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## Nuclear Energy Enabling Technologies (NEET)

# Advanced Sensors and Instrumentation (ASI) Annual Project Review

## Recalibration Methodology for Transmitters and Instrumentation


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May 21-22, 2013

# 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, Jamie Coble, Guang Lin, Brett Braatz)
  - AMS (Brent Shumaker)

- **Research directly supports primary goals of**
  - LWRS, SMR, ARC, NGNP, and MPACT

- **Supports secondary goals of**
  - AF and UNFD

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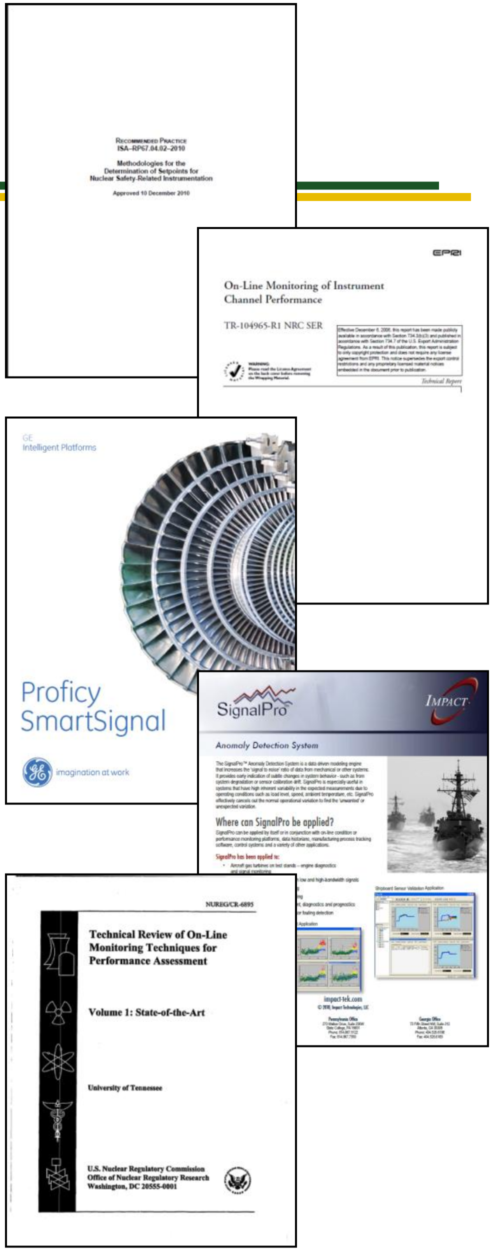
# Project Background

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

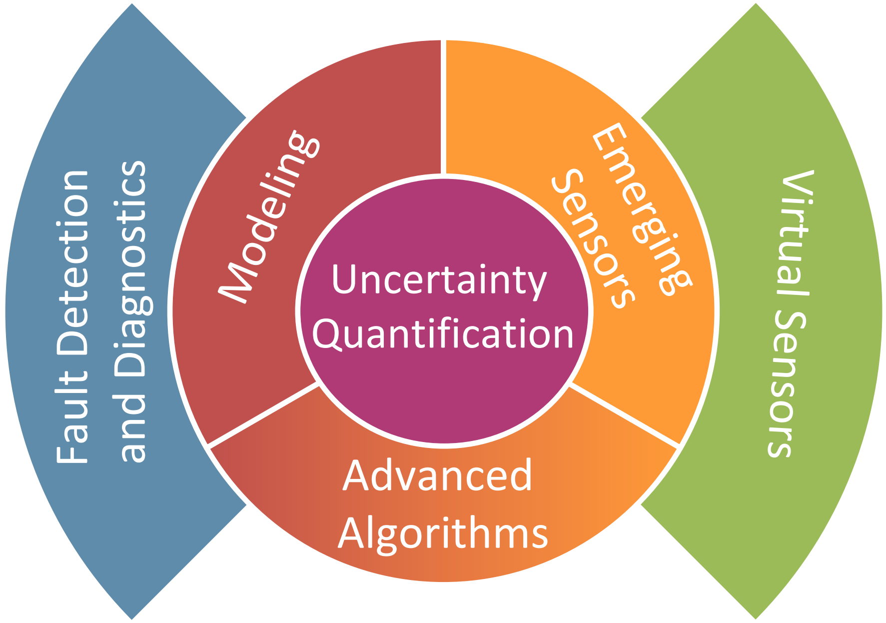
- **Current practices have several drawbacks**
  - Time consuming and expensive
  - Sensor calibration assessed infrequently
  - Contributes to ALARA
  - Unnecessary maintenance may damage healthy sensors

- **Open questions**
  - Temporarily accommodate limited sensor failure
  - Ensure reliability of next generation sensors and instrumentation
  - Robust methods for uncertainty quantification (UQ)



# Technology Impact

- **Standardized framework for next generation Online Monitoring (OLM) that supports**
  - Dynamic and steady-state operation
  - Real-time calibration assessment and signal validation
  - Considerations for emerging I&C technologies
- **Four-year project addresses cross-cutting areas**
  - Uncertainty quantification
  - Virtual sensors
  - OLM requirements for next-generation I&C



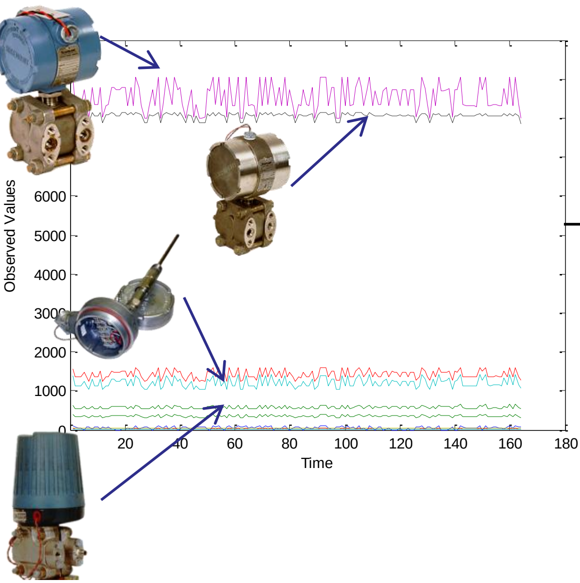
# Research Plan

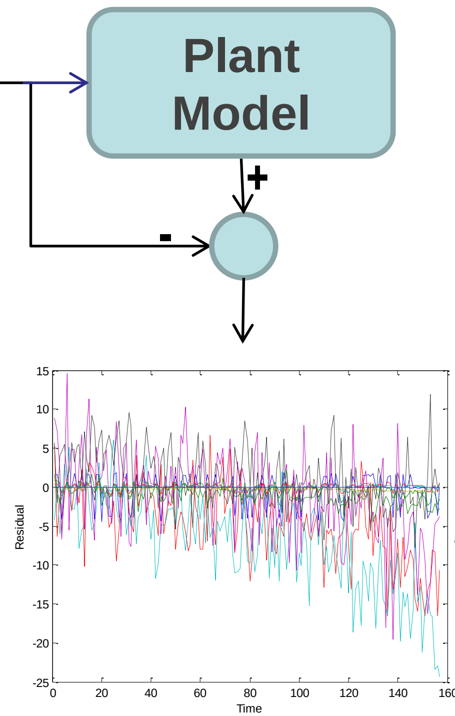
- **OLM Requirements and Technical Gaps assessment (FY12)**
- **Quantifying uncertainty in OLM results (FY13)**
  - Develop a model-neutral mathematical framework for estimating uncertainty in OLM under normal and anomalous plant operation conditions
- **Establishing methods for virtual sensors and signal validation (FY14)**
  - Evaluate how uncertainty drives minimum detection limits
  - 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 (FY15)**
  - Evaluate effect of proposed next generation I&C systems on OLM
- **Transition to demonstration in a suitable test-bed or operating plant (FY15/FY16)**
- **Budget**

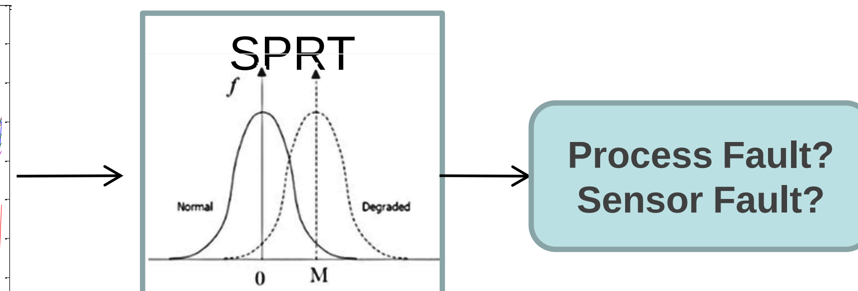
| FY12 | FY13 | FY14 | FY15 | FY16 |
|---|---|---|---|---|
| 225K | 304K | 310K | 500K | 500K |

# Technical Approach: Online Monitoring Overview

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



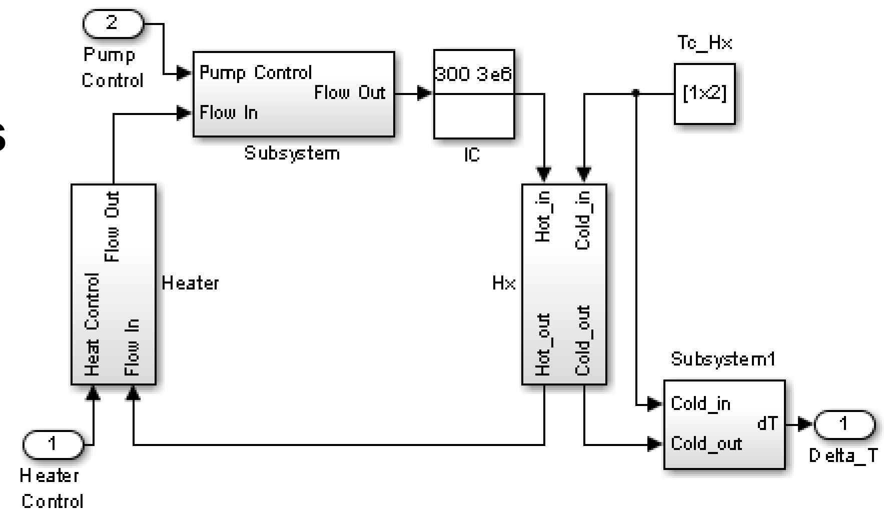



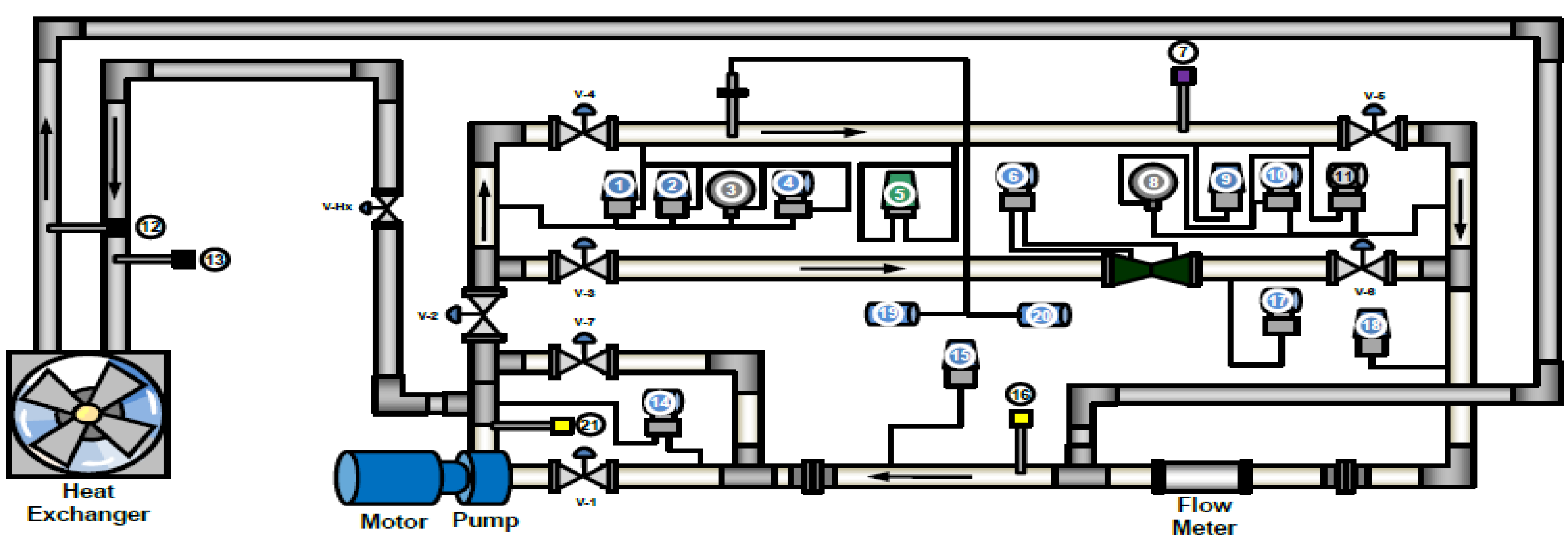
# Technical Approach: Uncertainty Quantification

- **Several possible approaches to UQ**
  - Deterministic sampling approaches
  - Stochastic approaches
  - Generalized linear model, Multivariate adaptive regression splines model
  - Multi-output Gaussian process model, polynomial chaos model
- **Evaluating approaches to determine appropriate UQ methodology**
  - Bayesian model selection (Bayesian LASSO, Bayesian Elastic net, etc.)
  - Cross-validation approaches
  - Evaluation based on information criteria (Akaike information criteria (AIC), Bayesian information criteria (BIC), etc.)
- **Validation of UQ methodology using simulated and experimental data**
  - Bayesian model calibration
  - Cross-validation approaches
  - Validation based on Mean Squared Prediction Error (MSPE)

# Data from Simulations and Testbeds to Evaluate UQ Methodology

- **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



# FY 12 Accomplishments

- **Reviewed state of the art in OLM for sensor calibration assessment and identified technical gaps (PNNL-21687)**
  - Standardized approach to uncertainty quantification
  - Method to establish acceptance criteria and evaluate the effects of acceptance criteria on plant setpoints
  - Method to provide virtual sensor estimates for unavailable measurements
  - Evaluation of the effects of digital I&C, wireless communication, and emerging sensor types on OLM
- **Development of initial research plan to address gaps**
  - Technical development to address gaps in FY13 – FY15
  - Demonstration in FY16
- **Journal/Conference papers**
  - “Extending Sensor Calibration Intervals in Nuclear Power Plants,” 2012 ANS Winter meeting
  - “Calibration Monitoring for Sensor Calibration Interval Extension: Identifying Technical Gaps,” 2012 Future of Instrumentation International Workshop

# FY 13 Activities

- **Development of preliminary framework for uncertainty quantification**
  - Comparison to current practices

- **Evaluation of UQ framework with simulated and experimental data**
  - Nominal operation
  - Anomalous operation (sensor faults and process faults)

- **Journal/Conference Papers**
  - “Online Sensor Calibration Assessment in Nuclear Power Systems,” *Invited paper*, IEEE I&M Magazine (to be published June 2013)
  - Planned presentation at ANS Utility Working Conference (August 2013) (Title TBD)

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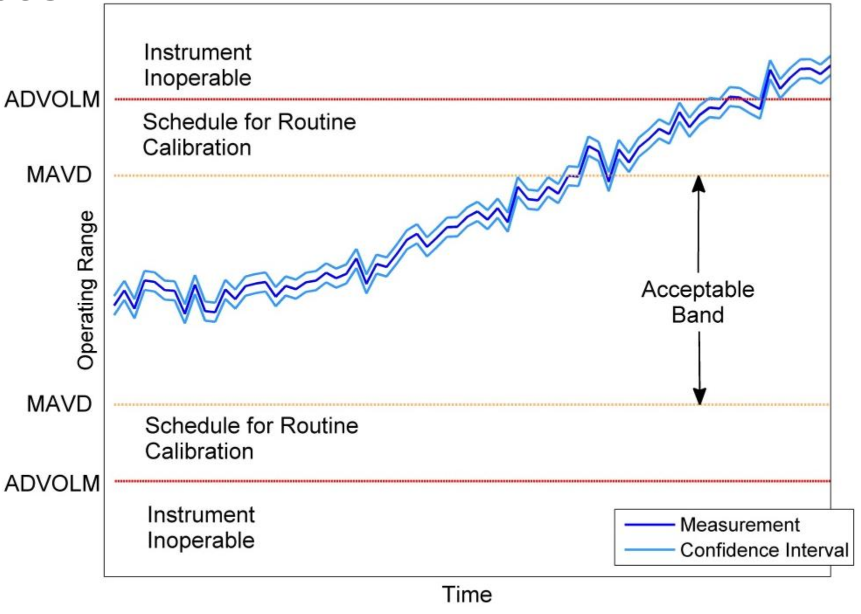
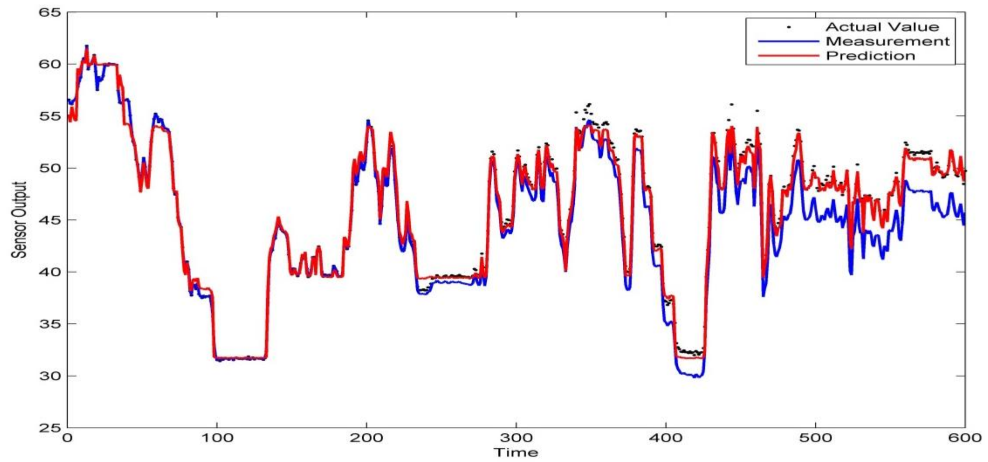
# Technical Approach: Signal Validation & Emerging I&C

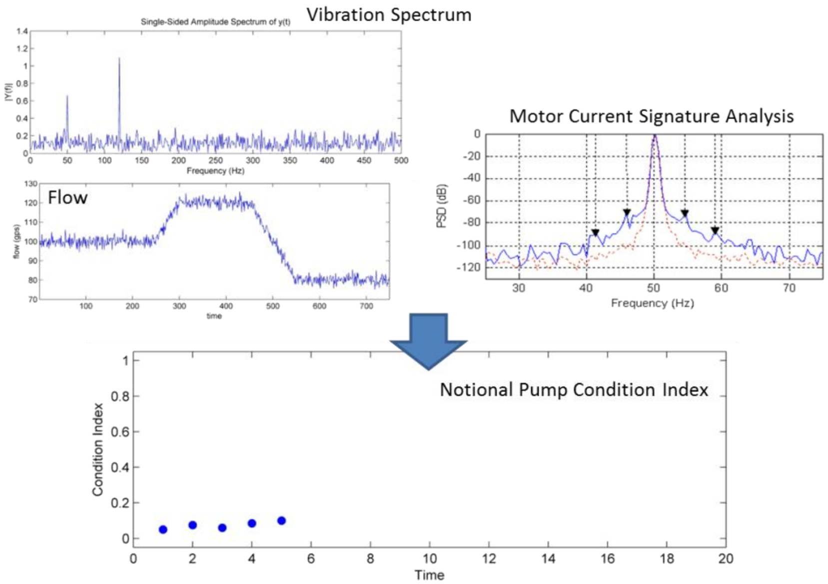
- **Proposed OLM programs require periodic recalibration of a limited set of sensors**
- **Signal validation could potentially alleviate that requirement with high-confidence assessment of sensor status**
  - Accurate uncertainty quantification
  - Combining disparate information sources
- **Signal validation approaches can also be used as a preprocessing step before advanced monitoring and control algorithms to ensure decisions are based on quality data**
- **OLM requirements using emerging I&C technologies unknown**



# Technical Approach: Virtual Sensors

- OLM estimates can replace faulty sensor measurements
  - Uncertainty must account for spillover of faulty reading into estimate




- Measurements can be combined to provide additional signatures that aren't currently measureable

# Planned Accomplishments

- **FY14**
  - Virtual sensors: Robust algorithms for estimating derived values for parameters that cannot be directly measured
  - Data integration methods for high-confidence signal validation
- **FY15**
  - Integrate UQ methods with virtual sensors and signal validation approaches
  - Methods to quantify effects of new sensing approaches and digital I&C on OLM
- **FY16**
  - Demonstration in a lab-scale system or secondary system at an NPP partner site

# Crosscutting Benefits

- **Project team interacting with cognizant experts from various DOE-NE programs to ensure broad-based input (e.g., LWRS, SMR, ARC, AF, MPACT)**
- **Interacting with industry experts to leverage current practices in OLM and UQ**
- **Defined list of requirements through survey of published literature and industry practices**
  - Uncertainty quantification
  - High-confidence signal validation
  - Virtual sensor estimation
- **Continued interactions**
  - Continue to engage experts in various DOE-NE programs
  - Participate in program reviews to gain input and concurrence from cognizant experts

# Crosscutting Benefits: LWRS, SMR, ARC, and NGNP

- **Unobtrusive assessment of sensor calibration**
  - Relaxation of interval-based recalibration requirements in favor of condition-based recalibration – reduced or eliminated unnecessary maintenance
  - Ensures performance of proposed sensors
  - Supports longer operational cycles, reduced maintenance requirements, and remote siting
- **Virtual sensor estimation**
  - Derive estimates of currently unmeasureable parameters
- **Potential applications in accident scenarios and transients**
  - Assess sensor measurement accuracy during accidents and transients
  - Provide necessary confidence in measurements during accidents using the virtual sensor concept
- **Signal validation as essential data preprocessing step for supervisory control and advanced health monitoring systems**

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# Crosscutting Benefits: AF, MPACT, UNFD

- **Sensor reliability assessment for new sensor technologies**
  - Ultrasonic sensors
  - Fiber optic sensors
  - Operation in harsh environments
- **Real-time validation of large data streams for process monitoring in fuel reprocessing plants**
  - Differentiating between sensor/detector faults and process changes
- **Potential application to monitoring performance of sensors in long-term used fuel storage facilities**
  - Applicability can be evaluated as sensor suites are designed and developed

# Transition to Competitive Research

- **Anticipated outcome for FY13**
  - Preliminary framework for uncertainty quantification
    - Model-neutral approach
    - Estimate uncertainty sources directly from data

- **Research areas for FY14-16**
  - Methodology for providing virtual sensor estimates and high-confidence signal validation
    - Integrate with UQ methodology
  - Evaluation of the effects of emerging sensors, digital instrumentation, and wireless transmission
  - Demonstration in an appropriate test-bed or facility will be necessary to ensure outcomes are tangible

# Conclusion

- **Research focused on addressing high-impact technical gaps to developing a standardized framework for 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.)