Demonstrating Autonomous Architectures for Microreactors Under Prototypic Conditions in PUR-1

2024 Microreactor Program Review

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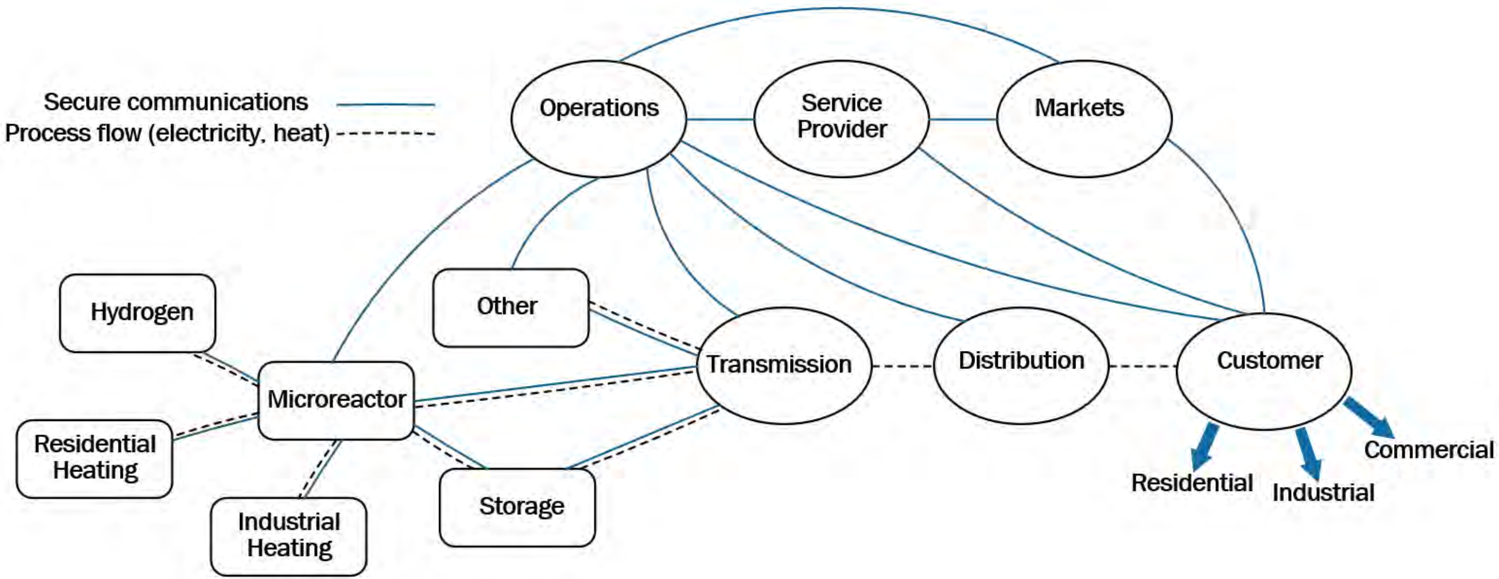
Team Info

- **Purdue**
  - Stylianos Chatzidakis (Assistant Professor and Associate Reactor Director, SRO)
  - True Miller (Reactor supervisor, SRO)
  - Brian Jowers (Electronics/I&C reactor staff, RO)
  - V. Theos, Z. Dahm, K. Vasili, K. Gkouliaras, W. Richards (Grad students)
- **UNM**
  - Mohamed El-Genk (Professor)
  - Timothy Schriener (Research Assistant Professor)
- **Collaborators**
  - Robert Ammon (Curtiss-Wright)
  - Rick Vilim (ANL)
- **TPOC:** Ben Baker (INL)

New technologies…new challenges



New reactor concepts =>
Significantly different requirements than existing fuel cycle facilities

Digitalization => New architectures and new vulnerabilities

New technologies => Quantum computing
Adversaries now have access to new tools with unprecedent capabilities

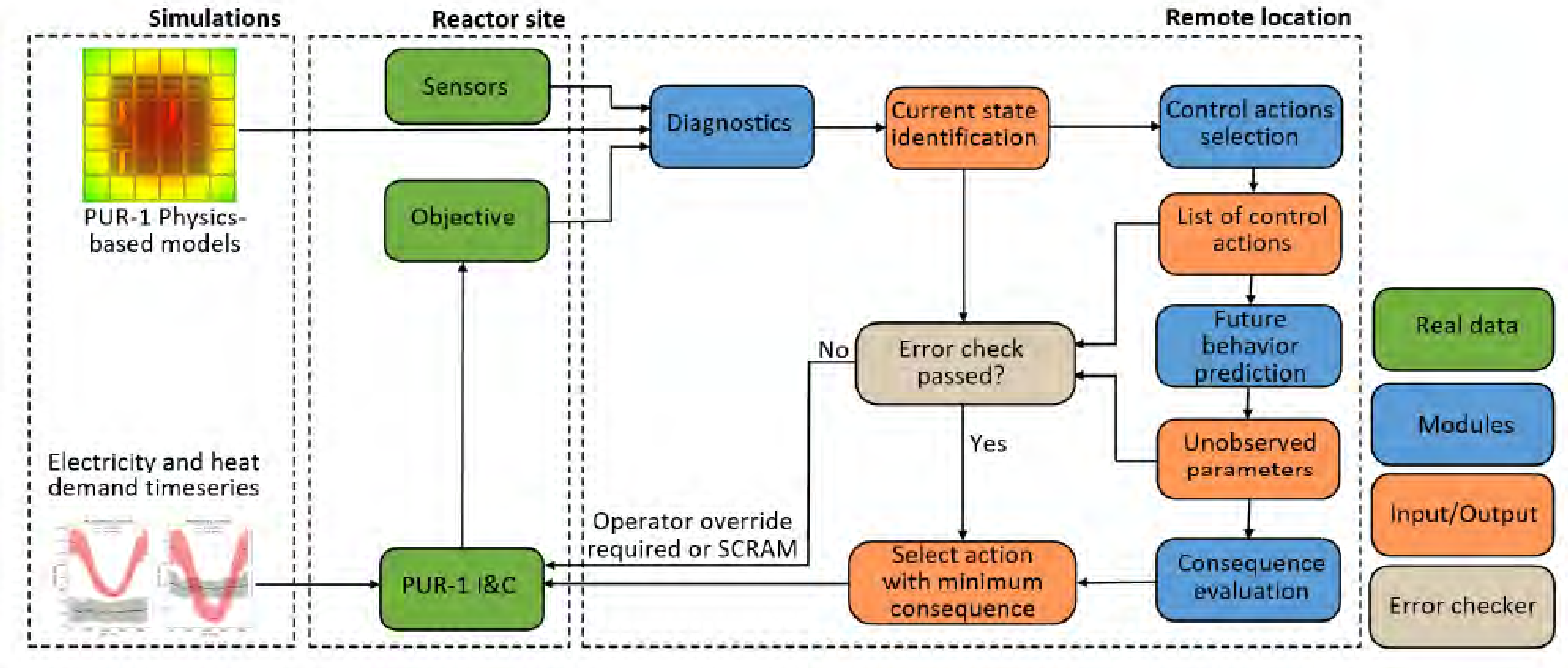
Goals & Objectives

Goal: Experimentally validate semi-autonomous control and demonstrate its use in PUR-1 and VSLIMM.

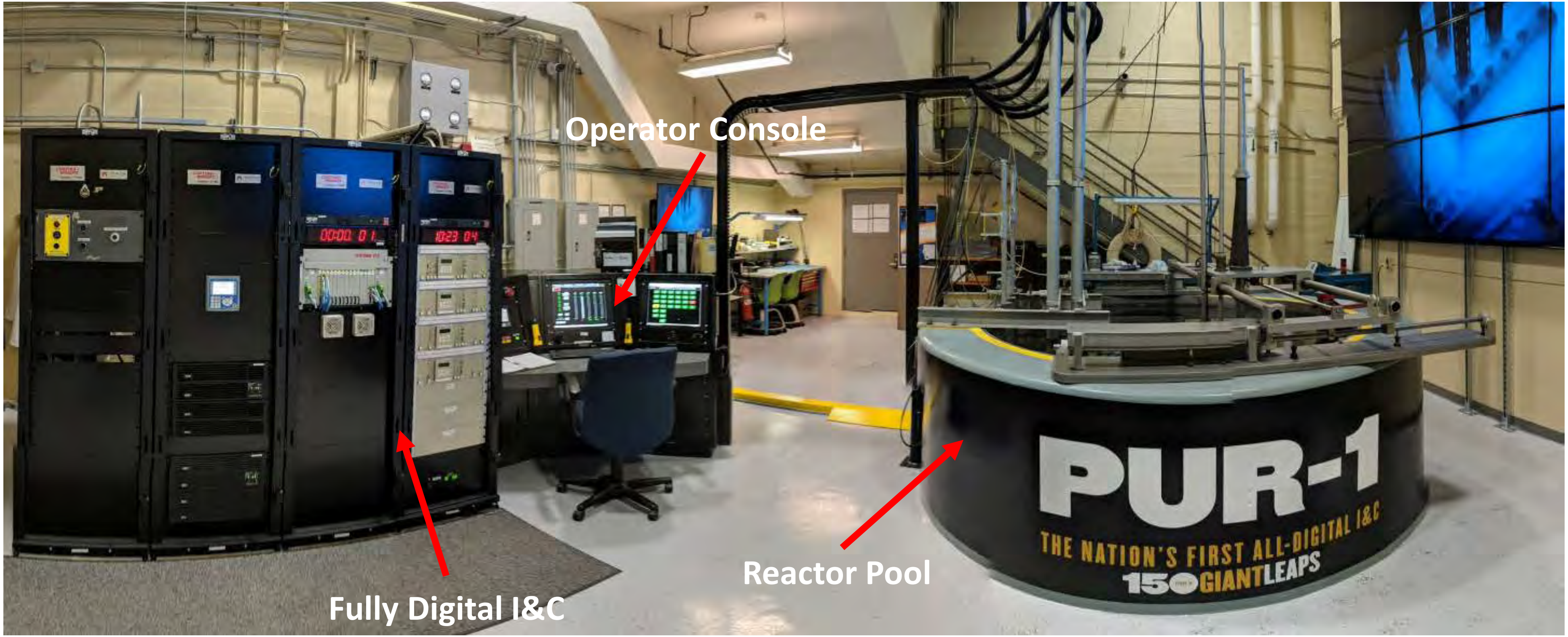
Objectives:

1. Develop a modular digital twin platform with various levels of automation using a remote workstation with AI/ML algorithms
2. Train AI/ML using physics-based microreactor models and real-time digital operation data collected from PUR-1
3. Perform testing and evaluate performance

Semi-autonomous Architecture



Introducing PUR-1



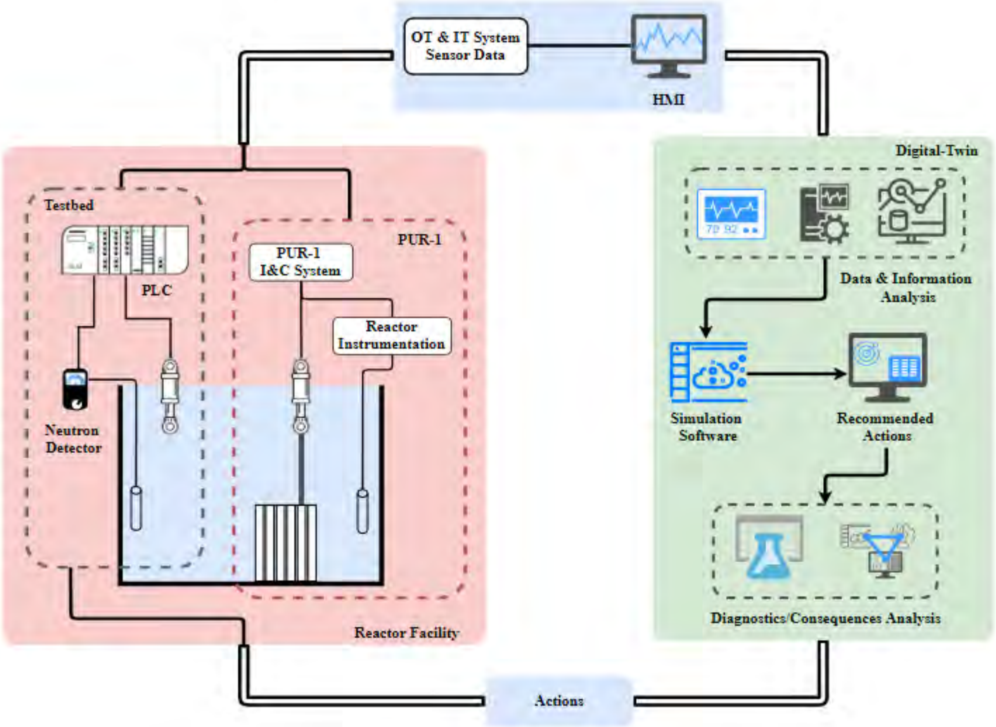
Before and after…

1960 - 2017

2019 - present

Towards a Real-Time Cyber-Physical Digital Twin

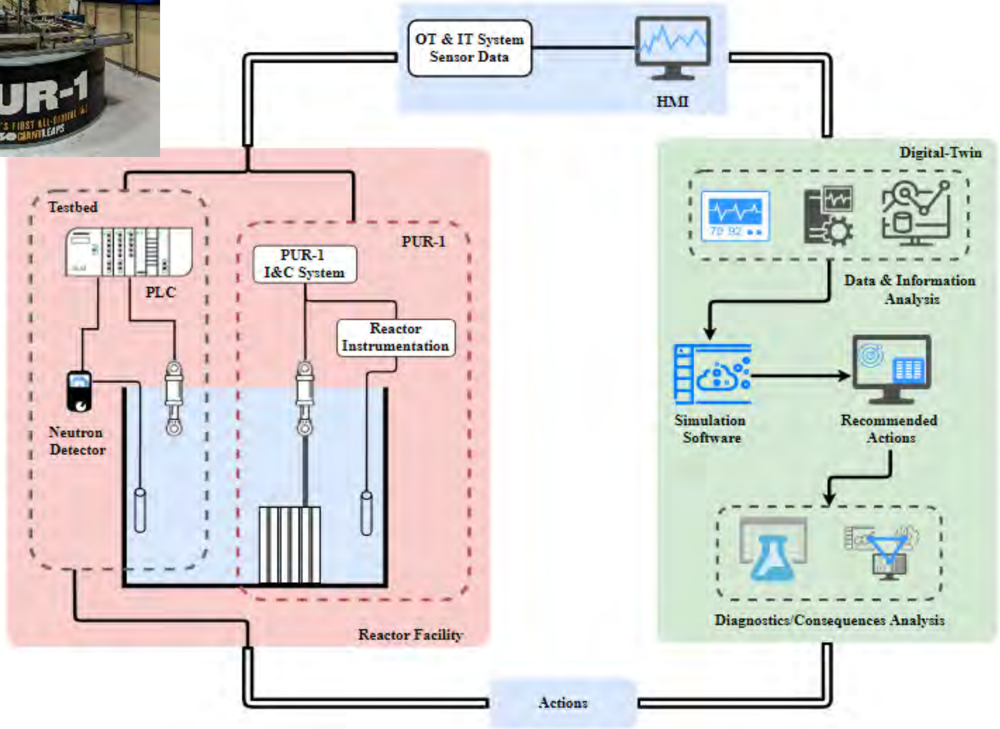
Physical



Digital/Cyber

Towards a Real-Time Cyber-Physical Digital Twin

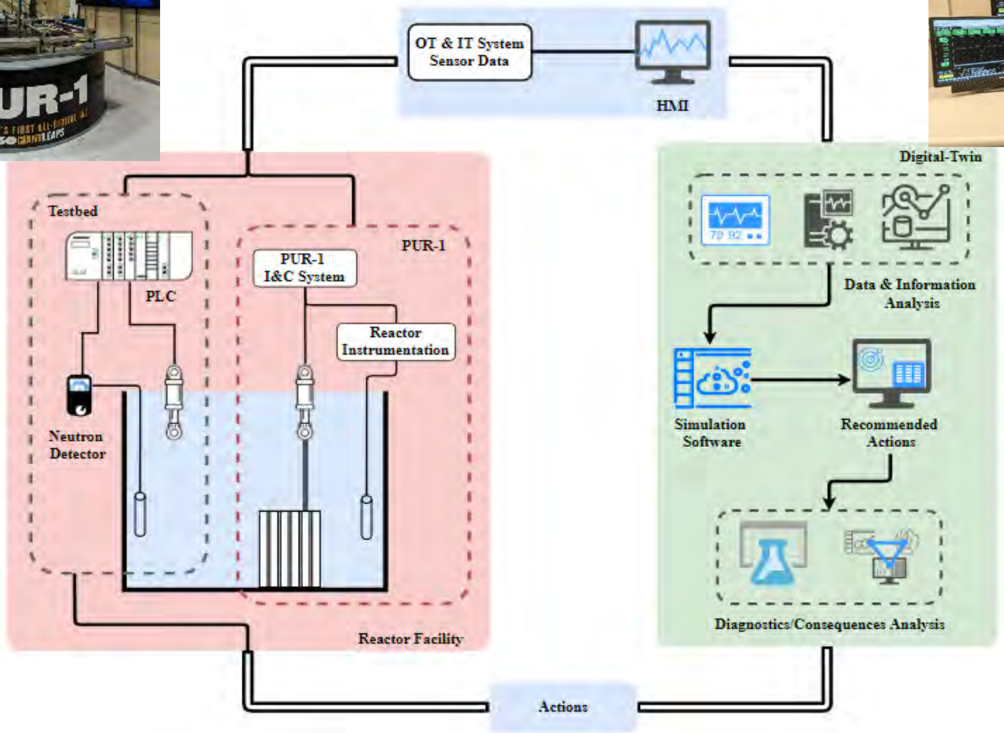
PUR-1



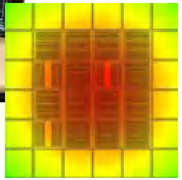
Towards a Real-Time Cyber-Physical Digital Twin

PUR-1

OT/IT Comms



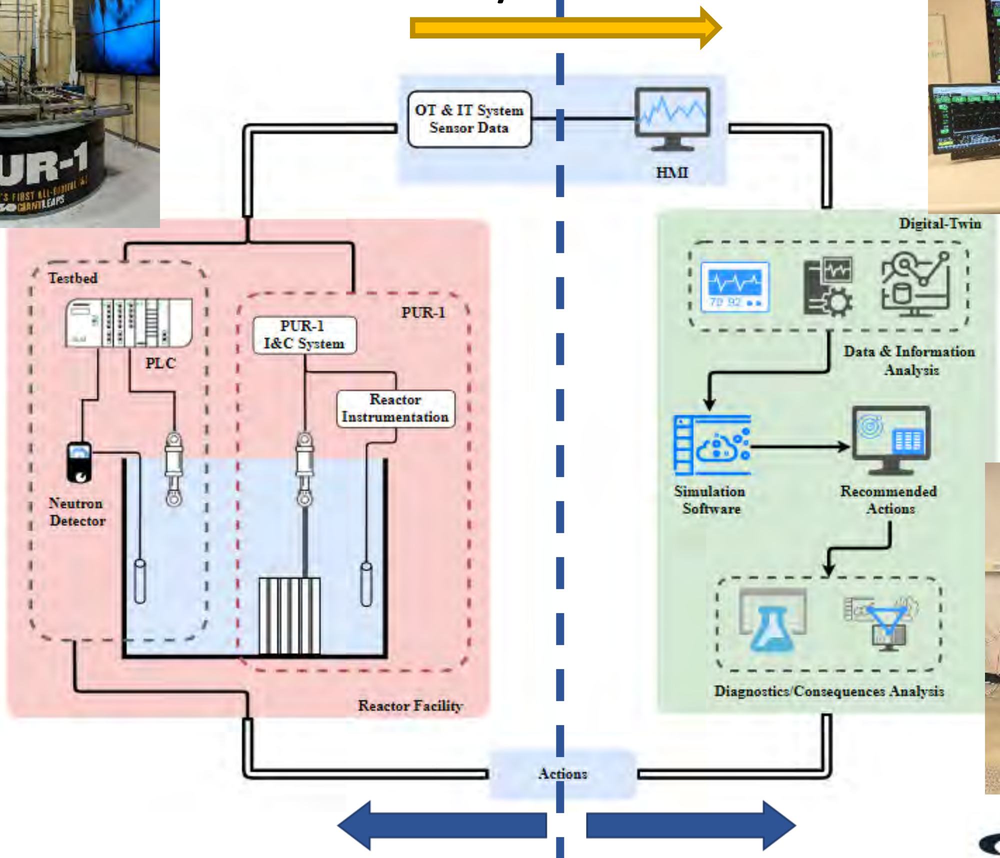
RMSS



Towards a Real-Time Cyber-Physical Digital Twin

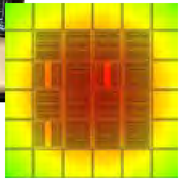

PUR-1

OT/IT Comms



PUR-1 Facility

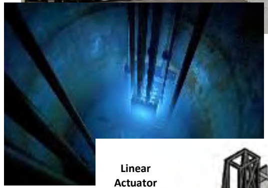
Remote location

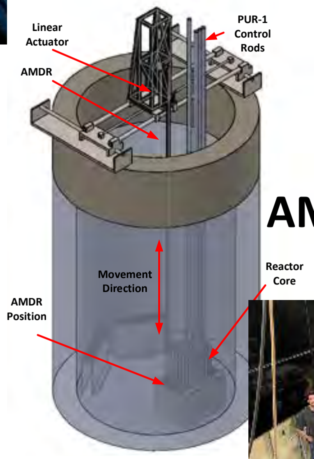
RMSS

Control rack

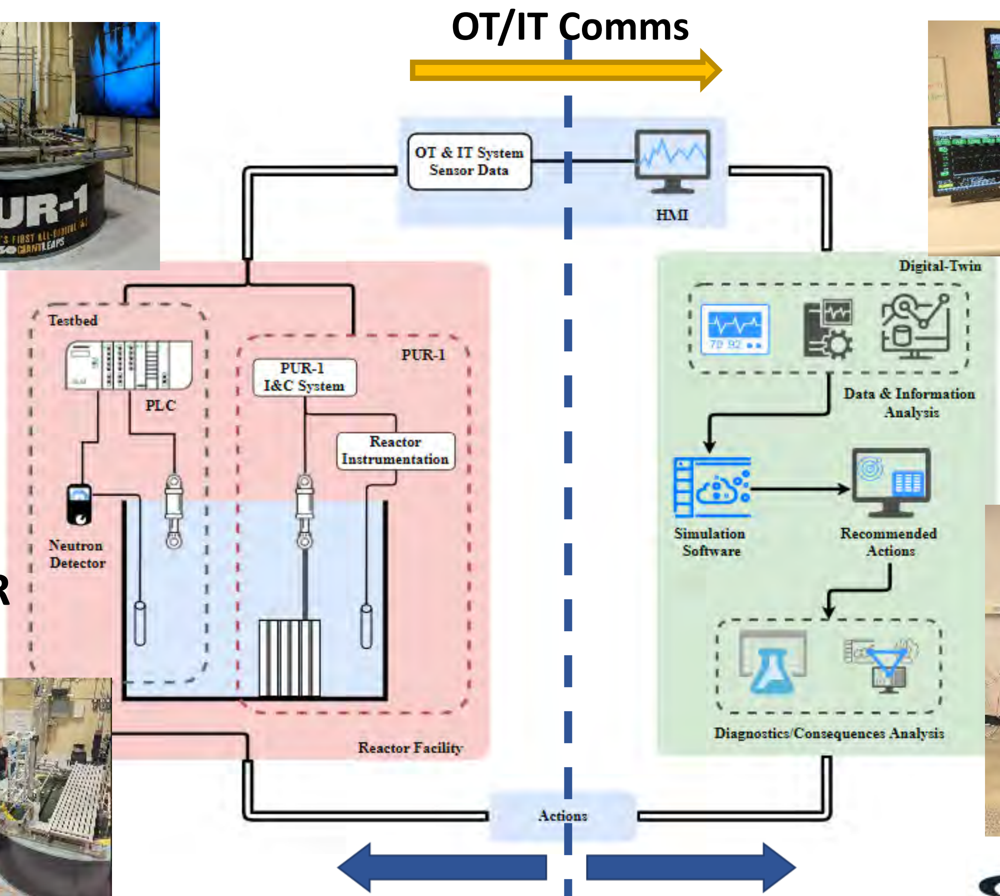
Towards a Real-Time Cyber-Physical Digital Twin

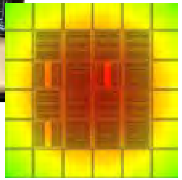


PUR-1



AMDR





RMSS

Control rack

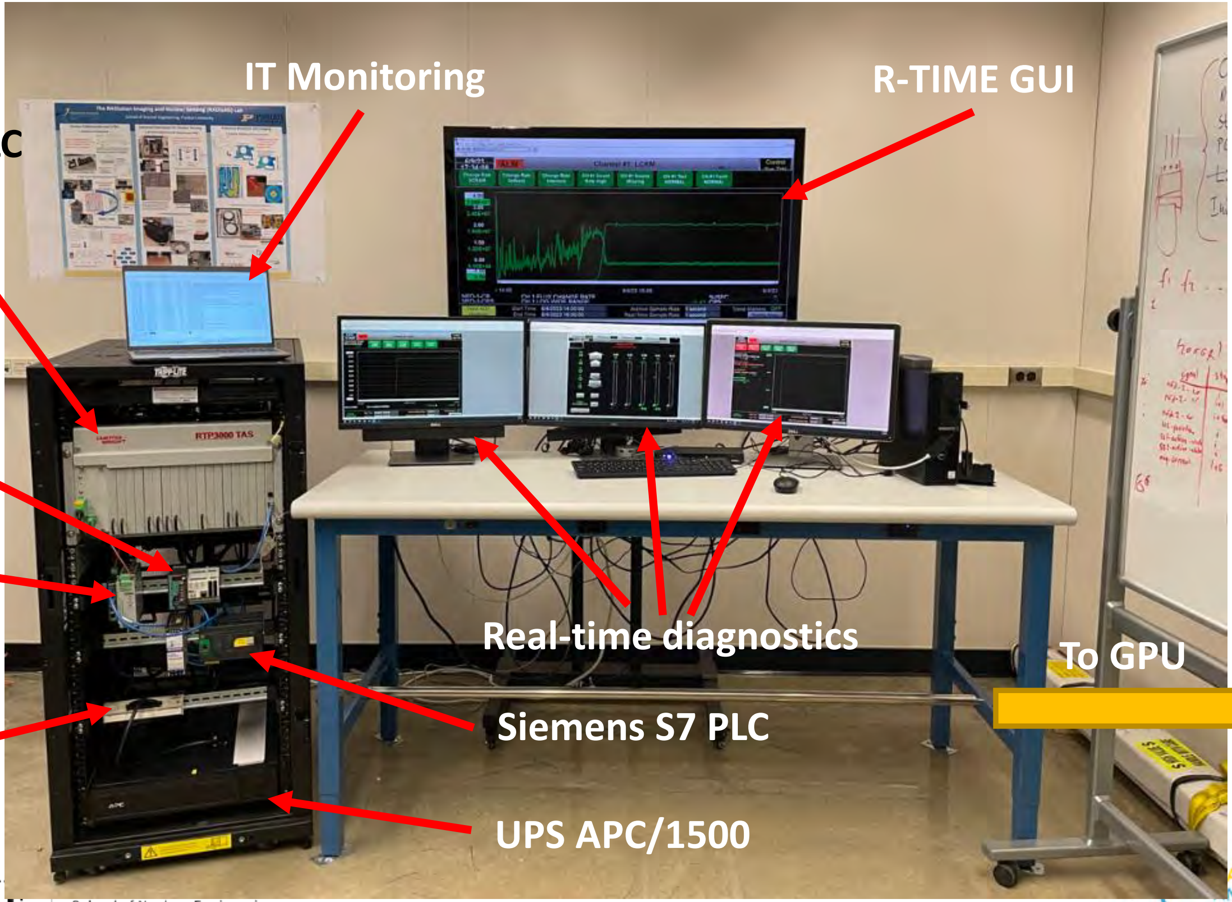
Digital/Cyber Remote Station

RTP 3000 TAS N+
Nuclear grade PLC
16 CH AI/AO
32 CH DI/DO

Field Programmable Gate Array

Power distribution unit

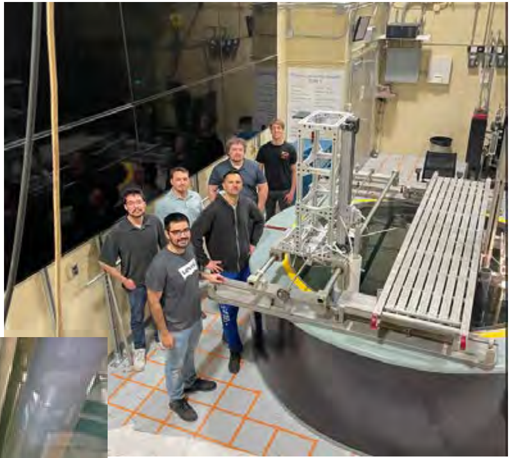
Actuator control

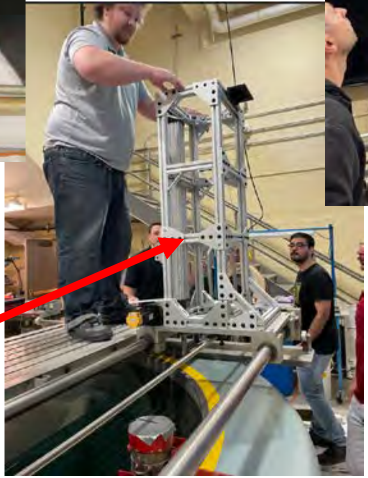


Stats:
2000 parameters
1kHz sampling

Installing and Testing AMDR

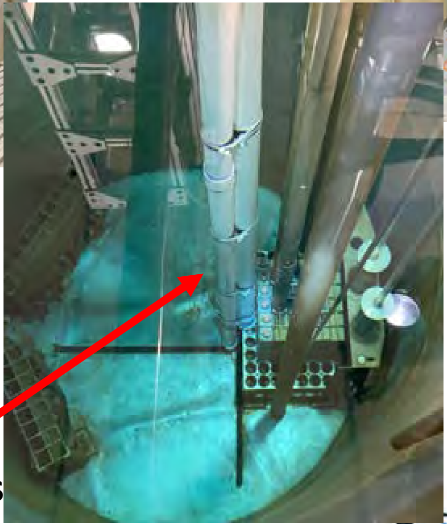
Actuator





Support structure

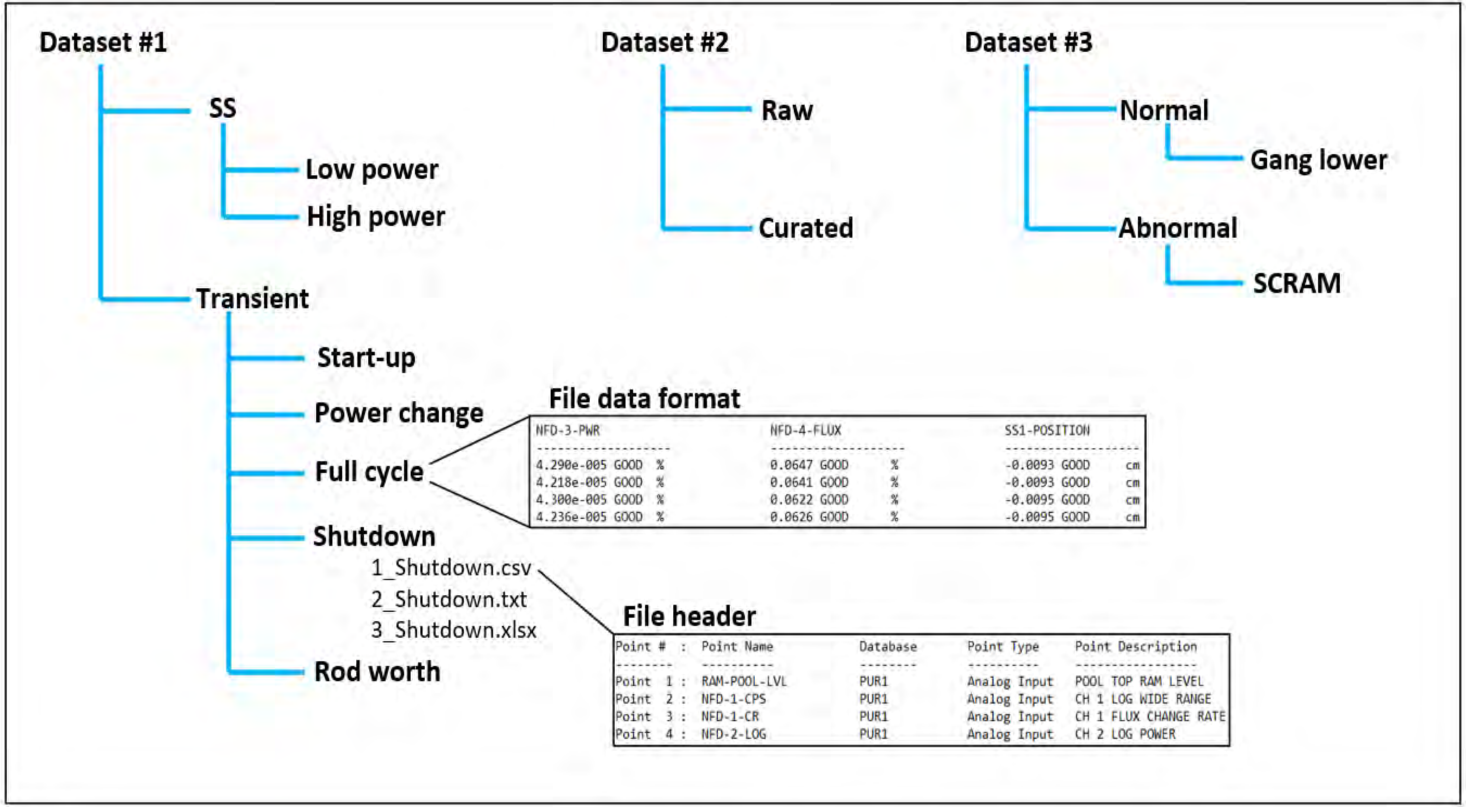
AMDR

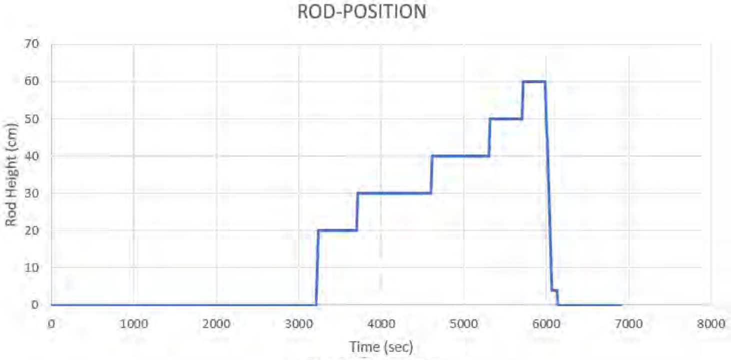


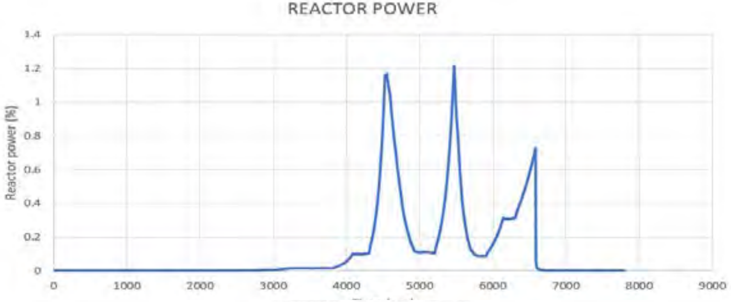
Guide tubes

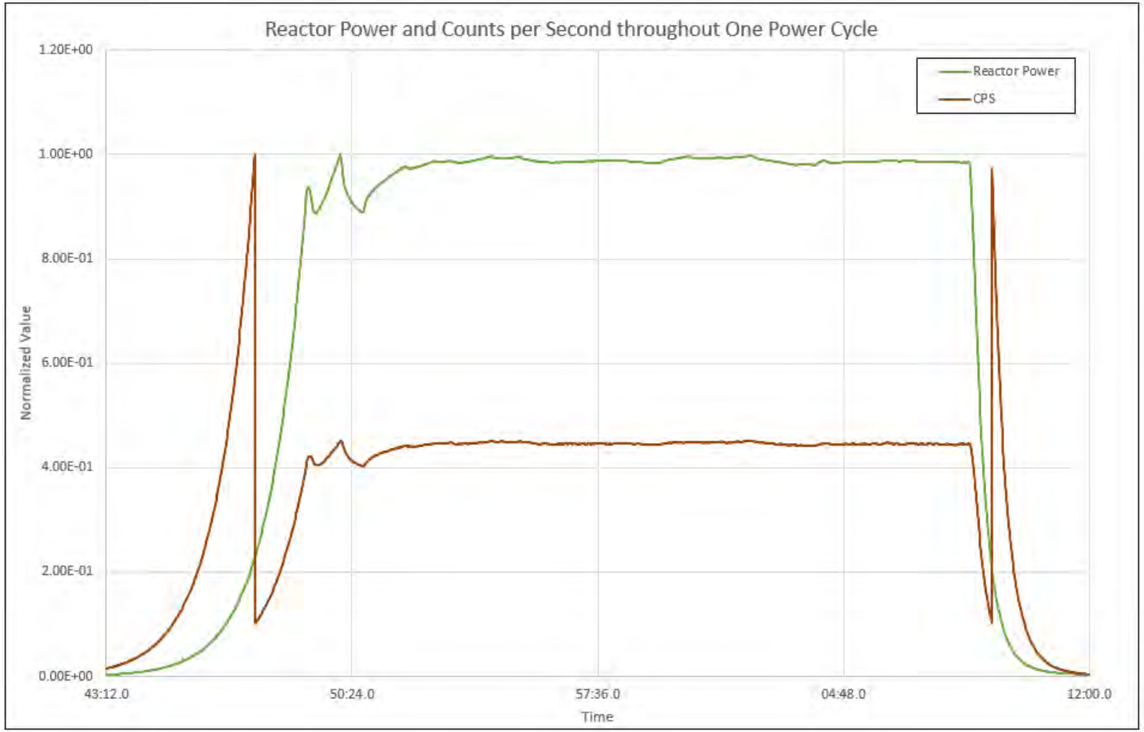
Completed May 2023

Datasets for Benchmarking



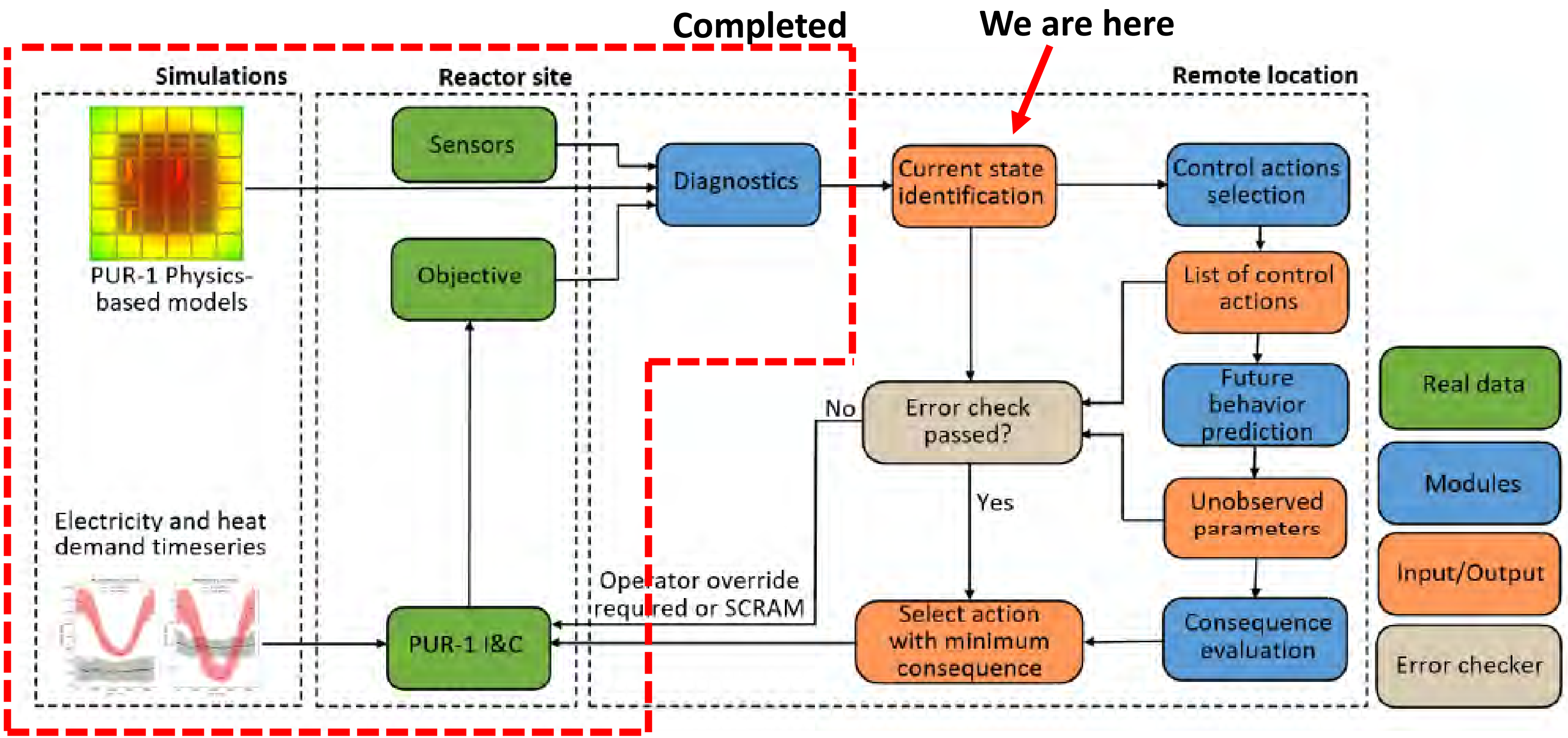






RADIATION IMAGING AND NUCLEAR SENSING LABORATORY

Semi-autonomous Architecture



Reactor State Identification

The following classes were defined for PUR-1 operational data

class	Instances (s)	Feature number
reactor startup	967 s	67 features
steady state 20%	876 s	67 features
steady state 50%	443 s	67 features
steady state 70%	145 s	67 features
steady state 90%	405 s	67 features
scrams	400 s	67 features
Gang lower	400 s	67 features

Reactor State Identification

- The data were checked for Null (limited Null values were found)
- The data were checked for outliers (No significant variations from min – max values)
- Check for Noise (methodology has been defined and published – need to be refined to handle multidimensional data)
- The data were Normalized (0-1)
- The data were split to 80%-20% (training/testing)
- Various ML approaches were investigated
- Various metrics were extracted (precision, recall, f1-score, accuracy, confusion matrix)

Necessary steps since we are dealing with real, operational data

Training

Do we have to use NN for this problem or classic ML and less complicated approaches suffice?

- SVM
- Random Forest
- Decision Trees
- Logistic Regression
- Naive Bayes

MULTICLASS CLASSIFICATION

- 7 classes
- 67 features each

vs

Neural Network

MULTICLASS CLASSIFICATION

- TBD

Results

- Other algorithms have similar results
- Naïve Bayes yields a small number of misclassifications

```
Predicting the Test set results for Logistic Regression:
Predicting the Test set results:
confusion matrix:
[[194   0   0   0   0   0   0]
 [  0 175   0   0   0   0   0]
 [  0   0  88   0   0   0   0]
 [  0   0   0  29   0   0   0]
 [  0   0   0   0  81   0   0]
 [  0   1   1   0   0  78   0]
 [  0   0   0   0   0   0  80]]
```

```
Predicting the Test set results for Random Forest:
Predicting the Test set results:
confusion matrix:
[[194   0   0   0   0   0   0]
 [  0 175   0   0   0   0   0]
 [  0   0  88   0   0   0   0]
 [  0   0   0  29   0   0   0]
 [  0   0   0   0  81   0   0]
 [  0   0   0   0   0  80   0]
 [  0   0   0   0   0   0  80]]
```

```
Predicting the Test set results for Decision Tree:
Predicting the Test set results:
confusion matrix:
[[194   0   0   0   0   0   0]
 [  0 175   0   0   0   0   0]
 [  0   0  88   0   0   0   0]
 [  0   0   0  29   0   0   0]
 [  0   0   0   0  81   0   0]
 [  0   0   1   0   0  79   0]
 [  0   0   0   0   0   0  80]]
```

```
Predicting the Test set results for Naive Bayes:
Predicting the Test set results:
confusion matrix:
[[193   0   0   0   0   0   1]
 [  0 174   0   0   0   1   0]
 [  0   0  88   0   0   0   0]
 [  0   0   0  29   0   0   0]
 [  0   0   0   0  80   0   1]
 [  0   0   0   0   0  80   0]
 [  0   0   0   0   0   0  80]]
```

Conclusions

- While NN are powerful tools for classification and regression tasks, other approaches can also be effective
- For classification tasks, RF, DT, LG, SVM and NB yield competitive results
- Slight misclassifications with NB
- For regression tasks RF, DT outperform NN
- Classic approaches handle effectively the non-linearity in the data
- Classic approaches need minimum amount of data
- NN results will possibly improve with further exploring the optimal architecture and increasing the amount of training data

Future Work

- Dimensionality reduction techniques
- PCA for reducing the amount of training features
- For classification further examining an optimal architecture
- Deep learning techniques
- Control rod predictions in different power levels
- Investigate the capability of predicting all control rods used (ss1, ss2, rr) instead of only 1 (rr)

Acknowledgements

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We also thank Rick Vilim from ANL, and John Jackson and Ben Baker at INL for fruitful discussions and expert input.

Questions?