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U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation

Pradeep Ramuhalli, Jamie Coble*, Brent Shumaker**, Ramakrishna Tipireddy, Megan Lerchen
Pacific Northwest National Laboratory
*University of Tennessee Knoxville
**Analysis and Measurement Services

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Project Overview

- **Goal: Develop and evaluate a standardized framework for next-generation online monitoring applicable to current and future nuclear systems**

- **Participants:**
  - PNNL (Pradeep Ramuhalli, Ramakrishna Tipireddy, Megan Lerchen)
  - University of Tennessee Knoxville (Jamie Coble, Anjali Nair)
  - AMS (Brent Shumaker)

- **Schedule**
  - Three years (FY 2015 – FY 2017)

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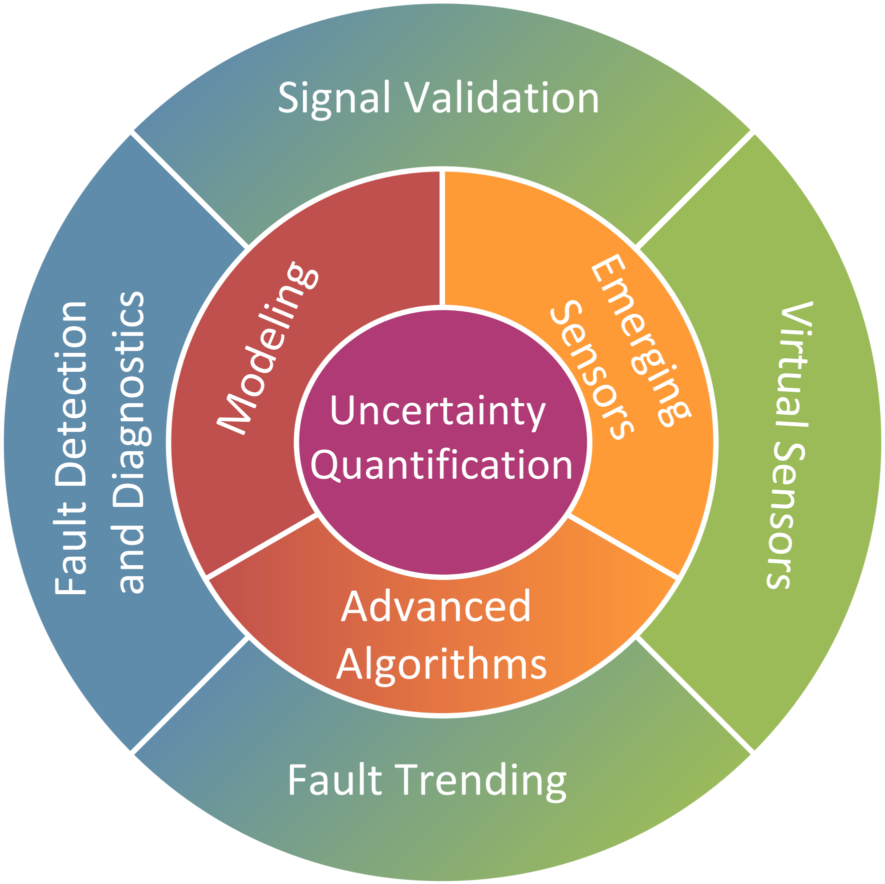
Objectives

- **Develop next-generation online monitoring applicable to current and future nuclear systems**
  - Apply data-driven UQ to develop methods for real-time calibration assessment and signal validation
  - Robust virtual sensors to augment available plant information
  - Technologies for sensor response-time monitoring
  - Considerations for emerging sensor technologies



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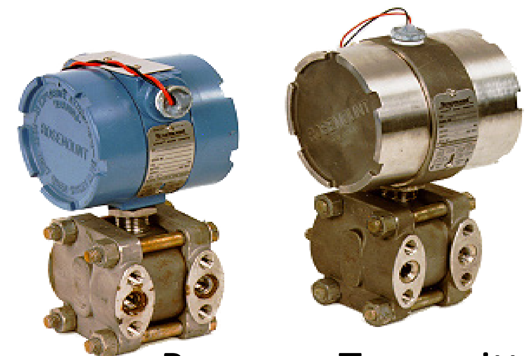
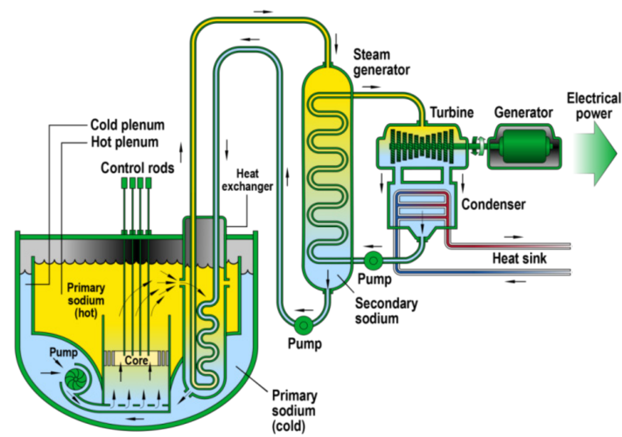
Project Background

- **Measurement reliability key to safe, economic and secure operation of nuclear systems**
  - Interval-based recalibration used to assure reliability

- **Current practices have several drawbacks**
  - Time consuming and expensive
  - Sensor calibration assessed infrequently
  - Contributes to unnecessary radiological dose
  - Unnecessary maintenance may damage healthy sensors
  - Potential for limited opportunities for maintenance in future nuclear systems
  - Different failure mechanisms for next-generation sensors and I&C



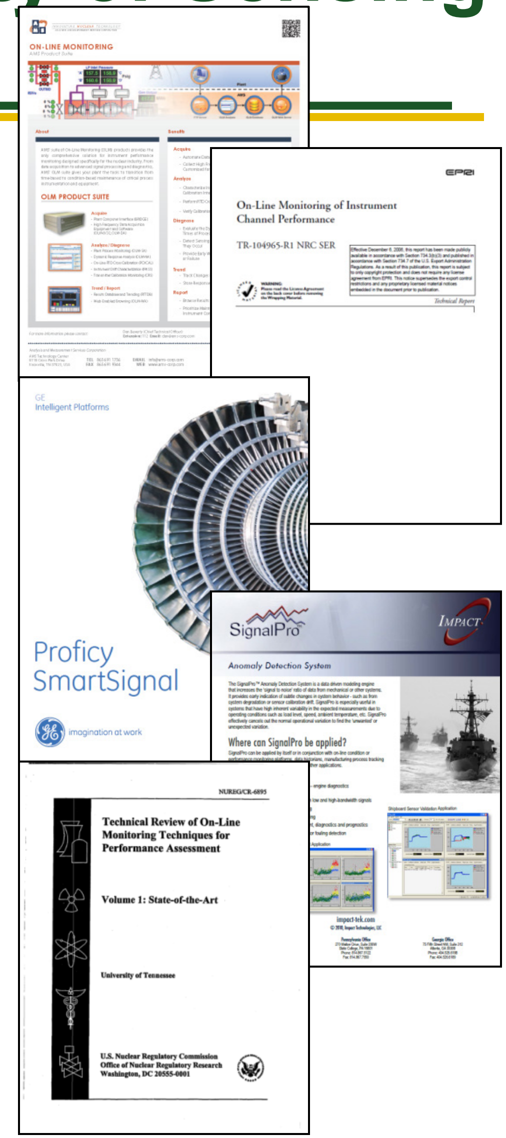
Pressure Transmitters



Sensor Performance Monitoring can Improve Reliability of Sensing

- **Online monitoring (OLM) supports condition-based calibration of key instrumentation**

- **OLM technologies can**
  - Temporarily accommodate limited sensor failure
  - Provide indications for measurements that cannot be made (virtual sensors)
  - Ensure reliability of next-generation sensors and instrumentation through formal methods for uncertainty quantification
  - Support extended sensor calibration cycles and reduce or eliminate TS-required periodic recalibration



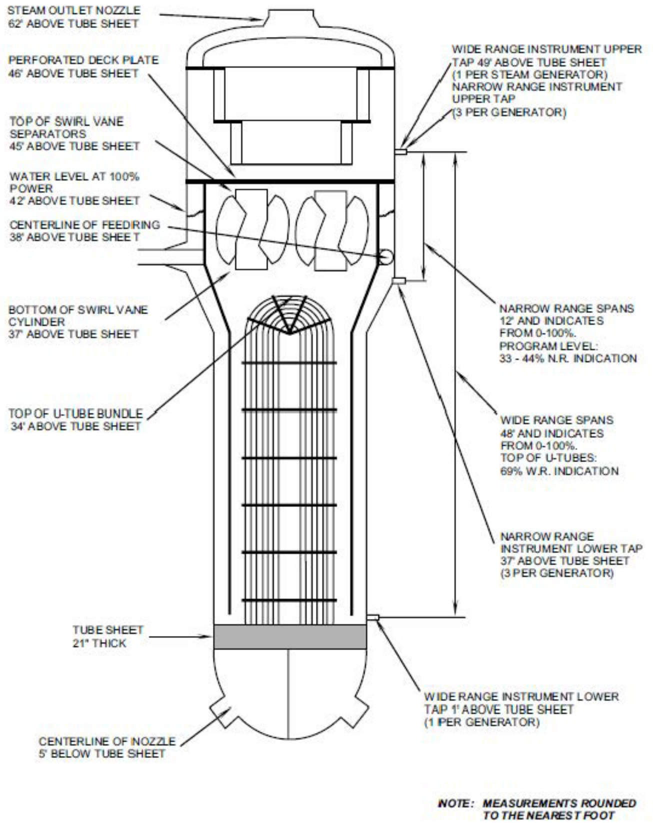
Technology Impact

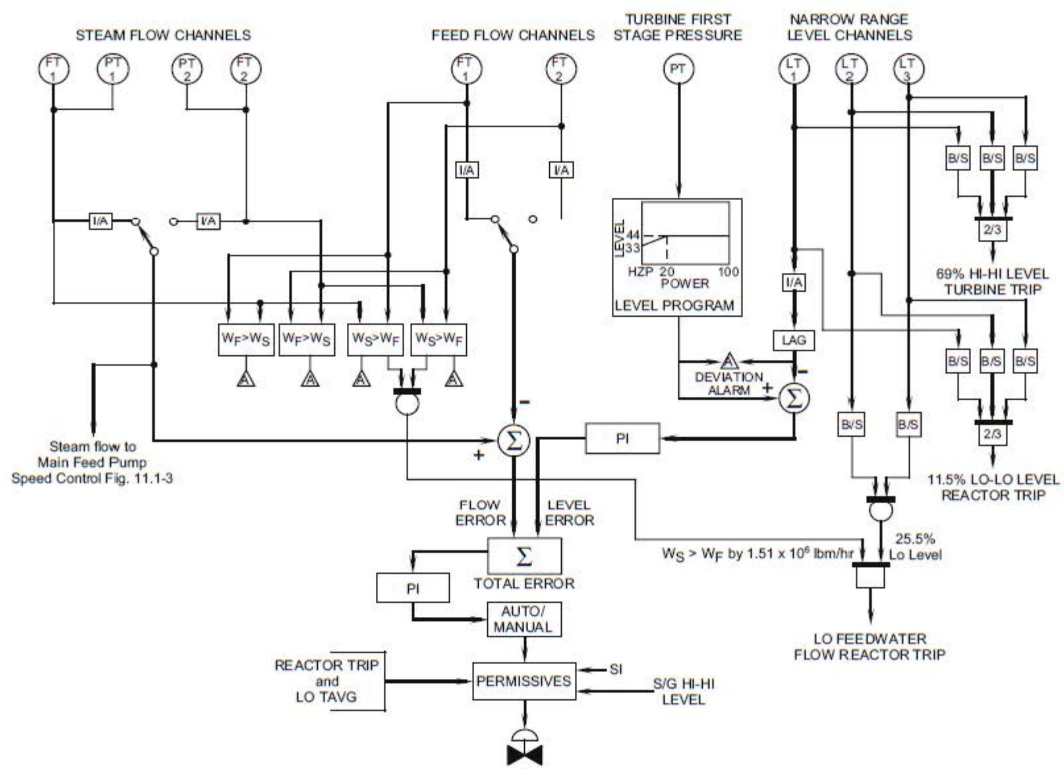
- **Framework for next generation OLM that enables**
  - Recalibration needs assessment for dynamic and steady-state operation
  - Short-term operation with a limited number of failing sensors, through the use of virtual sensor technology
  - Ability to derive plant information that currently cannot be measured using virtual sensors
  - Monitoring and detection of degradation in sensor response time
  - Predictive (over short-term) assessment of sensor failure
  - OLM framework for emerging I&C technologies

- **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*

Example
SG Level Measurement and Feed-water Control

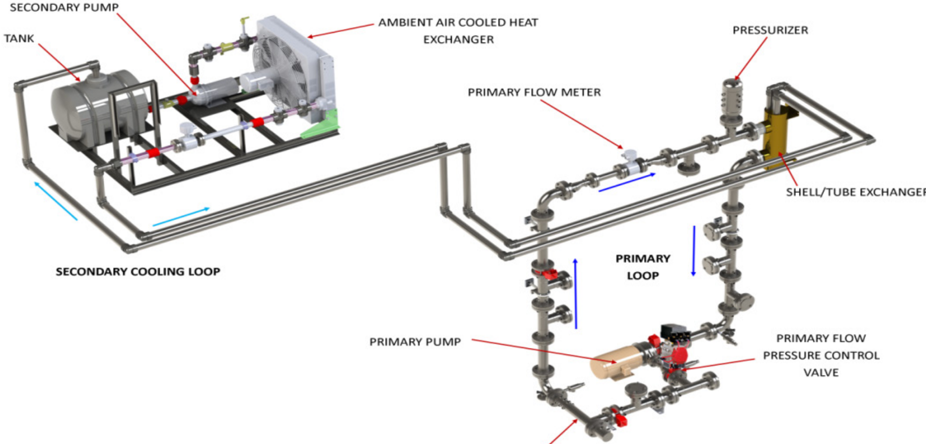


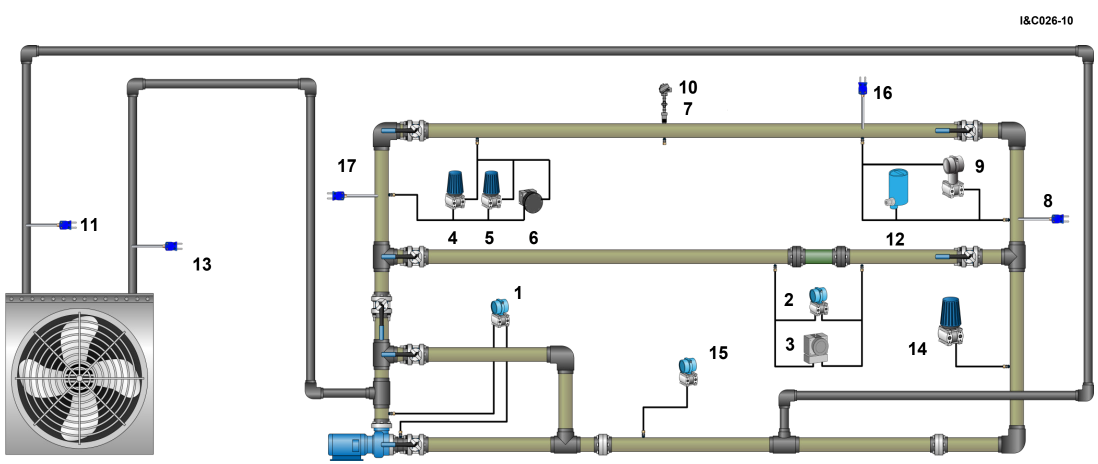


NRC ADAMS No. ML11223A293, Figures 11.1-1 and 11.1-4

Testbeds Simulate Heat Exchanger Operations

- **Simple heat exchanger loop**
- **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





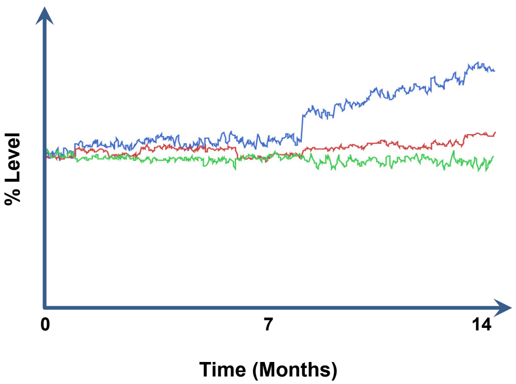
ITEM	ID	SENSOR TYPE	MANUFACTURER
1	FT-4-1	DIFFERENTIAL PRESSURE	ROSEMOUNT
2	FT-3-1	DIFFERENTIAL PRESSURE (SMART)	ROSEMOUNT
3	FT-3-2	DIFFERENTIAL PRESSURE	BARTON
4	FT-1-1	DIFFERENTIAL PRESSURE	FOXBORO
5	FT-1-2	DIFFERENTIAL PRESSURE	FOXBORO
6	FT-1-4	DIFFERENTIAL PRESSURE (SMART)	BARTON
7	TE-1-2	RTD (SMART)	ROSEMOUNT
8	TC-2-1	THERMOCOUPLE TYPE-J (SMART)	ROSEMOUNT
9	FT-2-1	DIFFERENTIAL PRESSURE	SCHLUMBERGER
10	CTRL-TEMP	RTD (SMART)	ROSEMOUNT
11	TC-HX-OUT	THERMOCOUPLE TYPE-J	OMEGA
12	FT-2-3	DIFFERENTIAL PRESSURE	HONEYWELL
13	TC-HX-IN	THERMOCOUPLE TYPE-J	OMEGA
14	CTRL-PSR	GAUGE PRESSURE	FOXBORO
15	PT-2	GAUGE PRESSURE	ROSEMOUNT
16	TC-LOOP-FAR	THERMOCOUPLE TYPE-E	OMEGA
17	TC-PUMP-OUT	THERMOCOUPLE TYPE-K	OMEGA

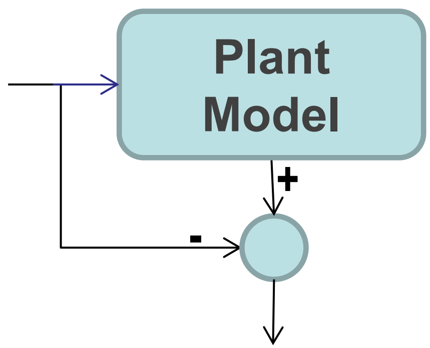
Research Tasks

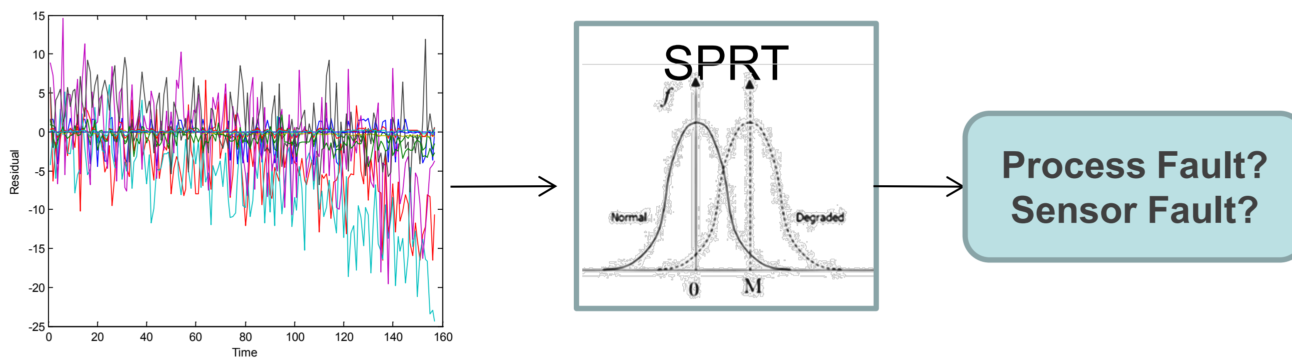
- **Signal validation and virtual sensors**
  - Evaluate how uncertainty drives minimum detection limits and acceptance criteria
  - Estimate expected measurement values (and associated uncertainties) for replacing faulted sensors
  - Evaluate the effect of using virtual sensors on OLM and OLM uncertainty
  - Develop guidelines for condition-based sensor recalibration
- **Assess impacts of next generation sensors and instrumentation**
  - Requirements definition for OLM in next generation I&C
  - Gaps assessment: Map algorithms (from other tasks) to requirements
- **Response time OLM**
  - Acceptance criteria development
  - Adapt research in signal validation for response time OLM
- **Verification and validation based on data from a suitable test-bed or operating plant**

Online Monitoring Overview

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







Gaussian Processes

- **Use Bayesian statistics to develop models and quantify uncertainty**
  - Combine what we already know (Prior) and the model discrepancy with the data (Likelihood).
- **General model:**

$$Y = \beta(x) = \mu(x) + w(x) + \varepsilon(x)$$

- **General approach:**
  - Assume prior for $\beta(x)$
  - Conditional prior distributions on parameters defining correlation functions represented through a basis expansion
    - Likelihood information using multi-output Gaussian processes that explicitly treat correlations between distinct output variables as well as space and/or time.
  - Bayesian inference (using a training data set) performed to extract posterior distributions
  - Update model in the light of new observations

High Confidence Signal Validation Through GP Modeling of Monitoring System Residuals

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- **Monitoring system residual is modeled as the combination of stationary (nominal) and dynamic (faulted) components**

$$r(z_i,\omega_i) = \underbrace{y(z_i,\omega_i)}_{1} - \underbrace{z_i}_{2} = \underbrace{\delta(z_i,\omega_i) + e_i}_{3} + \rho\underbrace{\eta(\Delta t_i, l_i)}_{4}$$

  - $y(z_i,\omega_i)$ **(1)** is the monitoring system prediction at point z_i, given model parameters ω_i
  - z_i **(2)** is the measurement from the system
  - The stationary component of the monitoring system residual is a combination of model inadequacy, $\delta(z_i,\omega_i)$, and measurement noise, e_i **(3)**
  - Anomalies manifest as dynamic component of residual, $\rho\cdot\eta(\Delta t_i,l_i)$ **(4)**, where Δt_i is the elapsed time from onset of fault, η is a function relevant to the type of fault with parameters l_i, and ρ is a constant between 0 and 1 related to the model sensitivity

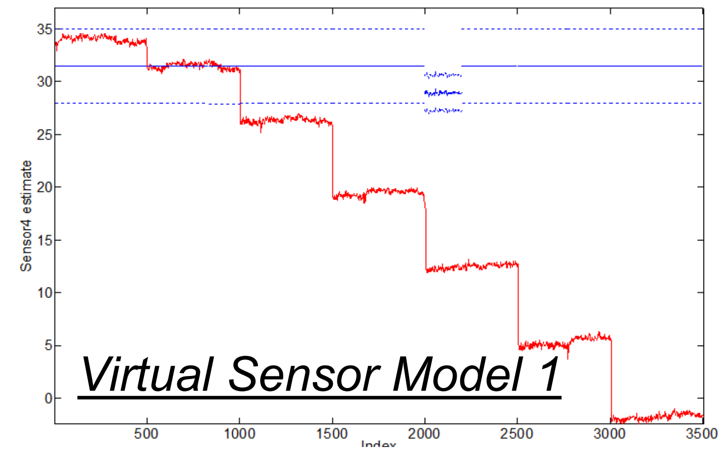
Implementation Status of Signal Validation

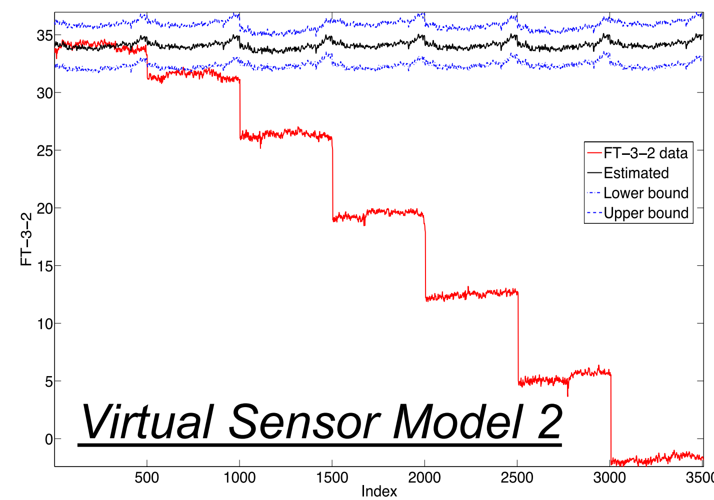
- **Initially focused on implementing the stationary component GP model**
  - Implementation is ongoing with testing using a variety of available data from small flow loops and reactor coolant loops

- **Assumptions:**
  - Measurements, z, follow a non-stationary Gaussian distribution
  - Monitoring system model, $y(z,\omega)$, is static and pre-defined
    - Auto-associative kernel regression is current focus
    - Framework is model agnostic
  - Healthy sensor residuals are stationary in time and across the sensor range

Virtual Sensing

- **Virtual sensor model using Gaussian Process**
  - Sensor drift: Data with one faulty sensor
  - Model inputs include control and process sensor measurements
  - Predicted sensor value includes uncertainty in prediction
  - Results indicate potential for predicting sensor data with uncertainty bounds, for sensor with drift
  - Uncertainty bounds for the predicted sensor values are dependent on richness of data used for generating the model – approaches, including collecting additional data, to tighten bounds being examined





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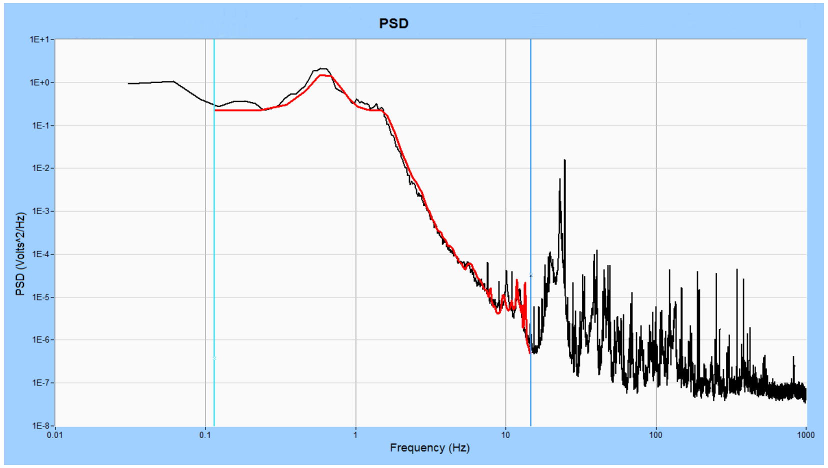
Sensor Response OLM

- **Automated Sensor Response OLM**
  - Dynamic response is a key indicator of sensor system performance and health
  - Traditional noise analysis methodology relies on knowledge from experienced engineers
  - Expert knowledge will be combined with automated analysis tools to provide accurate and repeatable sensor response results that can be integrated with other OLM analysis techniques
- **Noise Testing and Algorithm Development**
  - Acquire high-frequency noise data on nuclear-grade transmitters in the test loop
  - Simulate voids, leakages, and sensing line blockages to facilitate the development of robust sensor response evaluation and diagnostic algorithms



Accomplishments

- Implemented and evaluated initial approach to virtual sensing
- Identified needs for sensor response time OLM
- Implemented initial algorithm for signal validation based on Gaussian Process models for monitoring system residuals
- Update on signal validation and virtual sensing algorithm development (PNNL-24702)

- Journal/Conference papers and presentations
  - Coble, JB and A Nair, "High-Confidence Signal Validation for Online Sensor Calibration Assessment," Presented at *MFPT 2015*. Huntsville,AL: May 12-14, 2015.
  - Nair, A, and JB Coble, "A High Confidence Signal Validation Technique for Sensor Calibration Assessment in Nuclear Power Systems." 2015 ANS Winter Meeting and Nuclear Technology Expo. Washington, DC: November 8-12, 2015.

Next Steps

- **Signal validation**
  - Complete implementation and testing of sensor status and fault diagnostics using data-driven UQ
  - Input to advanced monitoring/control algorithms
- **Virtual sensing**
  - Alternate algorithms for virtual sensing
  - Uncertainty must account for spillover of faulty reading into estimate
  - Number of allowed virtual sensors, and duration of applicability to be determined
- **Response time OLM**
  - Implement and verify algorithms for noise analysis
- **OLM requirements using emerging I&C technologies**
- **Verification and validation of algorithms using data from test-beds as well as data from operating plants**

Conclusion

- **Research focused on addressing high-impact technical gaps to developing a standardized framework for robust next-generation online monitoring**
- **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
- **Outcomes support**
  - Improved reliability and economics for current and future nuclear systems
  - Deployment of advanced sensors (ultrasonic, fiber optic, etc.) and instrumentation (digital I&C, wireless, etc.)