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
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*
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
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
Research Plan

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

- Process for “Re-Calibrating” Sensor
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
**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
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
FY 2012 Accomplishments

Annual Project Report

  - 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)

Invention Report

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

Least Squares

\[ \mathbf{e}_{LS} = \mathbf{b} - \mathbf{p} \]

Minimize error “energy” \[ \| \mathbf{e} \|^2 \]

\[ \mathbf{b} = \text{Measurement vector with one degraded sensor} \]

\[ \mathbf{e} = \text{Error from degraded sensor} \]

\[ \mathbf{b} = \mathbf{p} + \mathbf{e} \]

AFTR-MSET

Minimize error “entropy”

\[ s_i = \text{Correction for } i^{th} \text{ sensor} \]
FY 2013 Activities

Inter-Sensor Monitoring – Detecting RTD Degradation

- Plant LWR regenerative heat exchanger lies among related RTDs
**FY 2013 Activities**

- Successfully Detected and Corrected for Failed Sensor during a Transient

![Graphs showing observed and estimated temperatures](image-url)
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
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
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
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
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