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Nuclear Energy Enabling Technologies (NEET)

Advanced Sensors and Instrumentation (ASI) Annual Project Review

Sensor Degradation Control Systems

Richard Vilim
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May 21-22, 2013

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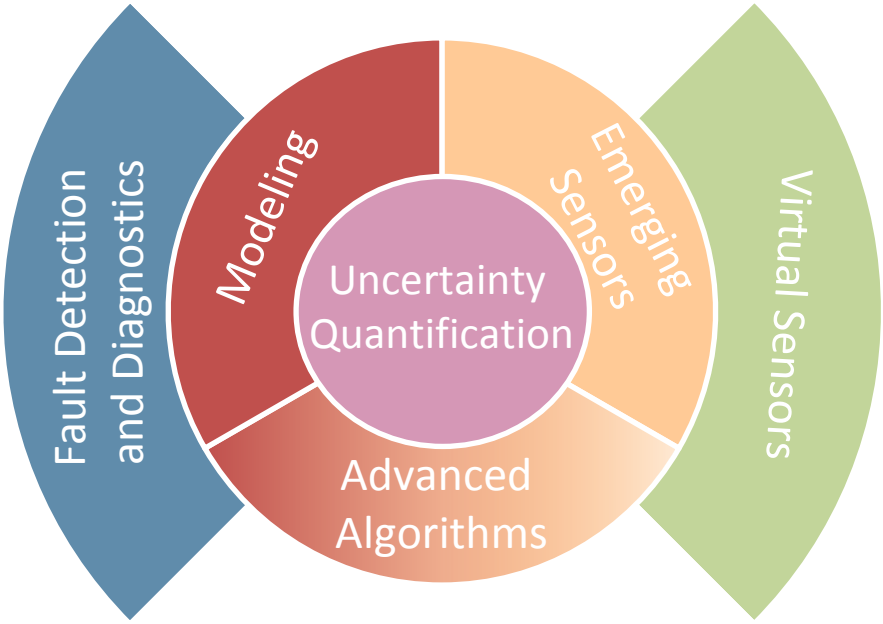
Project Overview

Background

- Sensors that operate in harsh environments undergo structural deterioration with time
  - *Material relocation, corrosion, cracking, and interface damage*
- Creates uncertainty during operation as to the health of the sensor and the accuracy of the reading



This project | By others

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Project Overview

Objectives

- Enable on-line monitoring of the condition of plant sensors
  - *Detect and identify failing sensors including during transient conditions*
- Greater sensitivity and reliability by applying engineering principles compared to approaches that use simple trending
  - *Fundamental knowledge of sensor processes (Intra-Sensor)*
  - *Conservation-based knowledge of flow of information in a network of plant sensors (Inter-Sensor)*
- Demonstrate in an operating power reactor
  - *Work with a utility to identify a test problem and to acquire data for analysis*

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Project Overview

- **Participants**
  - Rick Vilim, Alex Heifetz , Stefano Passerini (ANL)
  - Mohammed Yousaf (Exelon – self funded)

- **DOE-R&D programs benefitting**
  - **Light Water Reactor Sustainability (LWRS) Program**
  - **Small Modular Reactor (SMR) Program**
  - **Advanced Reactor Concepts (ARC) Program**
  - **Used Nuclear Fuel Disposition (UNFD) Program**

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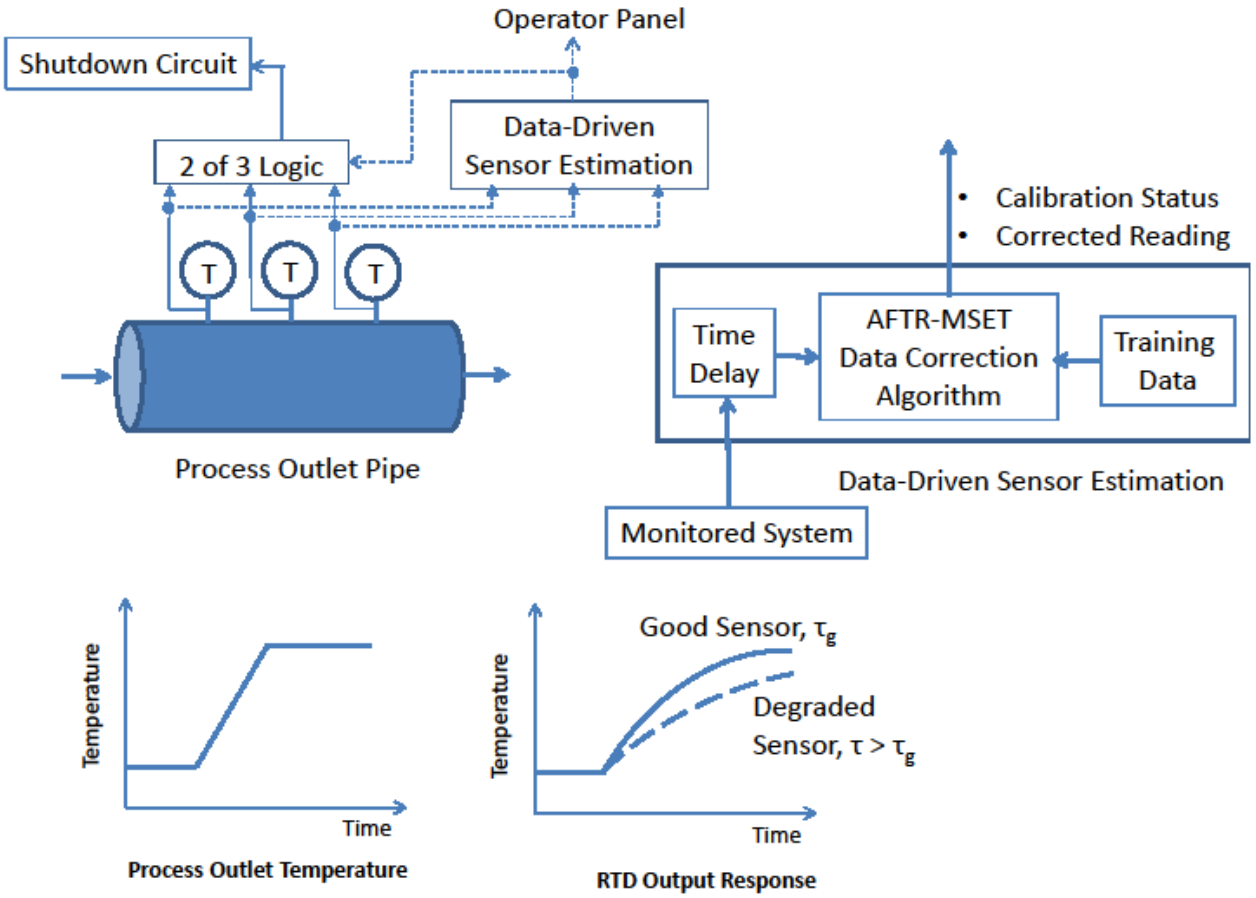
Technology Impact

- **Improved Knowledge of Sensor Health**
  - Greater operator confidence in validity of reading
  - Maintenance tasks can be better keyed to condition of the sensor
- **Increased Sensor-Reading Accuracy**
  - Greater electric generation efficiency related to tighter operating margins
  - Fewer shutdowns as a result of stretching sensor re-calibration intervals
  - Decreased maintenance and capital-costs associated with a reduction in number of required sensors
  - Enabler of advanced operator aids – Validated sensor readings are needed
- **Aid Deployment of Advanced Nuclear Energy Systems Presently Challenged by Sensor Technology**
  - Improved health monitoring of sensors in inaccessible locations
  - Reduced maintenance for sensors in cost-sensitive smaller units

Research Plan

- **Inter-Sensor Monitoring – Example with Multiple RTDs Input to PPS**



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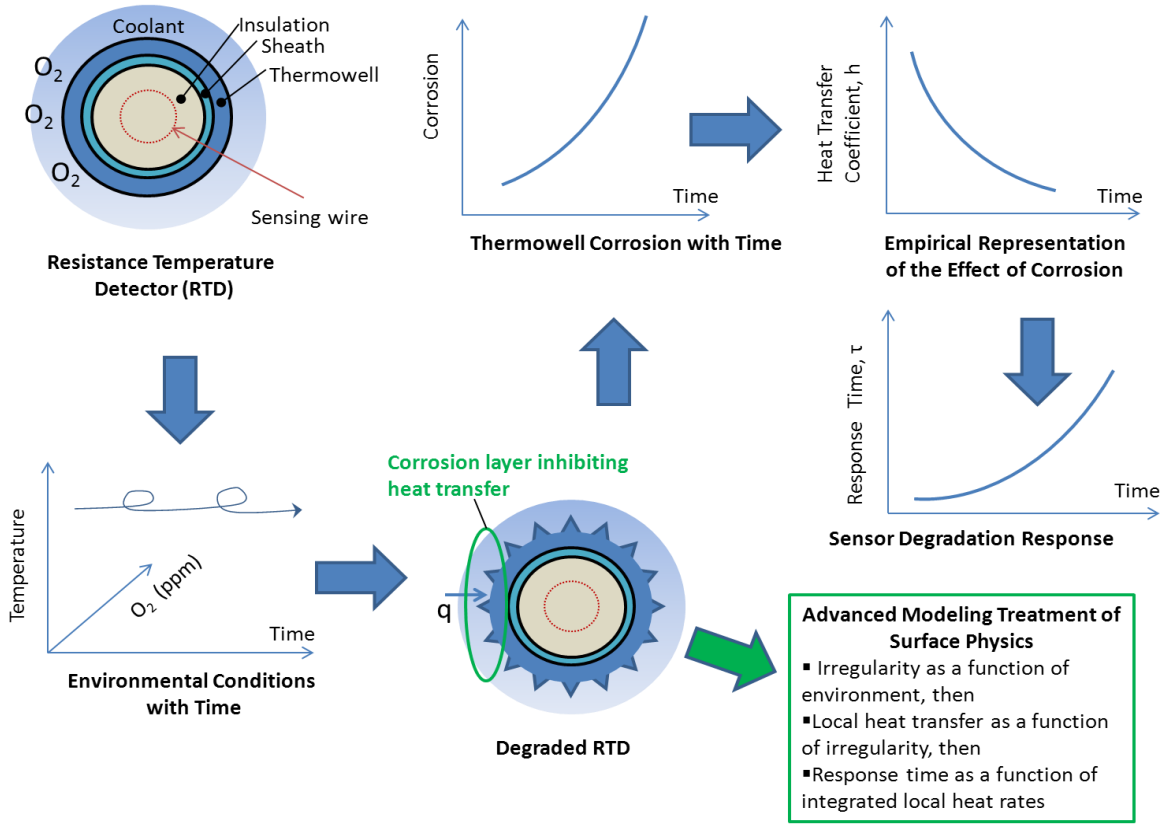
Research Plan

- **Intra-Sensor Monitoring – Example with Single RTD Input to PCS**



Process for "Re-Calibrating" Sensor

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Research Plan

- **FY 2012: $200K**
  - Inter-Sensor
    - Develop data-driven monitoring capability valid during transients and able to extrapolate
  - Intra-Sensor
    - Review literature on material degradation and identify opportunities for semi-empirical treatment – Begin treatment of an RTD
- **FY 2013: $200K**
  - Inter-Sensor
    - Perform proof-of-principle dynamic simulations of new monitoring method
  - Intra-Sensor
    - Continue on with more extensive modeling of RTD degradation
- **FY 2014: $350K**
  - Inter-Sensor
    - Install monitoring software on in-house plant simulator and perform integrated tests
  - Intra-Sensor
    - Plan and conduct an experiment to get RTD sensor degradation data
- **FY 2015: $350K**
  - Inter-Sensor
    - Assess false-alarm rate and degree of uncertainty reduction achievable
  - Intra-Sensor
    - Assess degree of achievable uncertainty reduction in sensed value for experiment data

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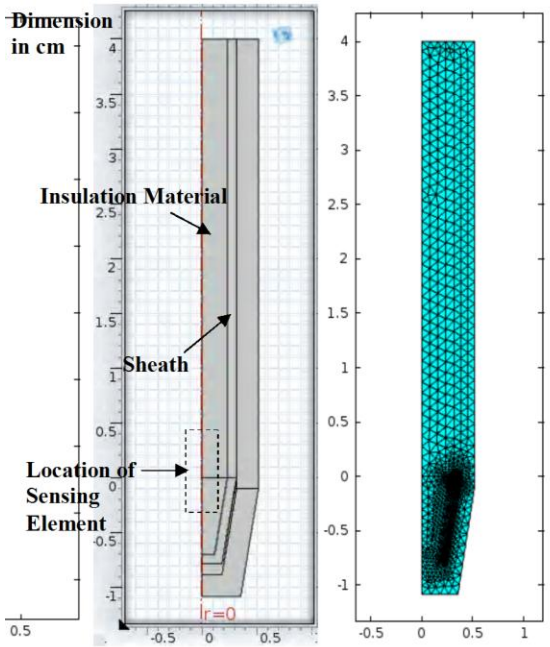
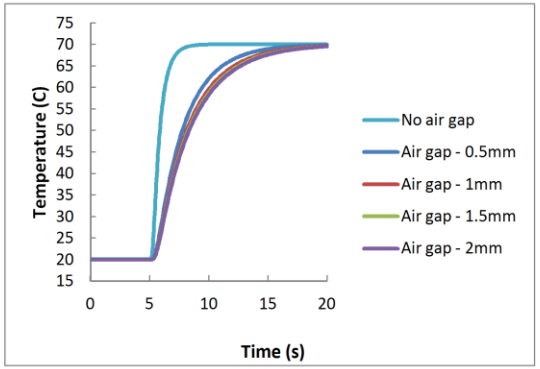
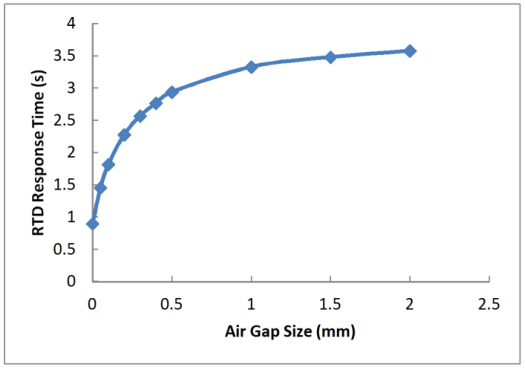
FY 2012 Accomplishments

Intra-Sensor Monitoring

- Quantified sensitivity of thermowell mounted RTD response to different degradation mechanisms
- A doubling of the resistance to heat flow doubles the RTD time constant







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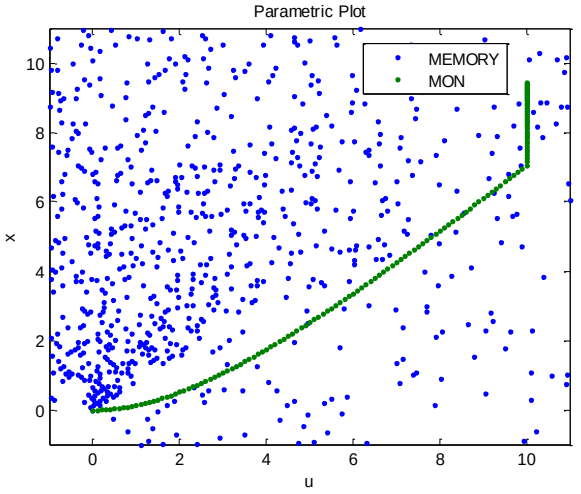
FY 2012 Accomplishments

Inter-Sensor Monitoring

- Methods in use today lack intrinsic capability to represent dynamic plant data or to extrapolate outside of training range
  - Source of false alarms
- Developed *Algorithm for Transient Multivariable Sensor Estimation* (AFTR-MSET) to remedy these deficiencies
- Performed proof-of-principle tests using plant-sensor simulation data for simple dynamic systems with failing sensors



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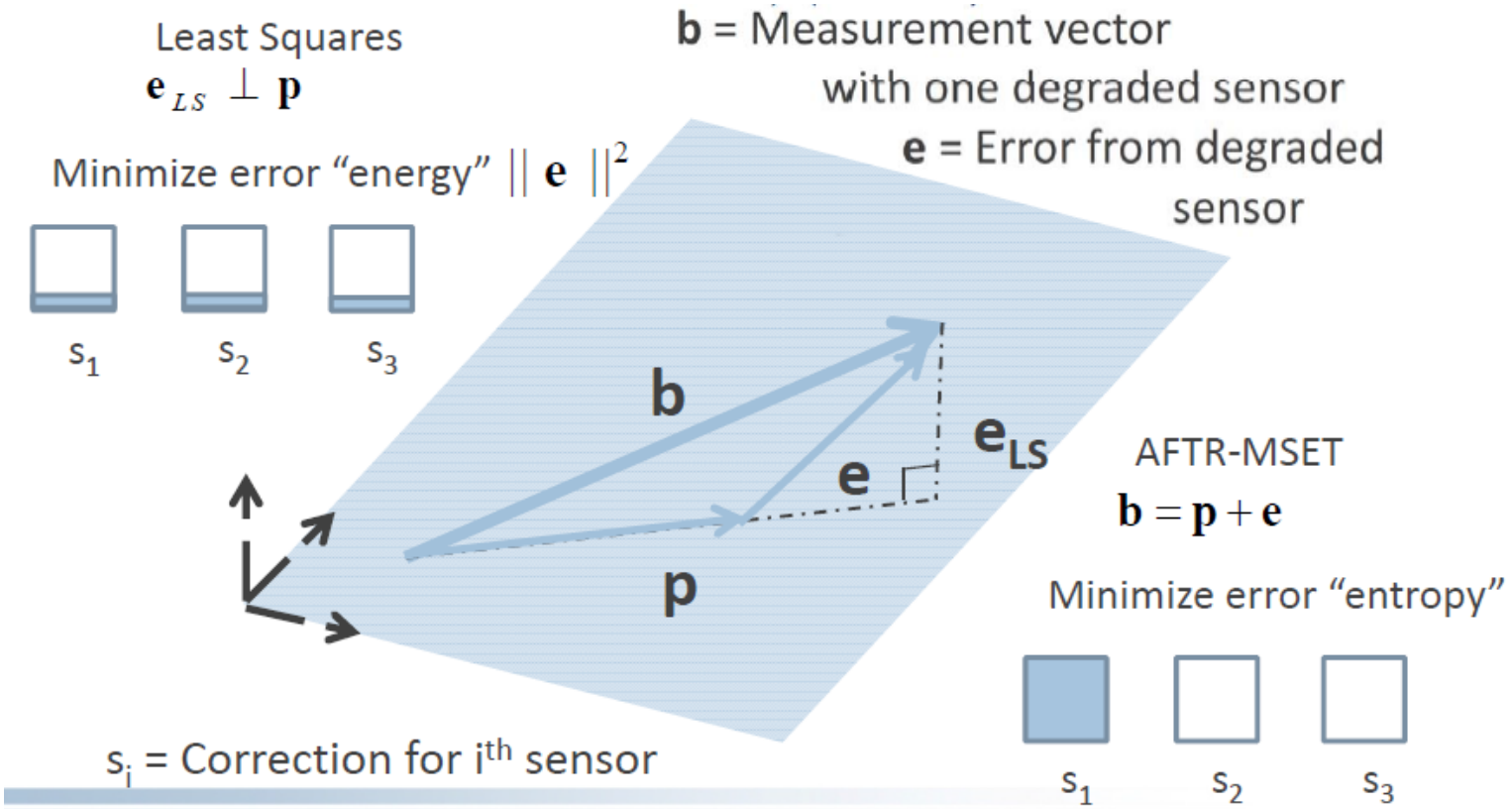
FY 2012 Accomplishments

- **Annual Project Report**
  - *Description of Algorithms for Detecting Sensor Degradation and Preliminary Tests Using Simulations,* ANL/NE-13-2 (November 2012)
    - Identifies intra- and inter-sensor problem classes and approaches for their respective treatment
    - Presents transient response dependence on degradation mechanisms in an RTD sensor
    - Identifies basis for *Multivariable State Estimation Technique* (MSET) fault detection algorithm inability to extrapolate and treat dynamic data
    - Describes concepts giving rise to AFTR-MSET algorithm
- **Publications**
  - R. B. Vilim, *et al*., *Improved Sensor Performance through Advanced Materials Modeling*, NPIC&HMIT (July 2012)
  - R. B. Vilim, *et al*., *Modeling the Aging Effects of Nuclear Power Plant Resistance Temperature Detectors*, NPIC&HMIT (July 2012)
- **Invention Report**
  - R. B. Vilim and A. Heifetz, *Algorithm for Transient Multivariable Sensor Estimation (AFTR-MSET),* Invention Report (April 2013)

FY 2013 Activities

Inter-Sensor Monitoring – AFTR-MSET Algorithm

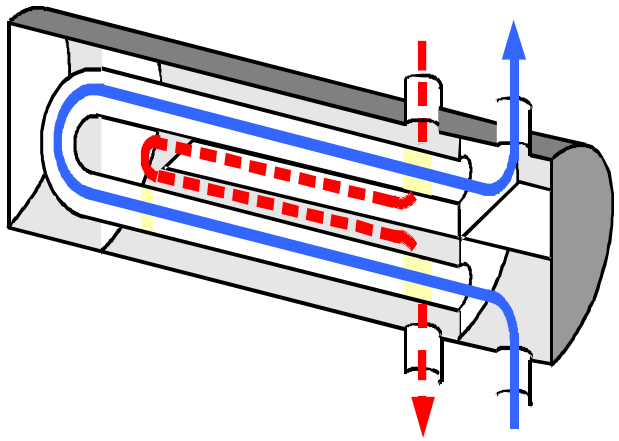
- Monitor sensors by looking to find that combination of plant basis vectors that gives the minimum "entropy" error
- Residual provides the degradation offset for re-calibration

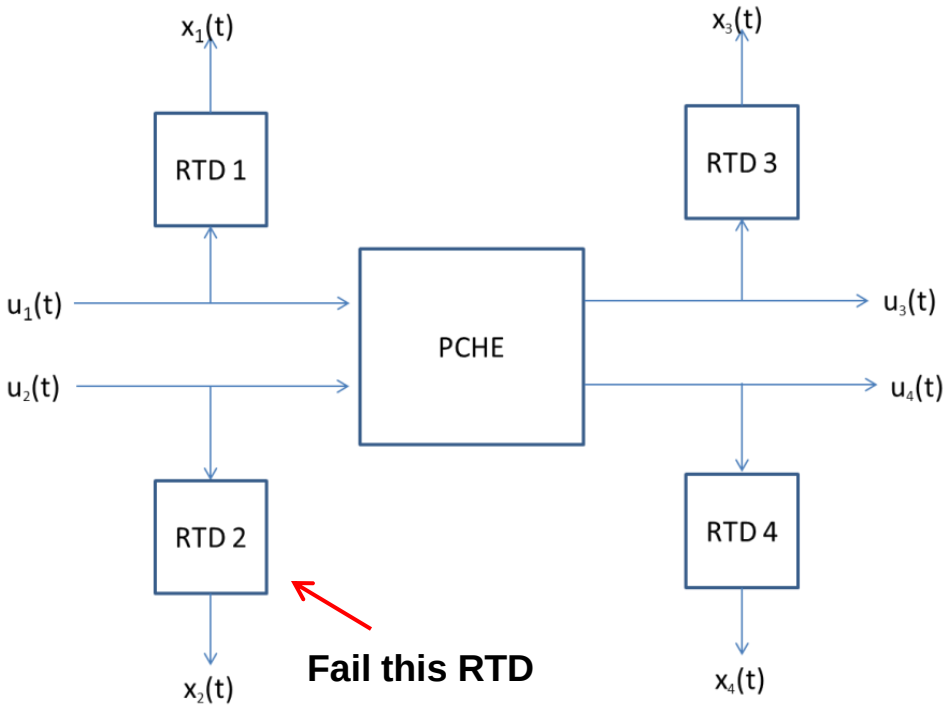


FY 2013 Activities

Inter-Sensor Monitoring – Detecting RTD Degradation

- Plant LWR regenerative heat exchanger lies among related RTDs





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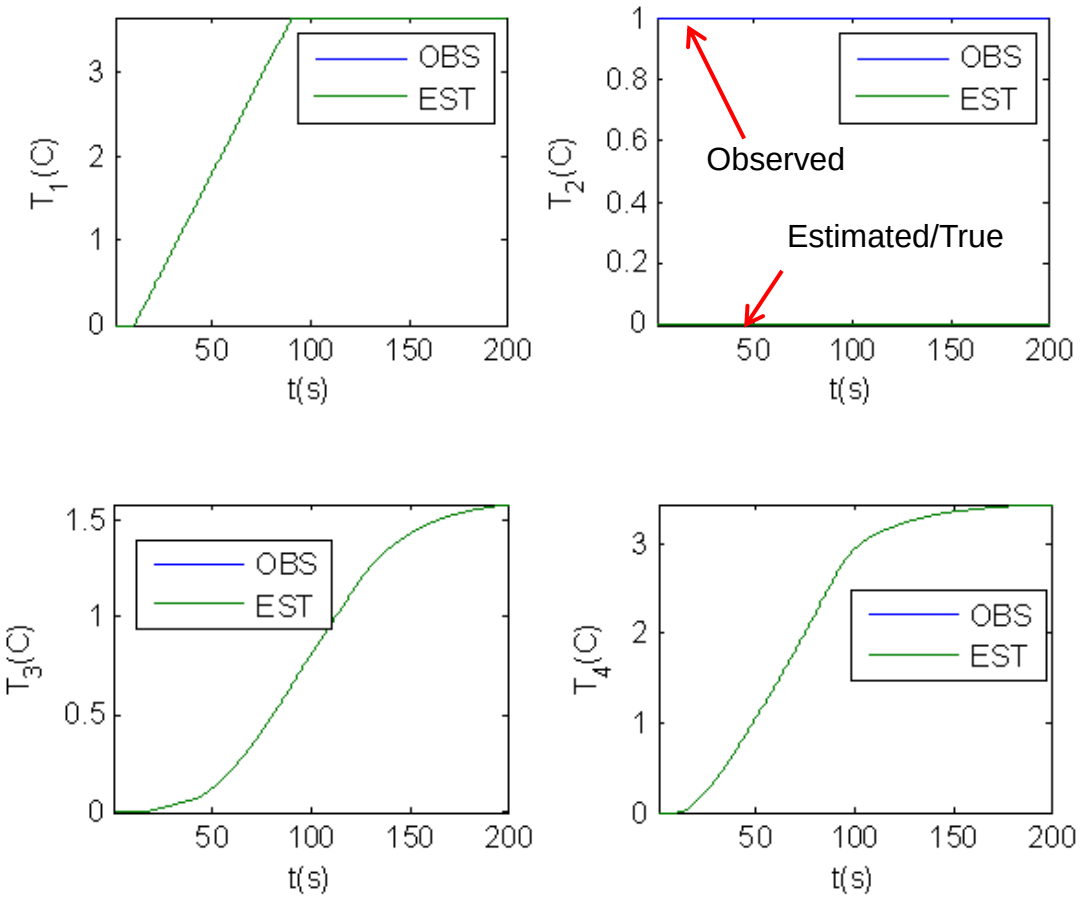
FY 2013 Activities

- **Successfully Detected and Corrected for Failed Sensor during a Transient**



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Planned Accomplishments

- **FY14**
  - Inter-Sensor
    - Complete AFTR-MSET algorithm development and testing
  - Intra-Sensor
    - Extend RTD degradation modeling to fouling
  - Interact with Exelon Nuclear
    - Obtain motor-bearing data from their monitoring system
- **FY15**
  - Inter-Sensor
    - Install monitoring software on in-house simulator platform for integrated testing
  - Intra-Sensor
    - Generate degradation fouling data by conducting an experiment or obtain data from utility
  - Apply methods to Exelon data
    - Perform parametric studies to assess false-alarm rate and sensitivity of algorithms
- **FY16**
  - Inter-Sensor
    - Assess degree of uncertainty reduction achievable in tests on in-house simulator platform
  - Intra-Sensor
    - Assess for degradation achievable uncertainty reduction incorporating model for RTD fouling
  - Propose a framework for integrating inter- and intra-sensor estimation methods

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Crosscutting Benefits

- **Light Water Reactor Sustainability (LWRS) Program**
  - Enhanced plant reliability and reduced human error
  - Supports an II&C demonstration pilot project beginning in FY 2015 to develop an *Advanced Online Monitoring Facility*
  - Post-accident sensor health monitoring - Works remotely – Normal access to sensors may no longer be possible
- **Small Modular Reactor (SMR) Program**
  - SMRs will require significant reductions in staffing to be economical
  - Reduction in operator workload by automating sensor surveillance and validation can aid this outcome
- **Advanced Reactor Concepts (ARC) Program**
  - ARC designs will likely have advanced digital control systems providing a platform to host advanced monitoring capabilities
- **Used Nuclear Fuel Disposition (UNFD) Program**
  - Long-term sensor performance monitoring

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Crosscutting Benefits

Utility Engagement

- Presented at Fleet-Wide Monitoring Group meeting, Dallas, Texas, September 2012
- Subsequently held technical exchanges with monitoring staff of a nuclear utility subsequent to Dallas meeting
- Working with utility to analyze plant monitoring data for operations exhibiting high false-alarm rate
- Will test monitoring methods on their plant data
- Expect to demonstrate reduced false alarm rates compared to status quo

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Transition to Competitive Research

- **Enables Next-Generation Monitoring Capabilities for Plant Operation Under Digital I&C System**
  - Apply across the plant to many systems
  - Integrate into plant operating procedures
- **Anticipated Hand-Off to Industry Upon Successful Utility Demonstration**
  - Transfer of intellectual property
- **Industry Commercialization Tasks**
  - Shrink-wrap and bullet-proof the software
  - Develop operator interface for use by non-experts
  - Select vendor for distribution and training

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Conclusion

- **Supports On-Line Monitoring of the Condition of Sensors**
  - Detect and identify failing sensors including during transient conditions
  - Greater sensitivity and reliability than is achievable by an operator
  - Detect the onset of degradation far in advance of the operator
- **Maintenance Costs are Reduced**
  - Maintenance tasks can be better keyed to condition of the sensor
- **Operators are Better Informed**
  - Greater confidence in validity of reading
  - Alerted to malfunctioning sensors
- **Tighter Operating Margins are Achievable**
  - Increased accuracy of sensor readings