with longer horizons
  - When frequent actions are needed (every second), PID performs better
  - When slow transients and less movements are preferred, MPC performs better.
- Neural network models has comparable performance when coupled with simple line search.

	Tracking Error in Mean Squared Error		
Action Horizon	MPC with SINDy	PID	MPC with Neural Network
1	0.000108	0.000033	0.000612
5	0.000120	0.000052	2.090680
10	0.000144	0.000480	0.001281
20	0.000637	0.000976	0.000948

	Number of Actions Taken		
Action Horizon	MPC with SINDy	PID	MPC with Neural Network
1	18	177	565
5	36	110	54
10	30	45	244
20	17	24	132

Summary and Path Forward

- The industry feedback on autonomous concept of operation of advanced reactors was presented and discussed.
- PKE model of PUR-1 with 6 delayed neutron groups and power feedback was developed.
- Different control algorithms using PUR-1 operational data and PKE model was developed and optimized using different optimization routines.
- In the budget period 2, **scenarios for PUR-1 testing will be developed and initial testing of ACORN on PUR-1 digital control system**.
- A graphic user interface will be developed for human-in-the-loop evaluation.

Idaho National Laboratory

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