Demonstrating Autonomous Control, Remote Operation, and Human Factors for Microreactors:

Architecture Development and Training of ML/DL Algorithms for VSLLIM Microreactor

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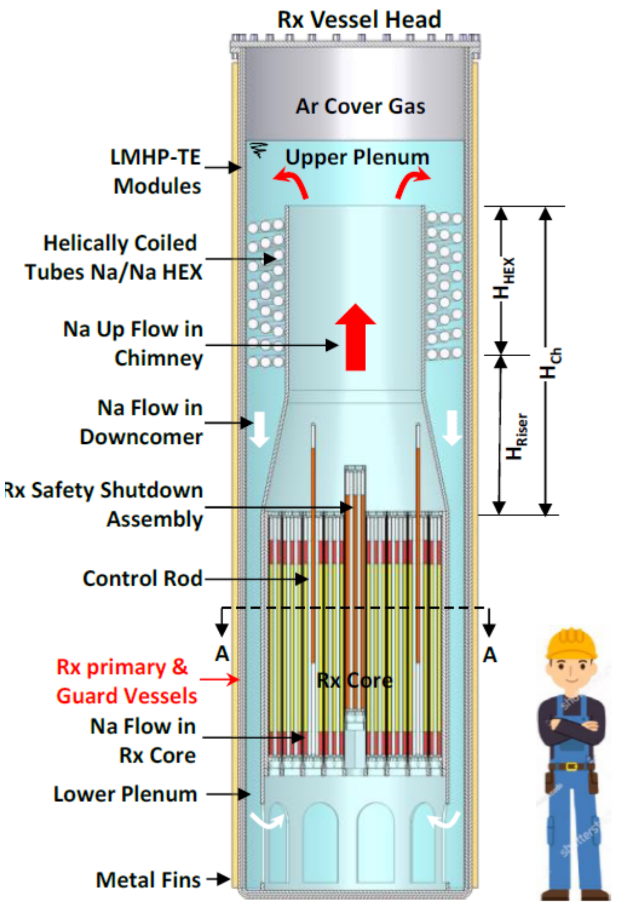
Objectives

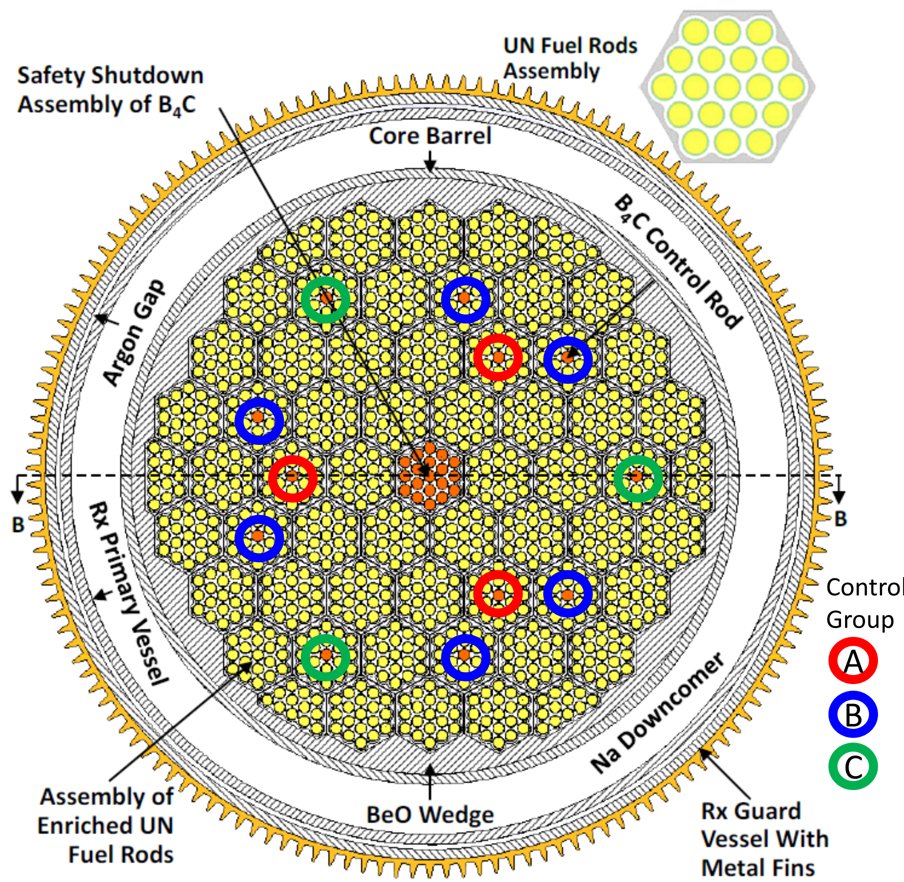
- Develop a dynamic model of the **V**ery **S**mall, **L**ong-**L**ife **M**odular (**VSLLIM**) microreactor developed at UNM-ISNPS
  - A walk away safe microreactor design for generating 1.0-10 MW(t)
  - Cooled by natural circulation of in-core liquid sodium
  - Offers passive and redundant decay heat removal, redundant reactor operation and control
  - Factory assembled and sealed and requires no onsite storage of fresh or spent nuclear fuel
  - Offers passive auxiliary electric power generation after reactor shutdown, independent of on-site and off-site power sources
- Use simulation results of VSLLIM dynamic model to train reactor controllers using ML algorithms
  - Generate data sets of reactor startup scenarios at different initial and final power for training neural networks of the ML algorithms
  - Implement trained neural network into a real-time reactor controller coupled to VSLLIM dynamic Simulink model
  - Test and validate accuracy of neural network for determining control rods displacements during simulated transients using the VSLLIM microreactor controller

Design Highlights: VSLLIM Microreactor

- 5.8 Full Power Year (FPY) lifetime at 10 MW_{th} and > 92 FPY at 1.0 MW_{th} .
- Cooled by natural circulation of in-vessel liquid sodium during nominal operation and after shutdown, aided by in-vessel chimney and compact Na-Na heat exchanger (HEX)

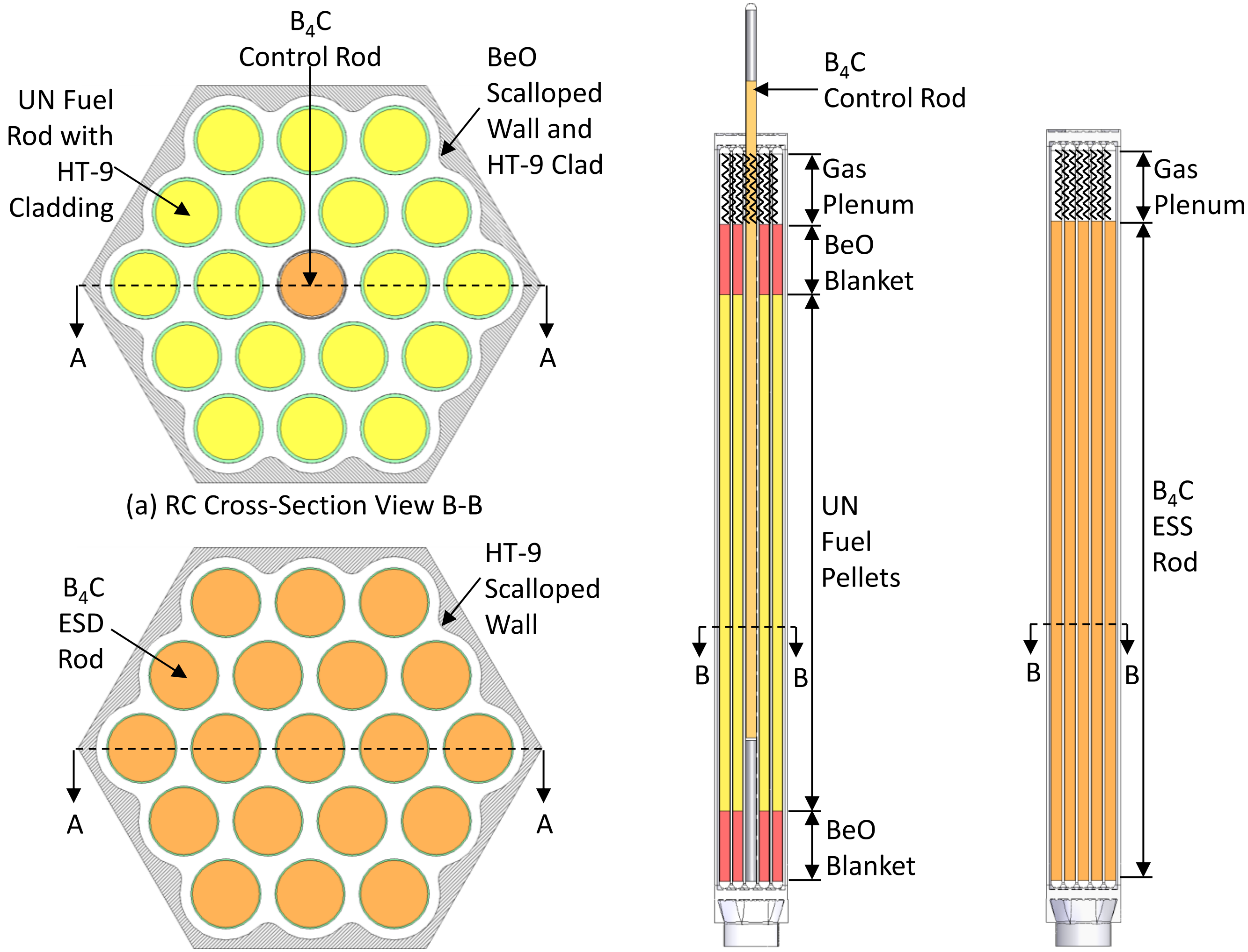


(a) A-A Longitudinal Cross-Sectional View



(b) B-B Radial Cross-Sectional View

VSLLIM: Control & Emergency Shutdown



(a) RC Cross-Section View B-B

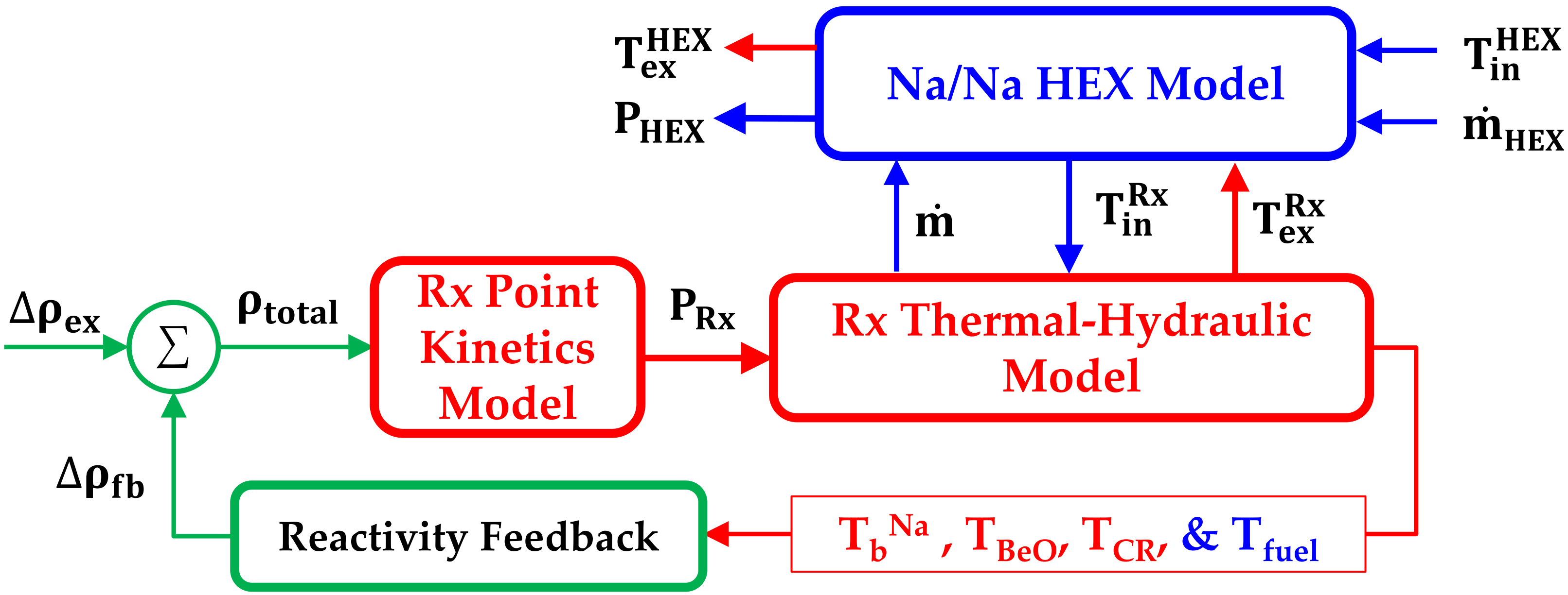
(b) ESD Cross-Section View B-B

(c) RC Cross-Section View A-A

(d) ESD Cross-Section View A-A

VSLLIM: Simulink Transient Model

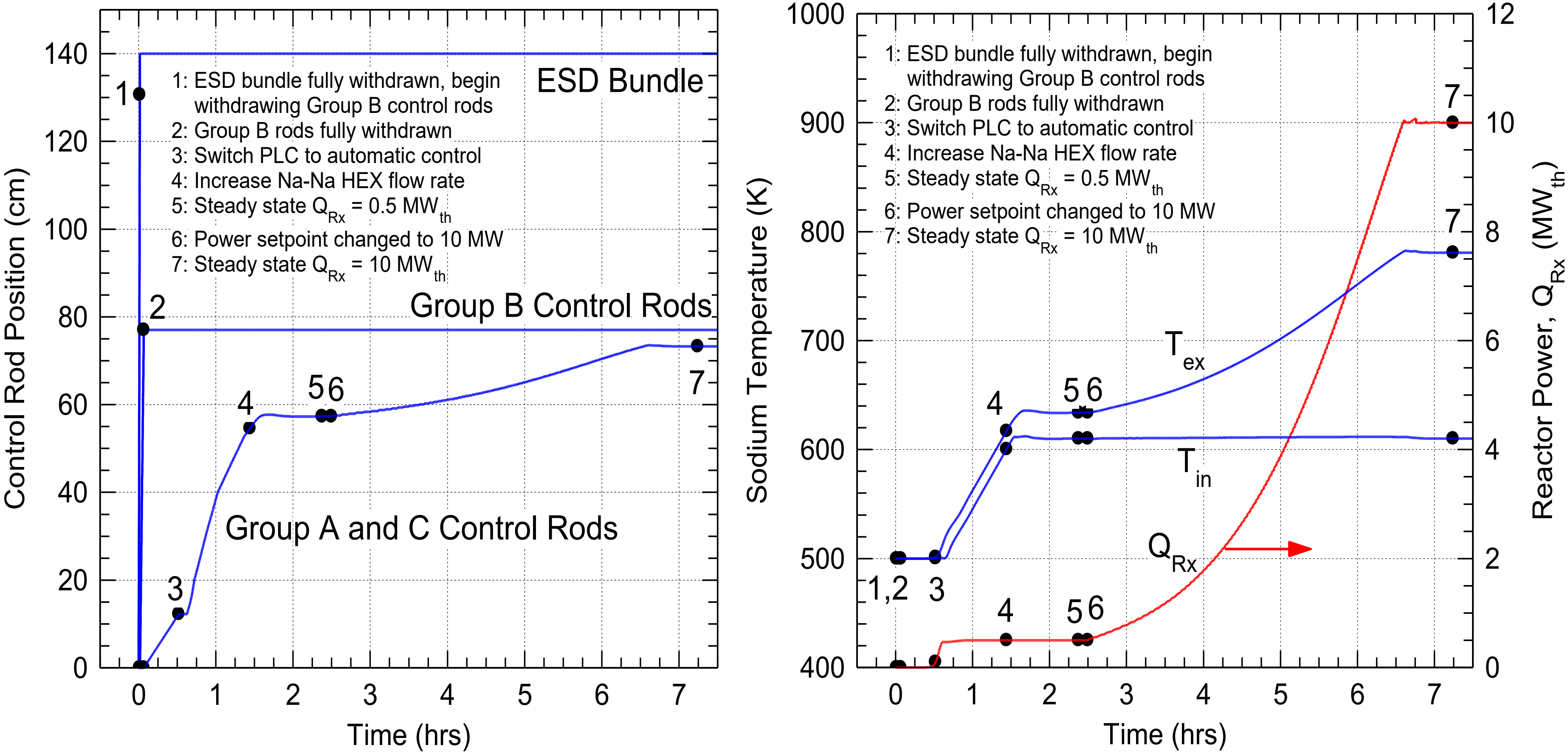
- **Couples 6-group point kinetics and Rx thermal-hydraulics models**
  - Solves steep point kinetics equations using robust exponential matrix technique using the 7th order Padé(3,3) function
  - Solution efficient, accurate and stable independent of timestep size
- **Point kinetics reactivity feedback**
  - Doppler broadening and thermal expansion of UN fuel, Na coolant, BeO shrouds, and B_4C control rods



$$\Delta\rho_{fb} = \Delta\rho_{fuel} + \Delta\rho_{Dop} + \Delta\rho_{Na} + \Delta\rho_{BeO}$$

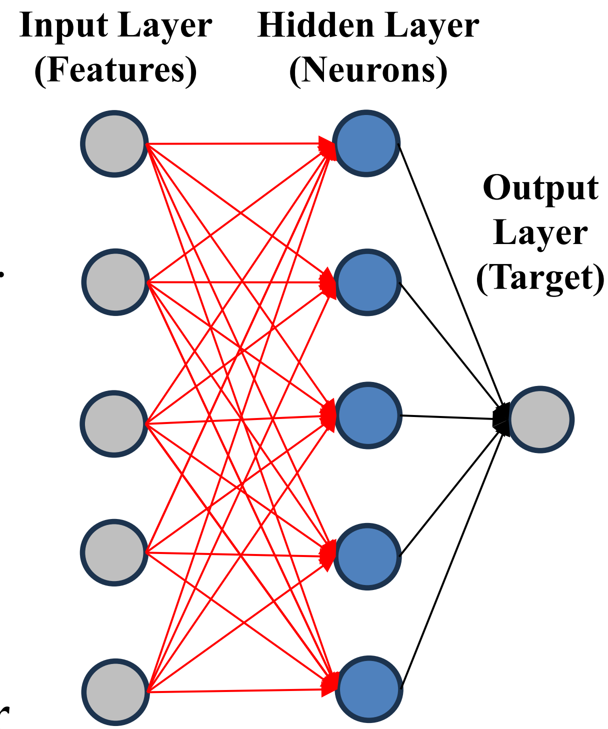
Simulation Results: Startup Transient

- **VSLLIM dynamic model simulates startup from subcritical state to nominal steady state operation at different thermal power levels (1.0 -10 MW(t))**
  - **First, Controller brings reactor steady state power to an Initial Setpoint P_1**
  - **It subsequently increases reactor power to a final Setpoint P_2**



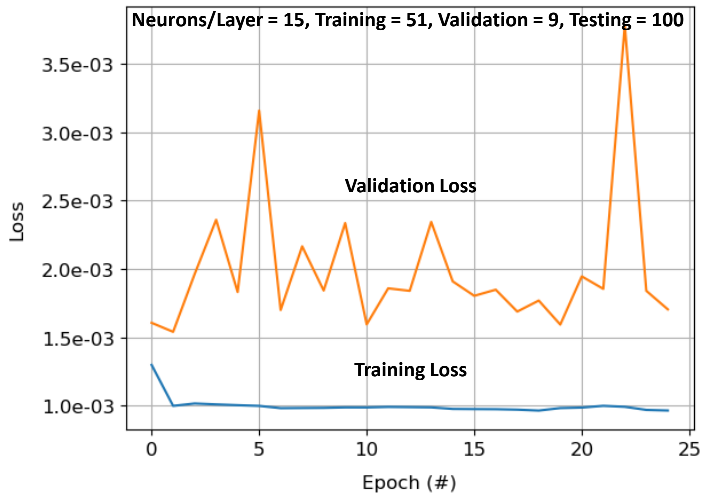
Neural Networks and ML Algorithm

- **Long Short-Term Memory (LSTM) algorithm**
  - Implements PyTorch library LSTM functions in Python code
- **Hyperparameters**
  - **5 Features:** Rx Power setpoints, **transient** Rx power, and liquid sodium flow rate and inlet and exit temperatures.
  - **One Target**: Group A & C control rods position.
  - **Neural Network**: single layer of 5, 10, and 15 neurons
  - **Learning Rate:** 0.001
  - **Optimizer**: AdamW with 0.1 weight decay
  - **Lookback window**: 20 (4 s)
- **Supplied ML Training data sets:**
  - **797** sets of simulated startup transient, with more than **956 million data points** for different Rx power set points, P_1 and P_2:
    - **P_1: 0.5 - 9.75 MW**
    - **P_2: 1.0 - 10.0 MW**

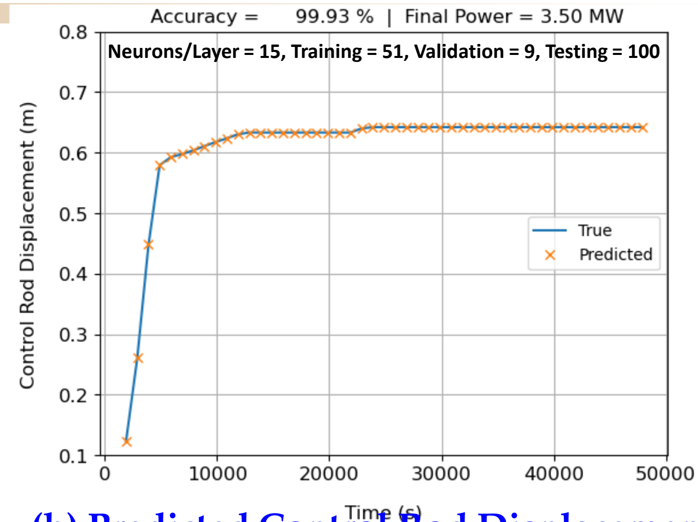


Network with 5 Neurons

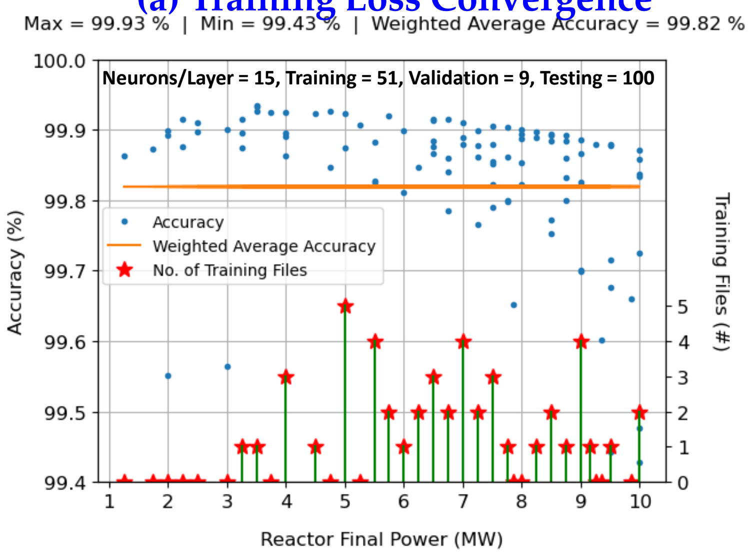
Results: LSTM ML Training



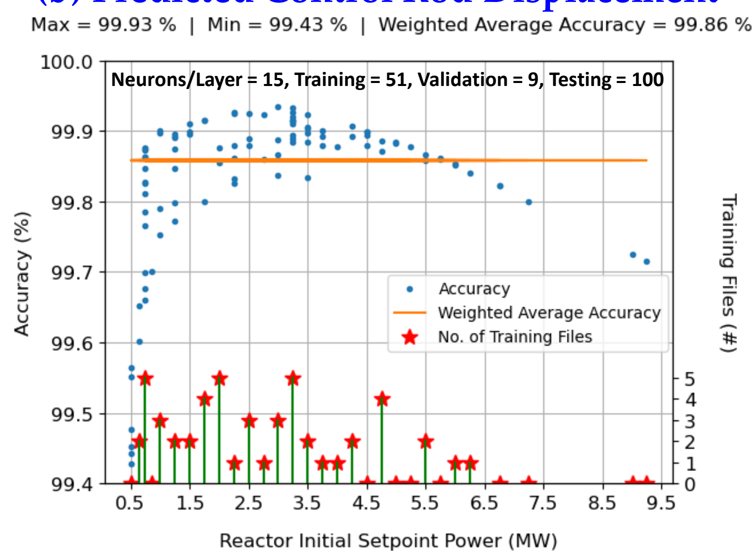
(a) Training Loss Convergence



(b) Predicted Control Rod Displacement



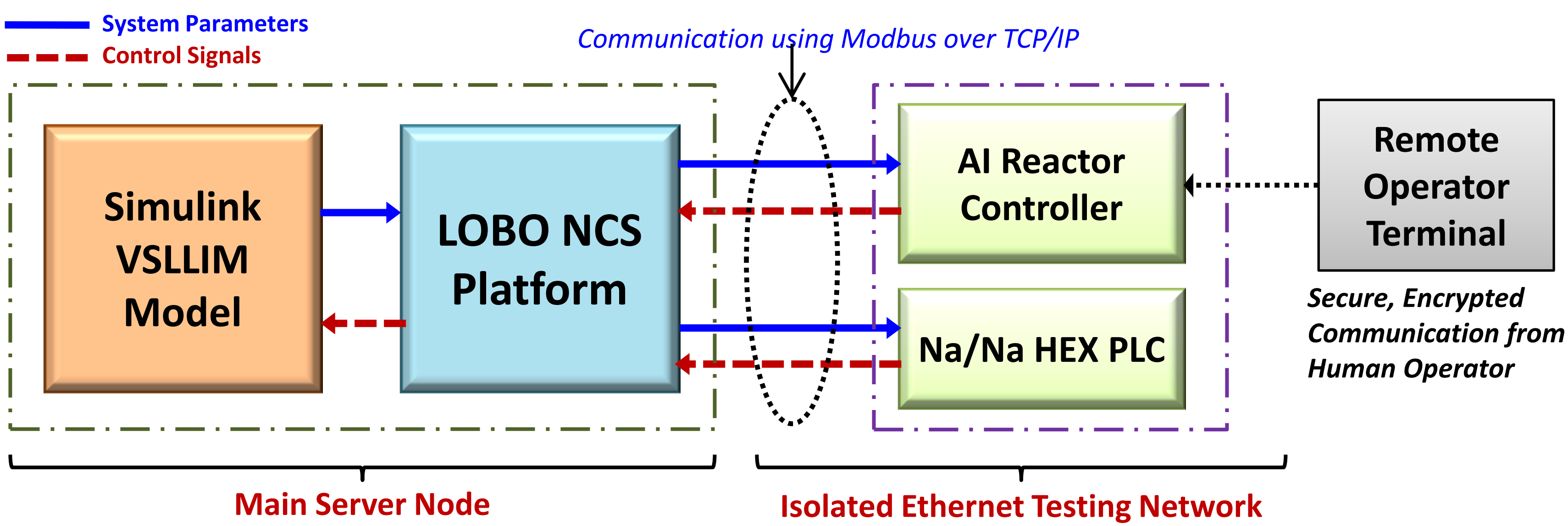
(c) Accuracy with Final Power P_2



(d) Accuracy with Initial Power Setpoint P_1

Ongoing & Future Work: Integrate AI Controller

- **Use LOBO Nuclear Cybersecurity (NCS) Platform, Developed by UNM-ISNPS in collaboration with Sandia National Laboratories (SNL).**
  - **Versatile for testing advanced digital I&C systems and cybersecurity analysis.**
  - **Couples physical hardware and emulated controllers to real-time Simulink model.**
- **Integrate trained neural network into reactor control PLC**
- **Begin testing the AI controller coupled to VSLLIM Simulink model for startup simulation sequences**



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