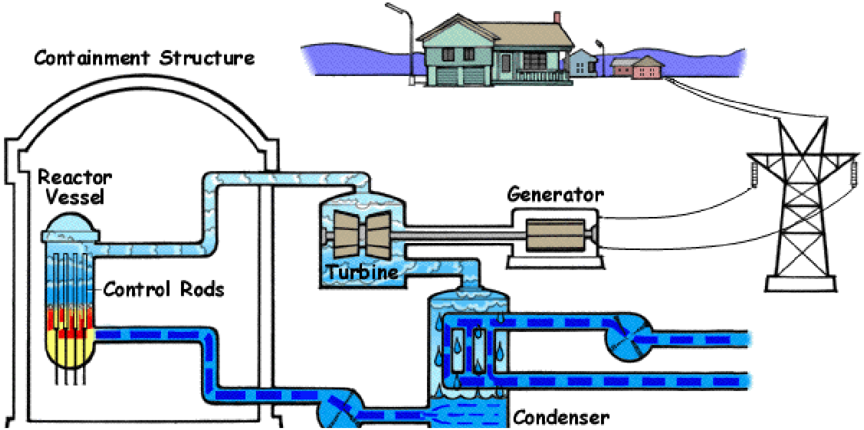
DATA-DRIVEN CONTROL IN THE EXISTING FLEET



HAOYU WANG
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Advanced Reactor Controls Workshop
July 12-14, 2023, Argonne National Laboratory, Lemont IL

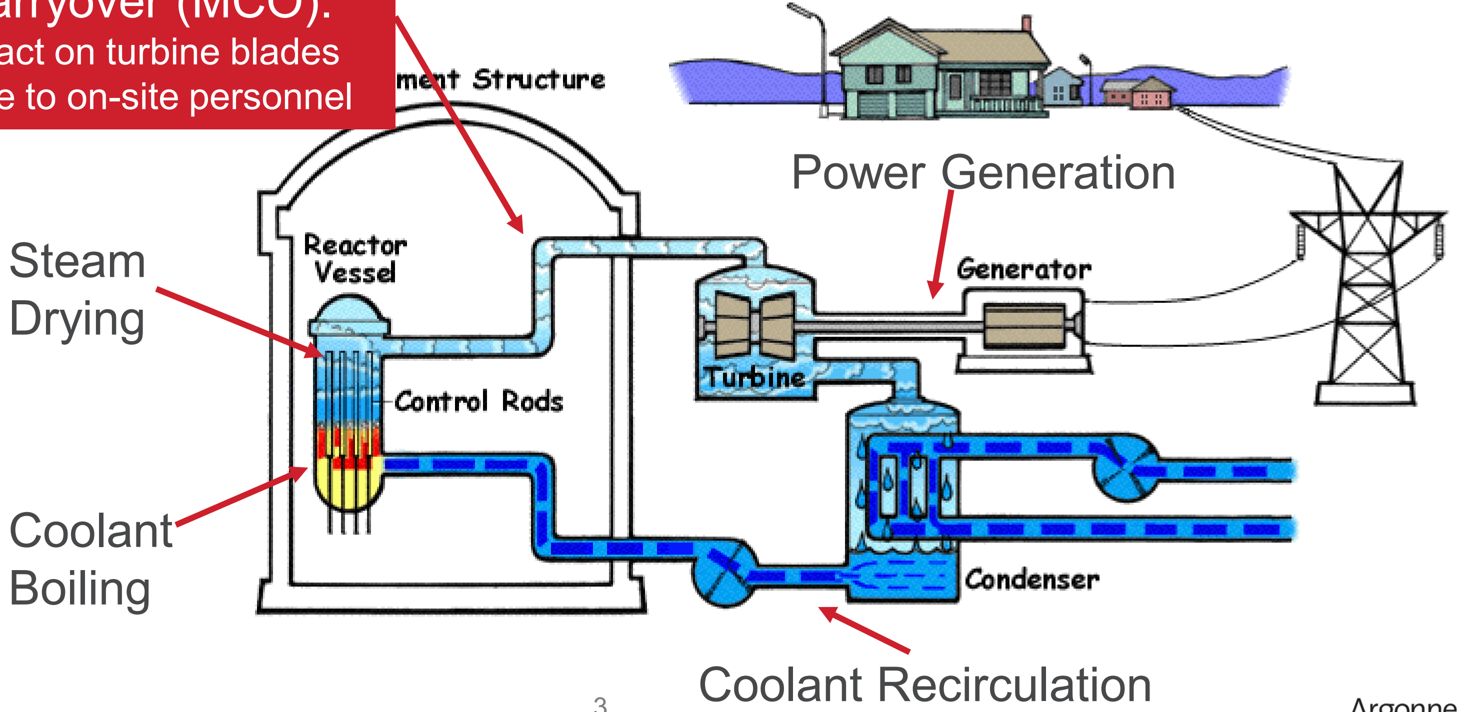
OBJECTIVES

- Develop a Data-Driven Digital Twin to aid in-cycle control of existing BWR fleet;
- Optimize the efficiency of operation during the planning stage of generation cycle:
  - Reduce the tear and worn of turbine components;
  - Reduce the radiation exposure of on-site personnel;
  - Increase the profitability of nuclear generation.

PROBLEM TO SOLVE: MCO PREDICTION

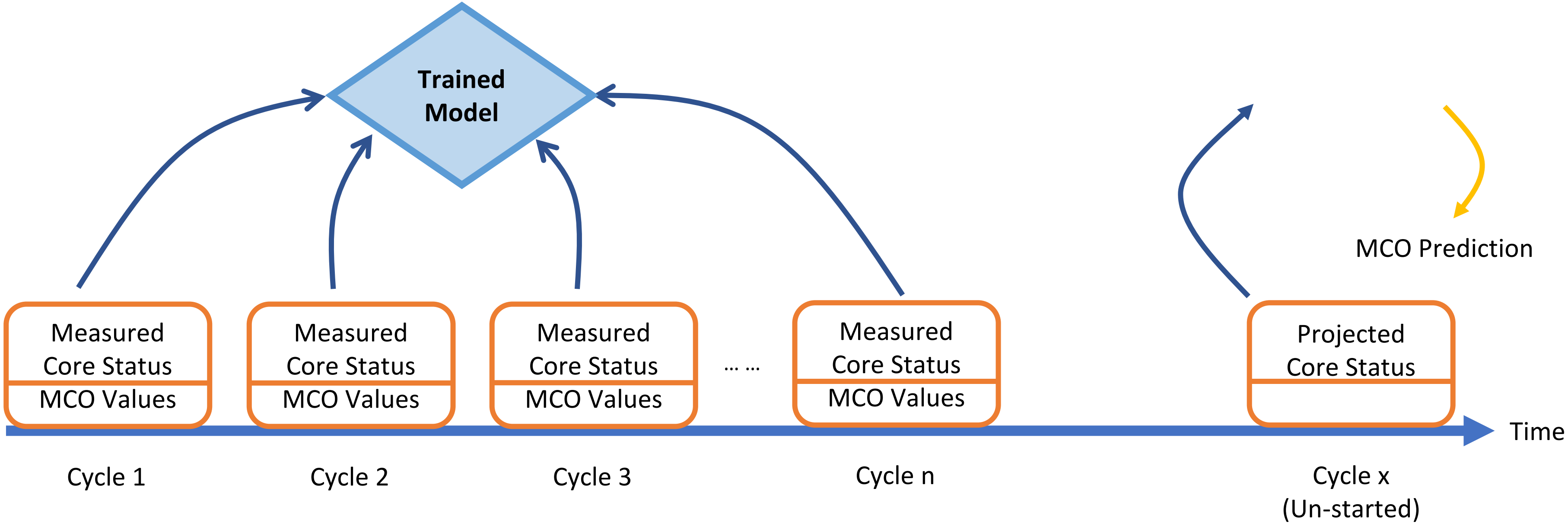
Un-separated liquid droplets: Moisture Carryover (MCO).

- Higher impact on turbine blades
- Higher dose to on-site personnel



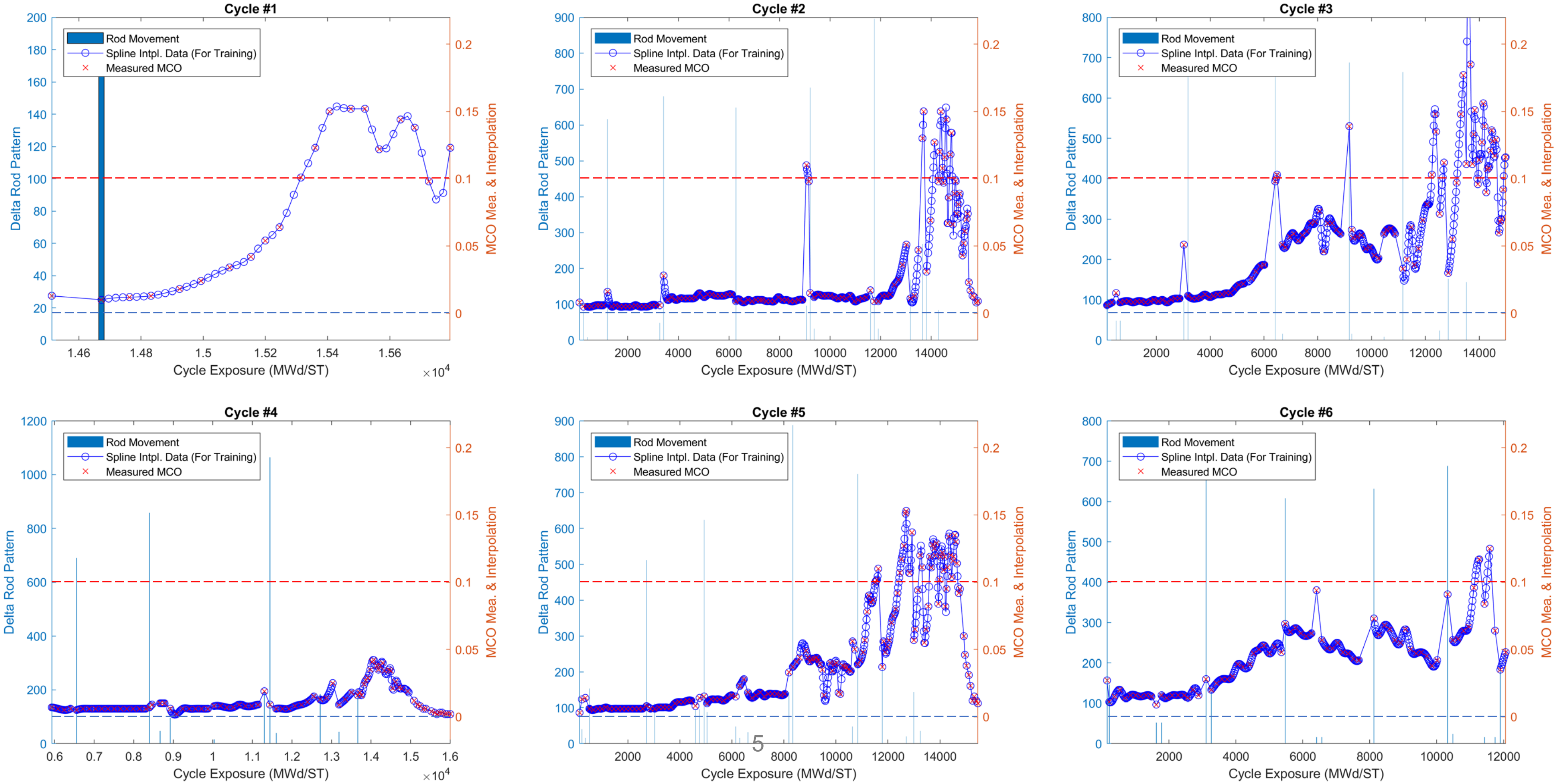
PROBLEM TO SOLVE: MCO PREDICTION

Un-started cycle prediction: Evaluate MCO using the projected core status.



Higher MCO at the end of each cycle;
7,000+ core variables behind each measurement

TRAINING DATA

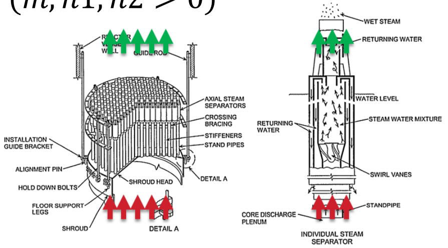


FEATURES AND TRAINING METHODOLOGY

Engineering analysis to determine the feature:

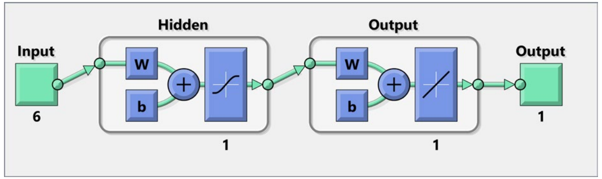
- Steam quality(***Q***) and Coolant flow rate (***V_L***)

$$MCO \sim \frac{1}{Q^m}\left(\frac{1}{{V_L}^{n1}} + {V_L}^{n2}\right) \quad (m, n1, n2 > 0)$$



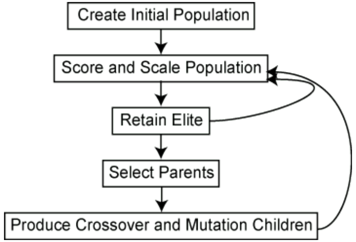
Physics-informed Model Selection:

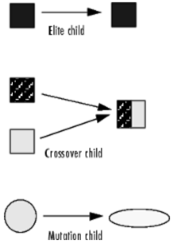
- Single-layer Neural Network with non-linear addition
- Mimic the nature of MCO (Aggregation of liquid droplets)



Hyper-parameter optimization:

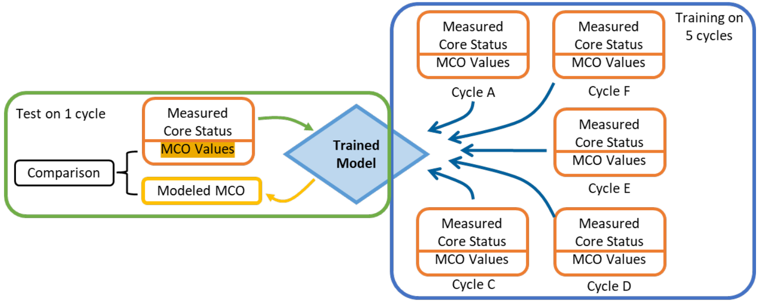
- Genetic Algorithm (Elite Survives)



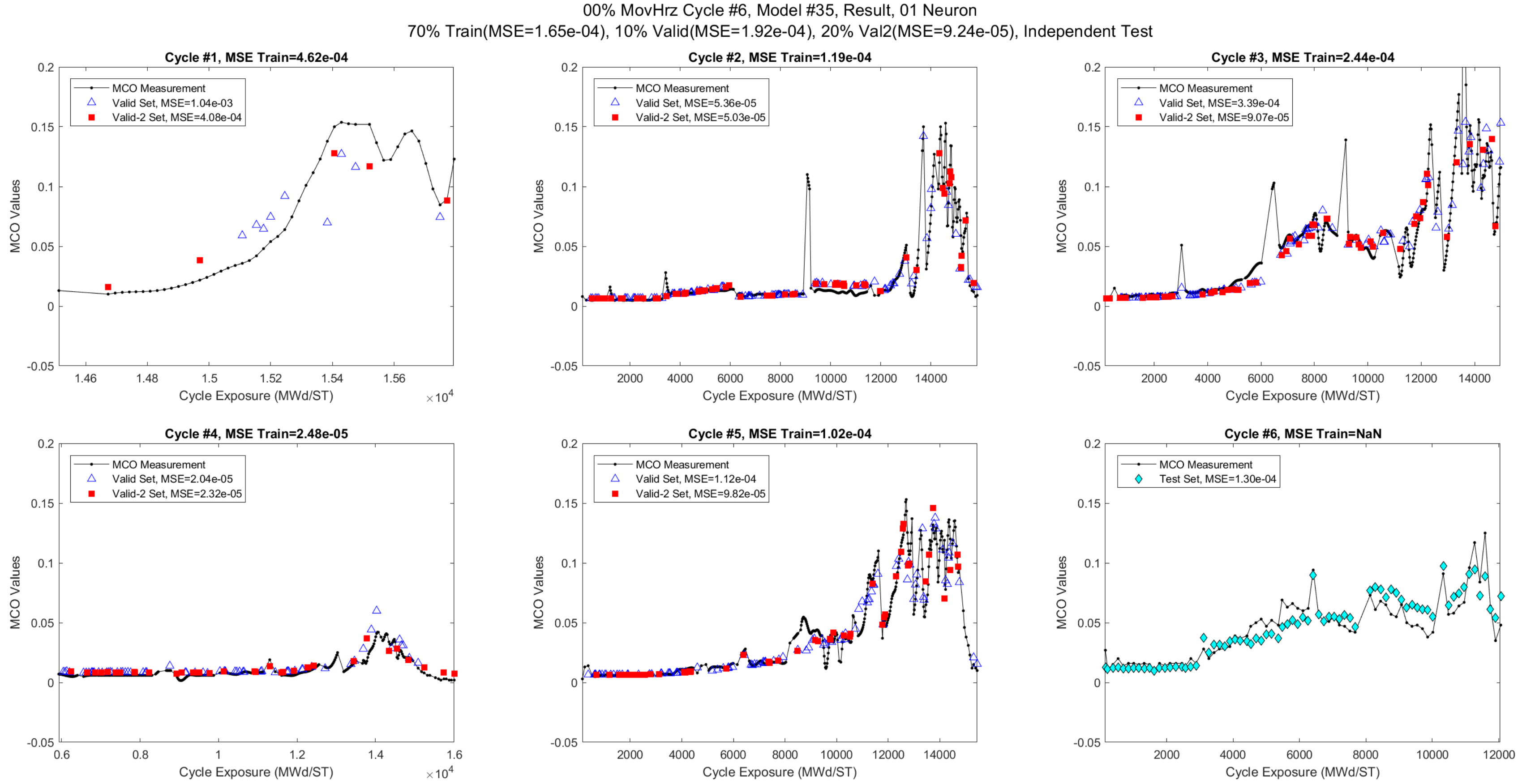


Avoid Overfitting:

- Leave-out one cycle, and cross-validation



MODEL PERFORMANCE: GENERALIZATION



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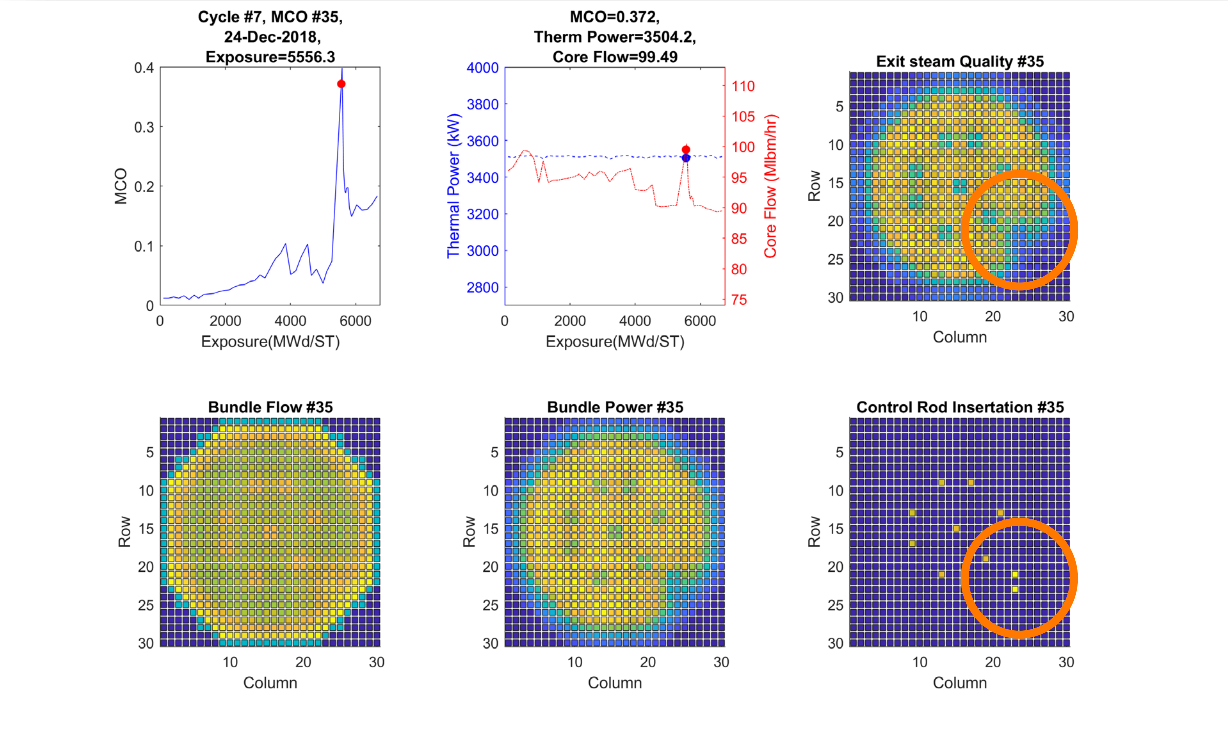
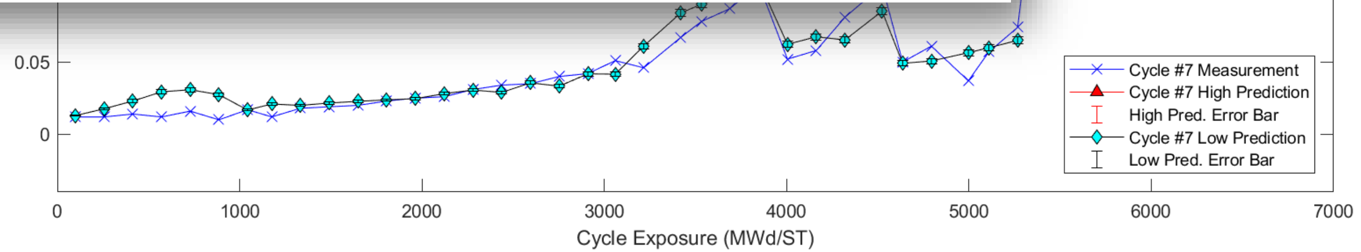
BLIND TEST

Asymmetry in 4th quadrant is a new physics, never seen in the training data





CONCLUSION

- BWR MCO was modeled using machine learning technique, which was never achieved by any other trivial methods;
- Collaborating nuclear facility is using this model for performance optimization;
- This model could be included in a feedback loop, to provide the feasibility to:
  – Automatic operation based on MCO prediction;
  – On-line learning and updating of the machine learning model for better accuracy.

THANK YOU

BACK-UP SLIDES

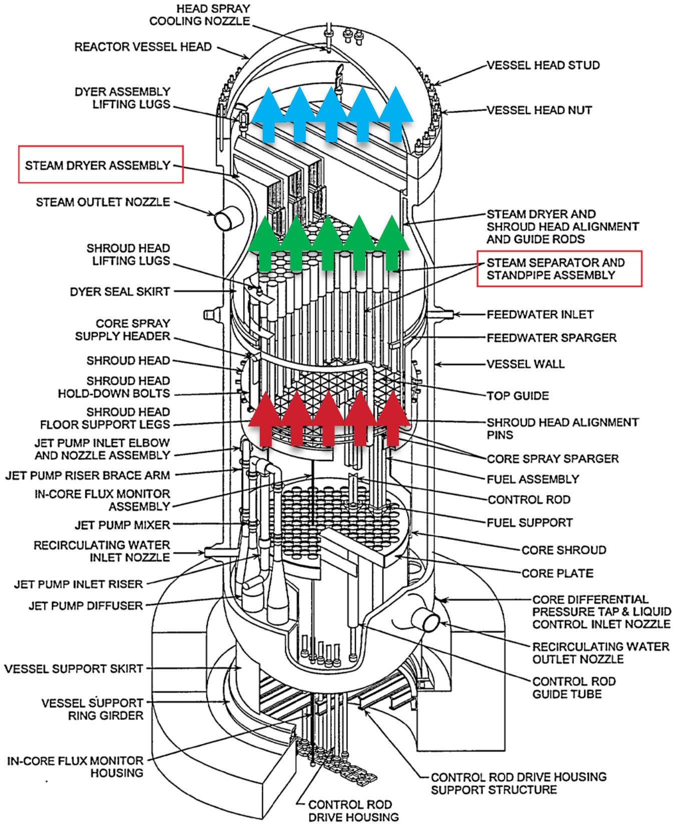
STEAM DRYING PROCESS

Steam drying in GE BWR/4 reactor :

(1)Steam Separator, upgrading the steam quality from ~30% to ~90%;

(2)Steam Dryer, upgrading the steam quality from ~90% to ~99.9%.

Saturated Steam Separators will elevate the Moisture Carryover



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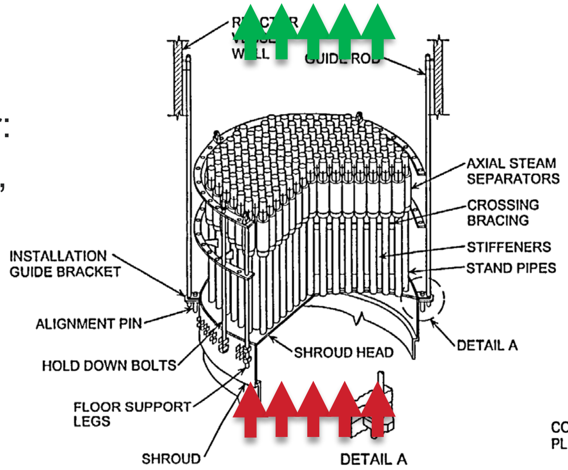
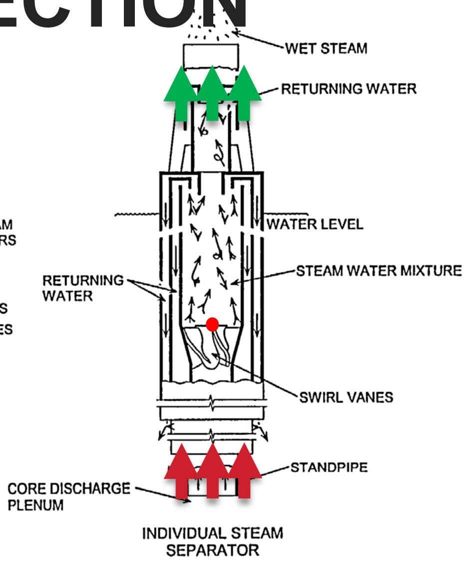
ENGINEERING FEATURE SELECTION

Before Entering the Separator:
Lower initial steam quality (***Q***),
Higher ***MCO*** :

$$MCO \sim \frac{1}{Q^m} \; (m > 0)$$





In Steam Separator :
Mixture passes swirl vanes,
Liquid Drops hit the wall and get separated.

Too low or too high Coolant flow rate ($\boldsymbol{V_L}$),
Higher ***MCO*** :

$$MCO \sim \frac{1}{{V_L}^{n1}} + {V_L}^{n2} (n1, n2 > 0)$$

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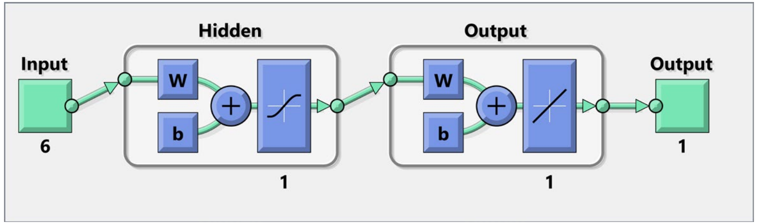
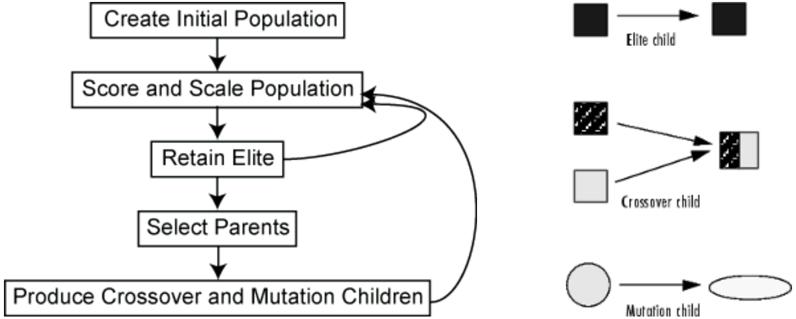
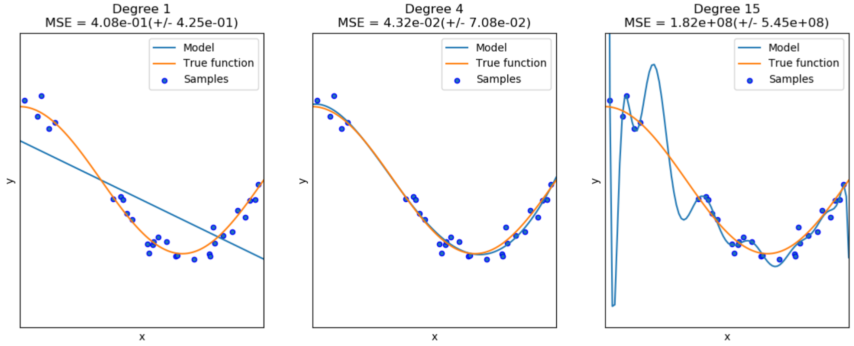
ML STRUCTURE

Nature of MCO:
Aggregation of liquid droplets
Model Selected:
Single-layer Neural Network
(non-linear addition included)
Hyper-parameter optimization:
Genetic Algorithm (Elite Survives)

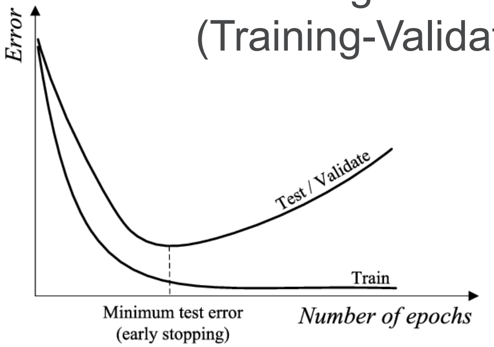


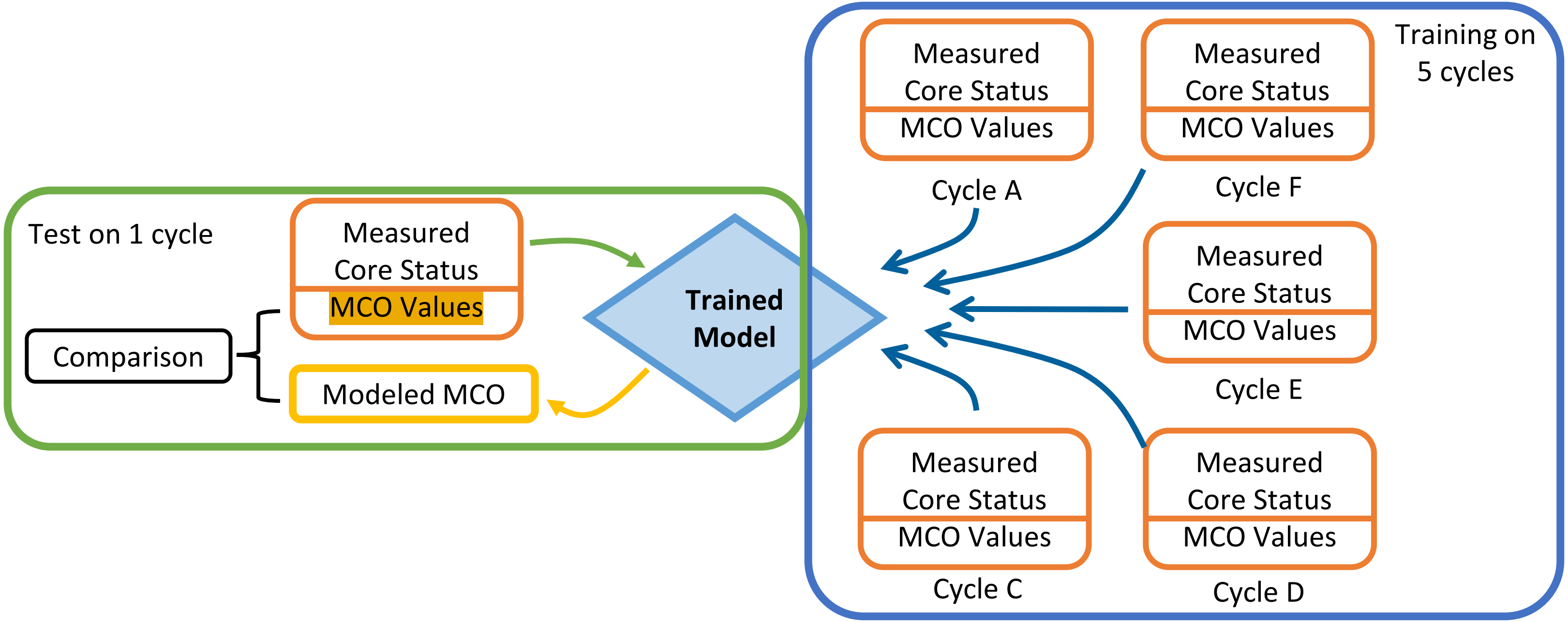




Underfit Normal Overfit

Avoid Overfitting (fitting the noise):
Data Segmentation
(Training-Validation-Test)




Test on 1 cycle
Measured
Core Status
MCO Values
Comparison
Modeled MCO
Trained
Model
Training on
5 cycles
Measured
Core Status
MCO Values
Cycle A
Measured
Core Status
MCO Values
Cycle F
Measured
Core Status
MCO Values
Cycle E
Measured
Core Status
MCO Values
Cycle C
Measured
Core Status
MCO Values
Cycle D

WHY?
NEW-PHYSICS AND DATA DIVERSITY

1. A machine learning model can only interpolates the points it sees.

2. Extrapolation is unreliable.

3. In order to get accurate interpolation, adequate sampling density of the input space must exist.