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Office Of Nuclear Energy
Advanced Sensors and Instrumentation
Annual Review Meeting

Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation

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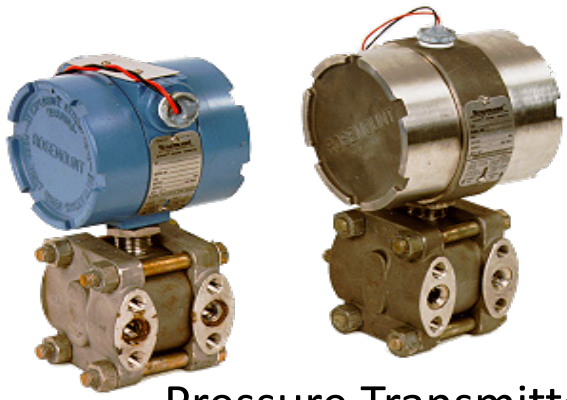
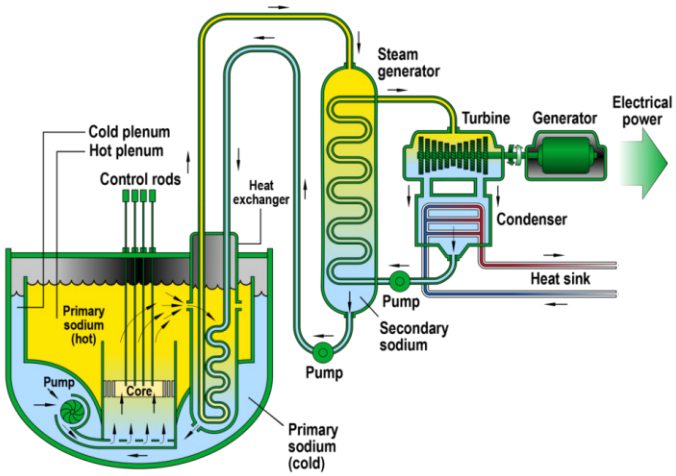
Background and Motivation

- **Measurement reliability key to safe, economic and secure operation of nuclear systems**
  - Interval-based recalibration used to assure reliability but have several drawbacks
- **Available online monitoring (OLM) technologies include technical gaps**
  - Robustness and improved uncertainty analysis
- **Need: Robust algorithms for OLM**
  - Monitoring sensor response *and* response time
  - Dynamic adaptation of acceptance criteria
  - Robust, reliable
- **Goal: Develop and evaluate robust next-generation OLM techniques**



Pressure Transmitters



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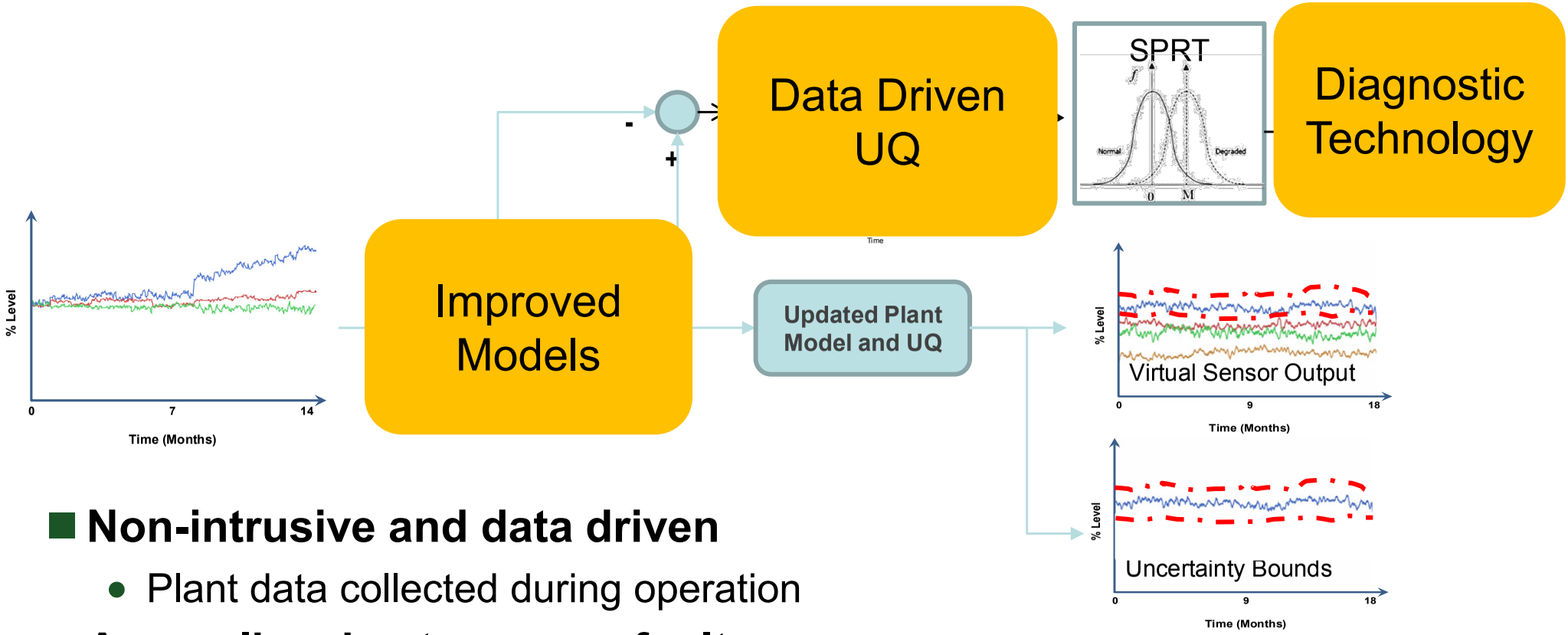
Approach: Focus on Models, Uncertainty Quantification (UQ)



- **Non-intrusive and data driven**
  - Plant data collected during operation
- **Anomalies due to sensor fault vs. process change**
- **Acceptance criteria define normal performance bounds**

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Technology Impact

- **Framework for robust OLM that enables**
  - Recalibration needs assessment for dynamic and steady-state operation
    - Sensor response and response time
  - Short-term operation with a limited number of failing sensors, through the use of virtual sensor technology
  - Ability to derive additional plant information using virtual sensors
  - Predictive (over short-term) assessment of sensor failure

- **Supports DOE-NE research objectives***
  - Improve reliability, sustain safety and extend life of current reactors
  - Improve affordability of new reactors

**Nuclear Energy Research and Development Roadmap, April 2010*

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Research Tasks

Response Time OLM

Virtual Sensors

Signal Validation

OLM Functions

Fault Detection and Diagnostics
- Threshold Selection
- Trends Analysis

Robust Models
- Automated Parameter Estimation
- Embedded UQ

OLM Residual Analysis
- Partition of Components
- Statistical Analysis

Research Tasks

Uncertainty Quantification

Verification and Validation

Foundations

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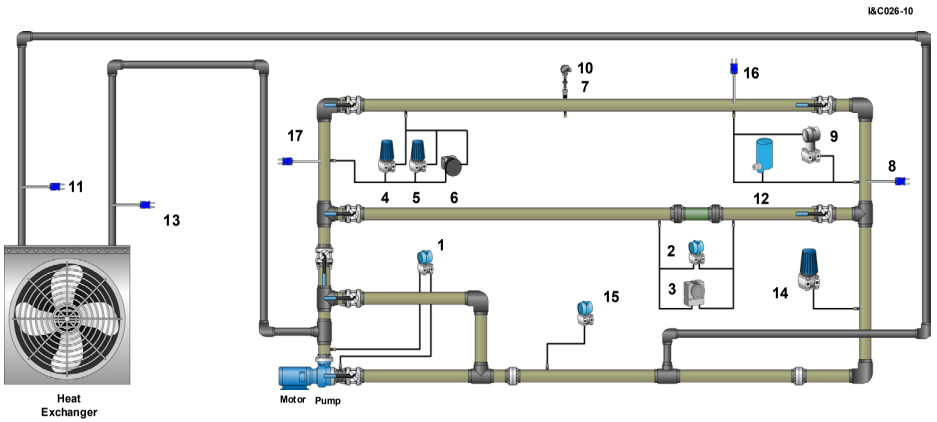
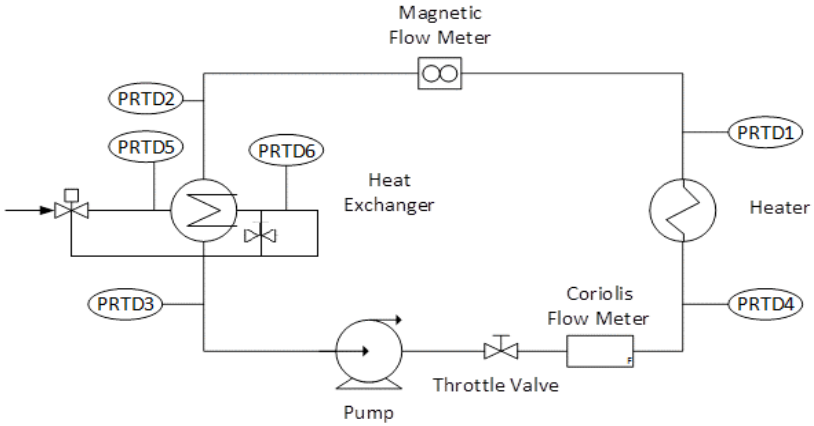
Testbeds Simulate Heat Exchanger Operations

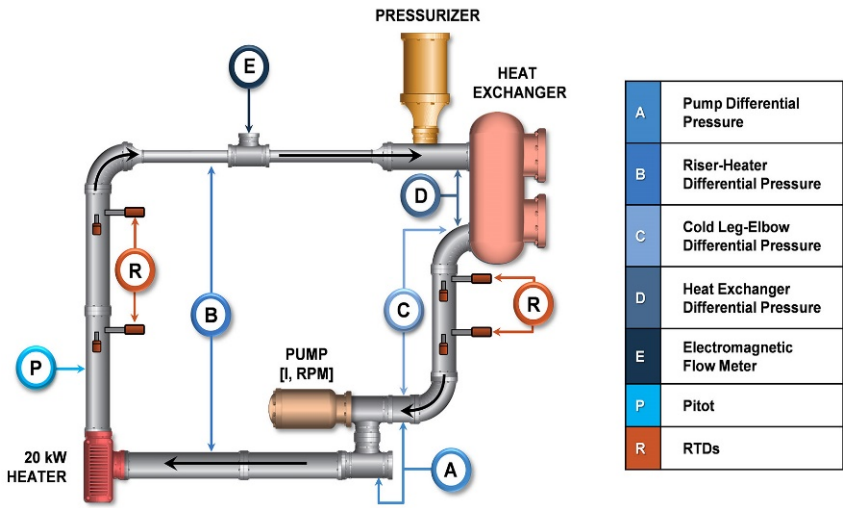
- **Multiple heat exchanger loops**
- **Sensor and instrumentation models coupled to loop model**
- **Prescribed uncertainty levels to directly study effects on sensed values and OLM results**
  - Normal and anomalous conditions
- **Access to data from plant operations**



Flow Loop 1



Simplified Flow Loop



Flow Loop 2

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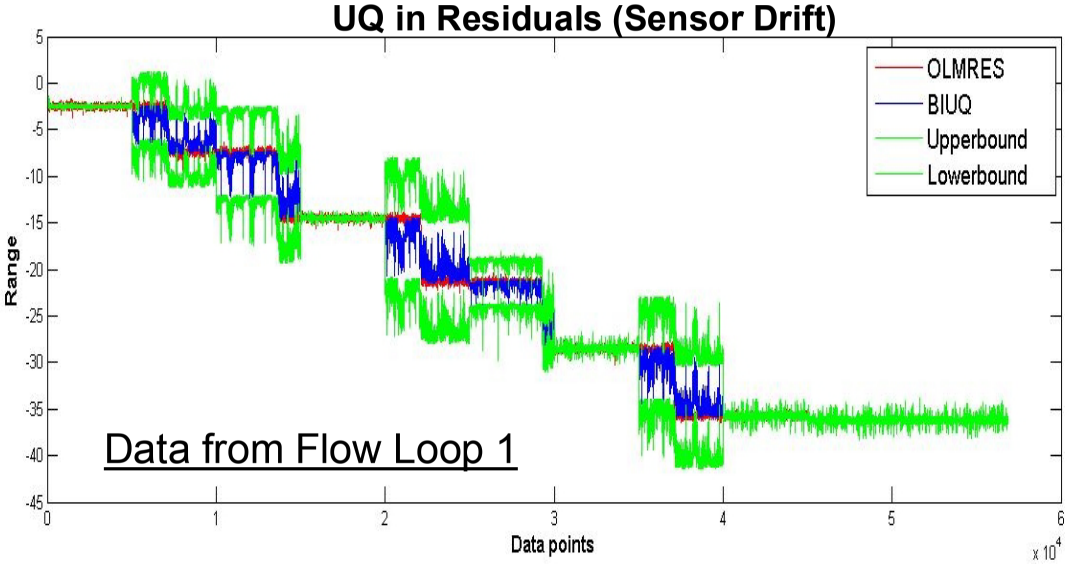
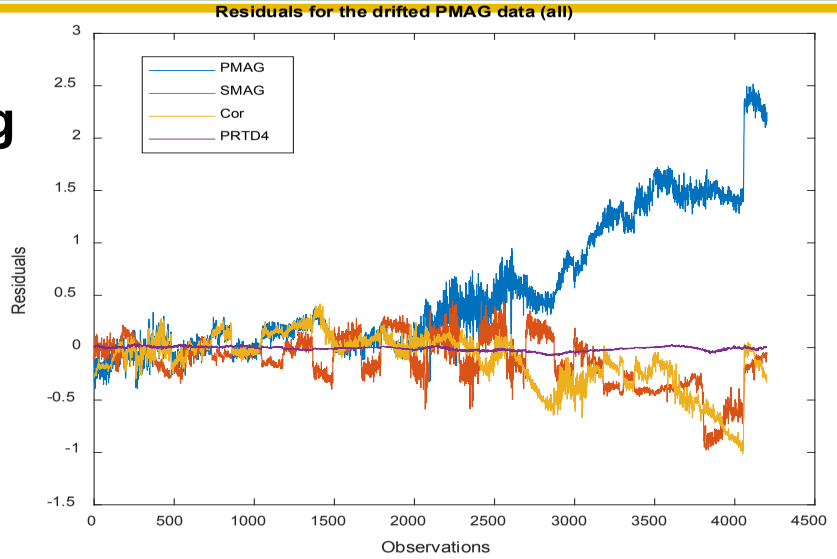
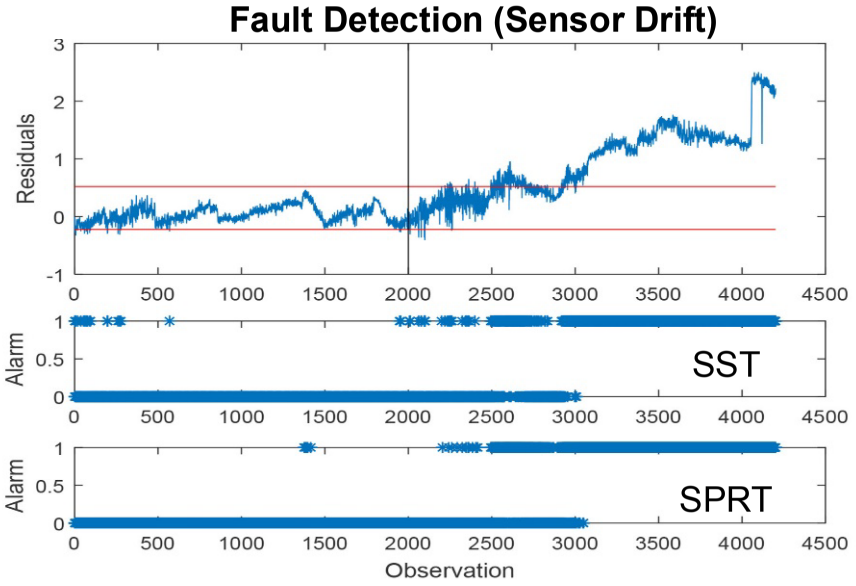
Results: UQ Assessment of OLM Residuals

- **UQ analysis indicates non-stationary model inadequacy component when using conventional OLM models**
- **Conventional OLM**
  - Fault detection: Reasonable performance if robust thresholding available
  - Data driven model parameters sensitive to cross-talk from drifting sensors
  - Diagnostics possible but difficult



Data from Flow Loop 1





Data from Simplified Flow Loop

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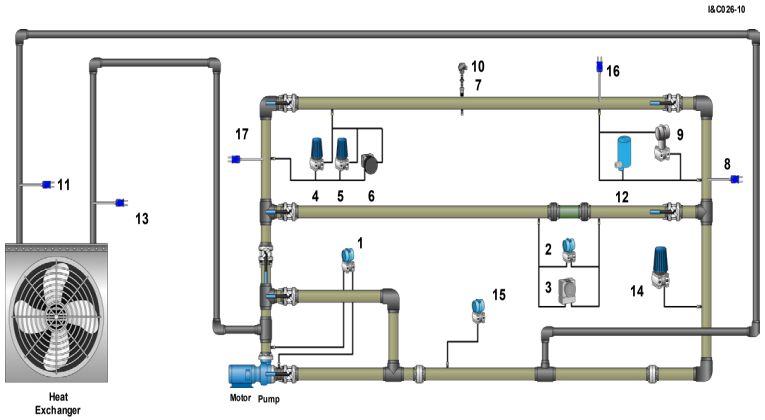
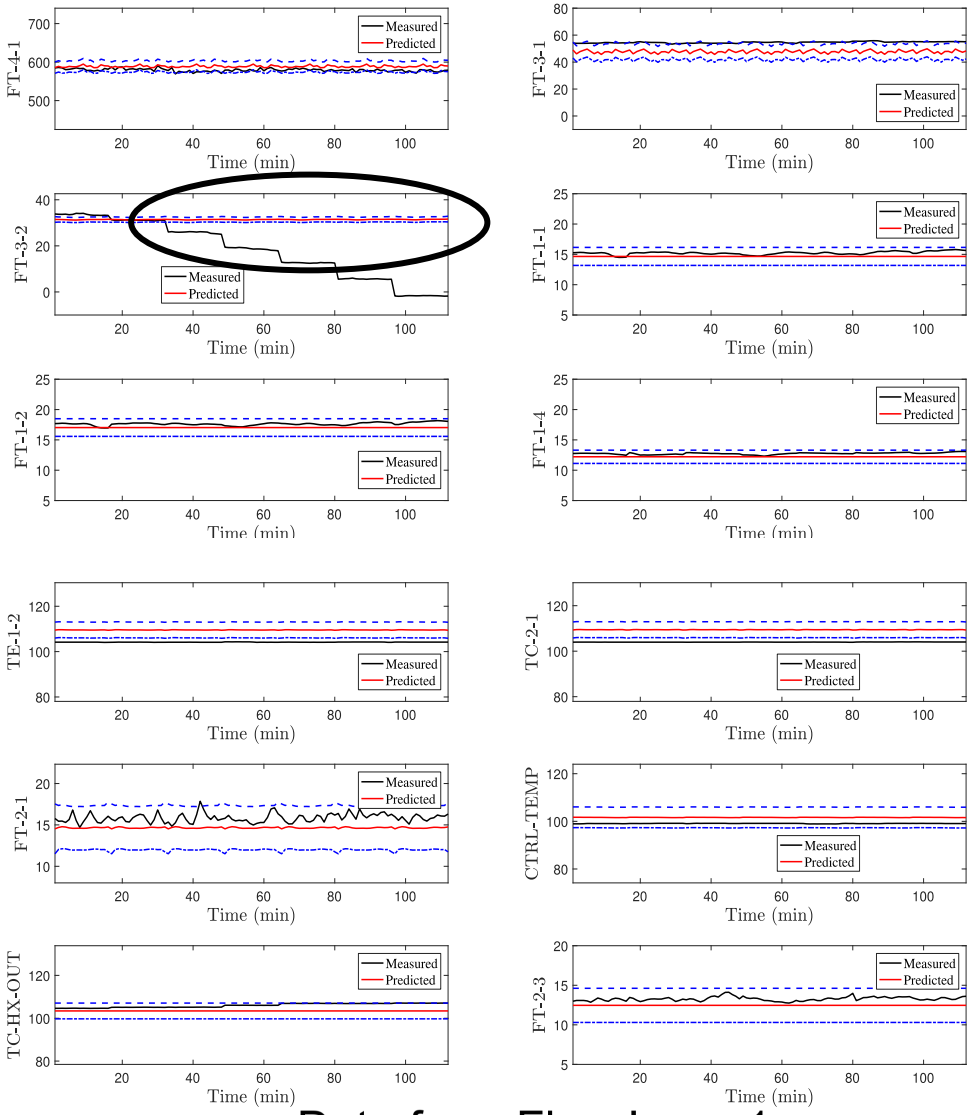
Results: Robust Models



- **UQ based models predictions robust to cross-talk**
  - Model predictions include uncertainty bounds
  - Tighter acceptance criteria, potentially earlier detection of faults
- **Model predictions may be applicable as virtual or software sensors**
  - Temporarily replace failing sensors
  - In-situ recalibration possibilities



Data from Flow Loop 1

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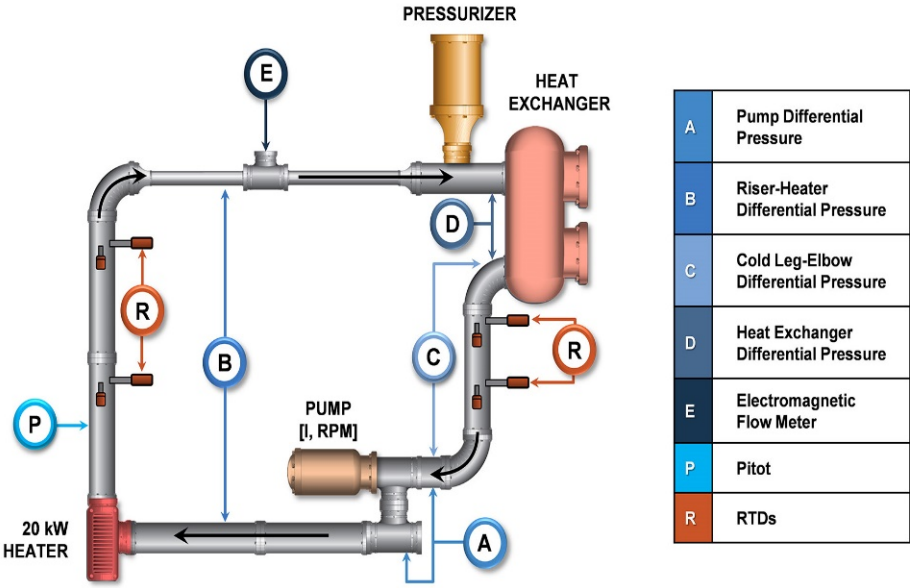
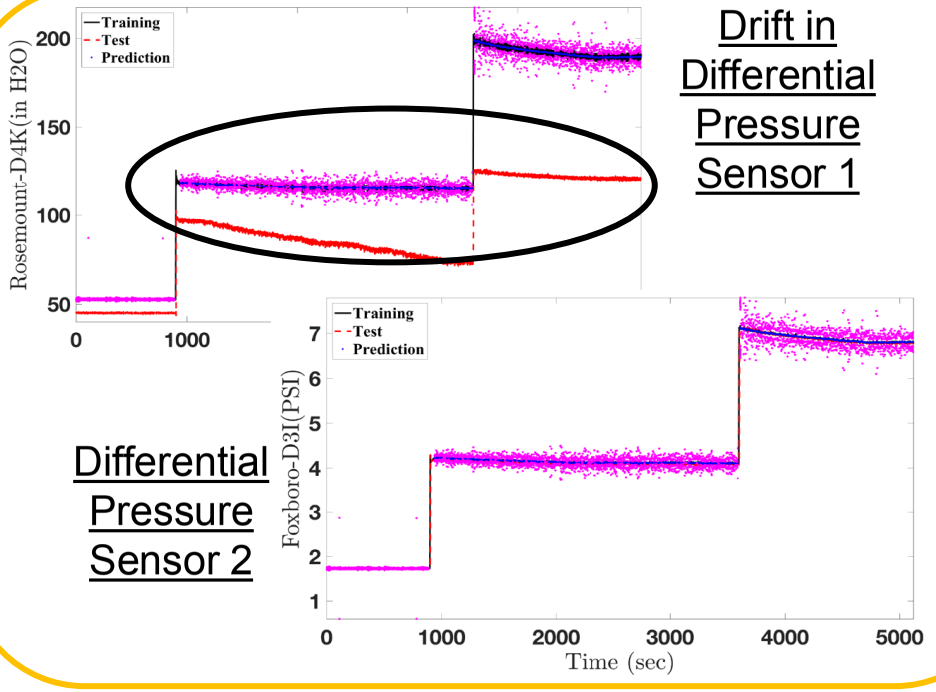
More Results: Robust Models and Virtual Sensors

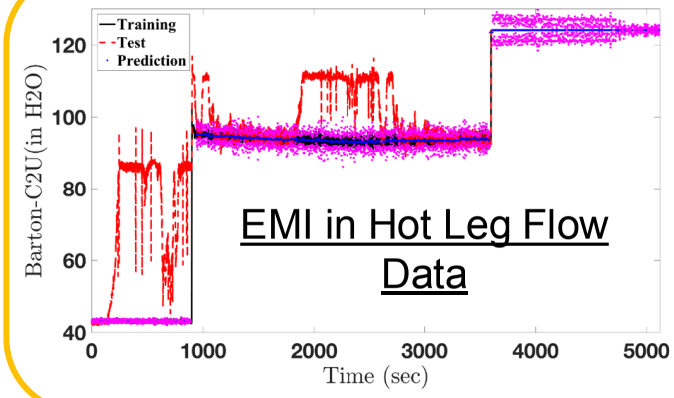


A	Pump Differential Pressure
B	Riser-Heater Differential Pressure
C	Cold Leg-Elbow Differential Pressure
D	Heat Exchanger Differential Pressure
E	Electromagnetic Flow Meter
P	Pitot
R	RTDs

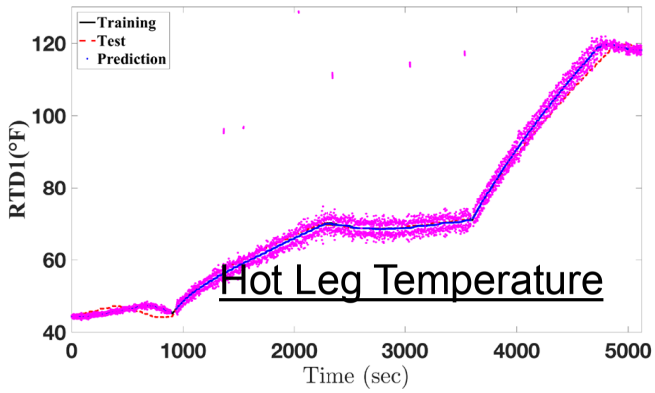


Drift in Differential Pressure Sensor 1

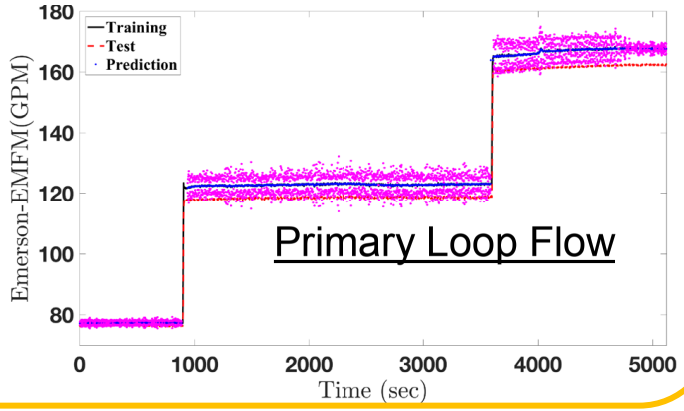
Differential Pressure Sensor 2



EMI in Hot Leg Flow Data



Hot Leg Temperature



Primary Loop Flow

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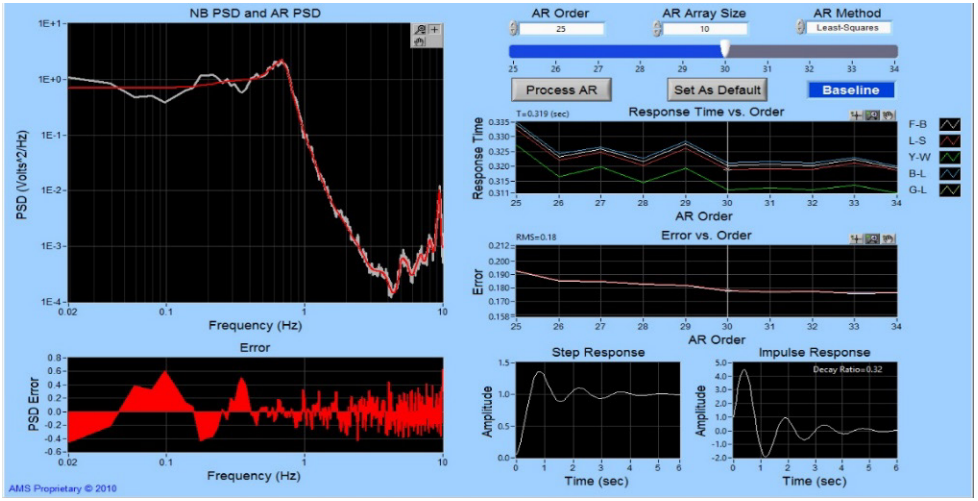
Results: Automation of Models for Response Time OLM



Model Selection for Noise Analysis

Item #	Tag	Automated AR			Manual Noise Analysis			AR Avg (sec)	Manual Avg (sec)	Difference (sec)	AR Stdev (sec)	Manual Stdev (sec)
		2016	2015	2013	2016	2015	2013					
PWR1-1	TAG001	0.26	0.29	0.27	0.27	0.27	0.27	0.27	0.27	0.00	0.01	0.00
PWR1-1	TAG002	0.31	0.33	0.30	0.31	0.31	0.32	0.31	0.31	0.00	0.01	0.00
PWR1-1	TAG003	0.29	0.27	0.27	0.28	0.28	0.26	0.28	0.27	0.01	0.01	0.01
PWR1-2	TAG001	0.13	0.13	0.12	0.15	0.15	0.15	0.13	0.15	-0.02	0.00	0.00
PWR1-2	TAG002	0.14	0.16	0.15	0.16	0.17	0.17	0.15	0.17	-0.02	0.01	0.00
PWR1-2	TAG003	0.14	0.15	0.15	0.15	0.16	0.16	0.15	0.16	-0.01	0.00	0.00
PWR1-2	TAG004	0.18	0.19	0.16	0.19	0.18	0.19	0.18	0.19	-0.01	0.01	0.00

Example Response Time Assessments

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Summary of Key Findings

- **Data driven, UQ-based models can overcome robustness issues with conventional OLM**
- **Models enable reliable fault detection and act as virtual sensors**
- **Models applicable to steady-state and dynamic sensor response monitoring**
- **Results suggest significant time-savings due to automation of OLM**
  - Additional savings likely from avoiding unnecessary calibration and continued operation (avoiding derating or shutdown due to failing sensors)

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Next Steps

- **Complete and submit publications**

- **Determine options for pilot studies of technology**
  - Steam generator level monitoring
  - Feedwater flow sensors
  - Other applications?

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Accomplishments

- **Developed and demonstrated robust models for OLM using laboratory and plant data**
  - Sensor steady state and dynamic response monitoring
- **Developed and demonstrated a potential method for improving fault detection and diagnostics through UQ-based analysis of OLM residuals**
- **Results indicate potential for significant savings**

- **Publications**
  - Technical reports documenting research results in FY15-FY17
  - Over 12 journal/conference papers to date; 2 journal papers under preparation
  - PhD Dissertation (In process, Anjali Nair, UT-Knoxville)
  - M.S. Thesis (Anjali Nair, UT-Knoxville)
  - M.S. Project (Sam Boring, UT-Knoxville)

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Conclusion

- **Research focused on addressing high-impact technical gaps to developing robust next-generation online monitoring technology**

- **Research outcomes enable**
  - Extended calibration intervals and relief of even limited periodic assessment requirements
  - Assessment of sensor measurement accuracy with high confidence
  - Derived values for desired parameters that cannot be directly measured
- **Research Outcomes support**
  - Improved reliability and economics for current and future nuclear systems