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Nuclear Energy Enabling Technologies (NEET)

Advanced Sensors and Instrumentation (ASI) Annual Project Review

Design for Fault Tolerance and Resilience

Richard Vilim, ANL
Ken Thomas, INL

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Project Overview

Goal

- To improve operational reliability, improve nuclear safety, and reduce human error through the development of advance NPP control automation in lieu of procedure-based operator actions.

Objectives

- Develop technology to assist and support operators with complex fault diagnosis and selection of appropriate mitigation control actions
  - Advises NPP control room operators of the time-critical plant conditions and allows them to enable an automated response to mitigate the fault.
- Develop fault detection and diagnosis technologies that underlie the operator support technology
- Demonstrate on full-plant simulator

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Project Overview

Participants

- Rick Vilim, Alex Heifetz, Young Park, Stefano Passerini (ANL)
- Wen Pu (UIUC)
- Ken Thomas (INL)
- Ron Boring (INL - associated research staff for the Human Systems Simulation Laboratory)

DOE-R&D programs benefitting from this work

- Light Water Reactor Sustainability (LWRS) Program
- Small Modular Reactor (SMR) Program
- Advanced Reactor Concepts (ARC) Program

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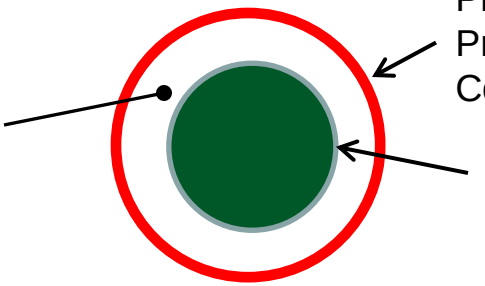
Technology Impact

- **Trade-off today between automatic versus operator control**
  - Automatic system actions required when there is insufficient time for operators to diagnose and respond to fast-moving design basis events – These events result in reactor trips and safety actuations
  - Procedure-based actions preferred for less time-critical situations where operators can make a more accurate diagnosis and more nuanced control
- **Certain events handled manually by operators today would benefit from new technology that combines the best of both: fast automatic response with accurate diagnosis and nuanced actions**
  - Would mitigate plant transients much quicker and avoid reactor trips and safety system actuations



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Research Plan

Today

Envisioned

Sensor Validation

Algorithms and Computation

First Principles Models

Enhanced Operator Diagnostic Alarms and Display

Library of Scripts for Corrective Actions for Specific Faults

Automated Control Using Computer-Based Procedures

Confirmation of Desired Fault-Response Outcome

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Research Plan (cont'd)

- **FY 2012: $600K**
  - Algorithms and Integration
    - Begin task of modernizing fault detection and identification algorithms and software
  - Operator Support Technology
    - Identify opportunities for automated control in place of procedures-based manual control
- **FY 2013: $300K**
  - Algorithms and Integration
    - Complete enhancements to the PRODIAG software package
    - Begin application of fault diagnosis algorithms to non-safety grade function of the CVCS
  - Operator Support Technology
    - Install a systems code on the simulator complete with input deck for generic light water reactor
- **FY 2014: $500K**
  - Algorithms and Integration
    - Complete integration of fault diagnosis software and control algorithm simulation capability
  - Operator Support Technology
    - Develop script-based prompting and conduct human factors assessment of operator support technology
- **FY 2015: $500K**
  - Algorithms and Integration
    - Perform full-scale simulator tests of integrated fault diagnosis and automated control for range of faults
  - Operator Support Technology
    - Advance simulator capability for demonstration to utility industry

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FY 2012 Accomplishments

- **Design to Achieve Fault Tolerance and Resilience, INL/EXT-12-27205, September 2013.**
  - Describes opportunities for replacing procedure-based manual control with automated control
  - Describes issues and approaches associated with NPP run-back to house loads following loss-of-load transient
- **Description of Fault Detection and Identification Algorithms for Sensor and Equipment Failures and Preliminary Tests Using Simulations, ANL/NE-12-57, November 30, 2013.**
  - Presents results from Algorithm for Transient Multivariable Sensor Estimation (AFTR-MSET) for detecting sensor degradation and substitution of the degraded sensor reading with a high-quality estimate
  - Presents findings of review of PRODIAG for diagnosing component fault
  - Describes plan to modernize PRODIAG automated reasoning capabilities

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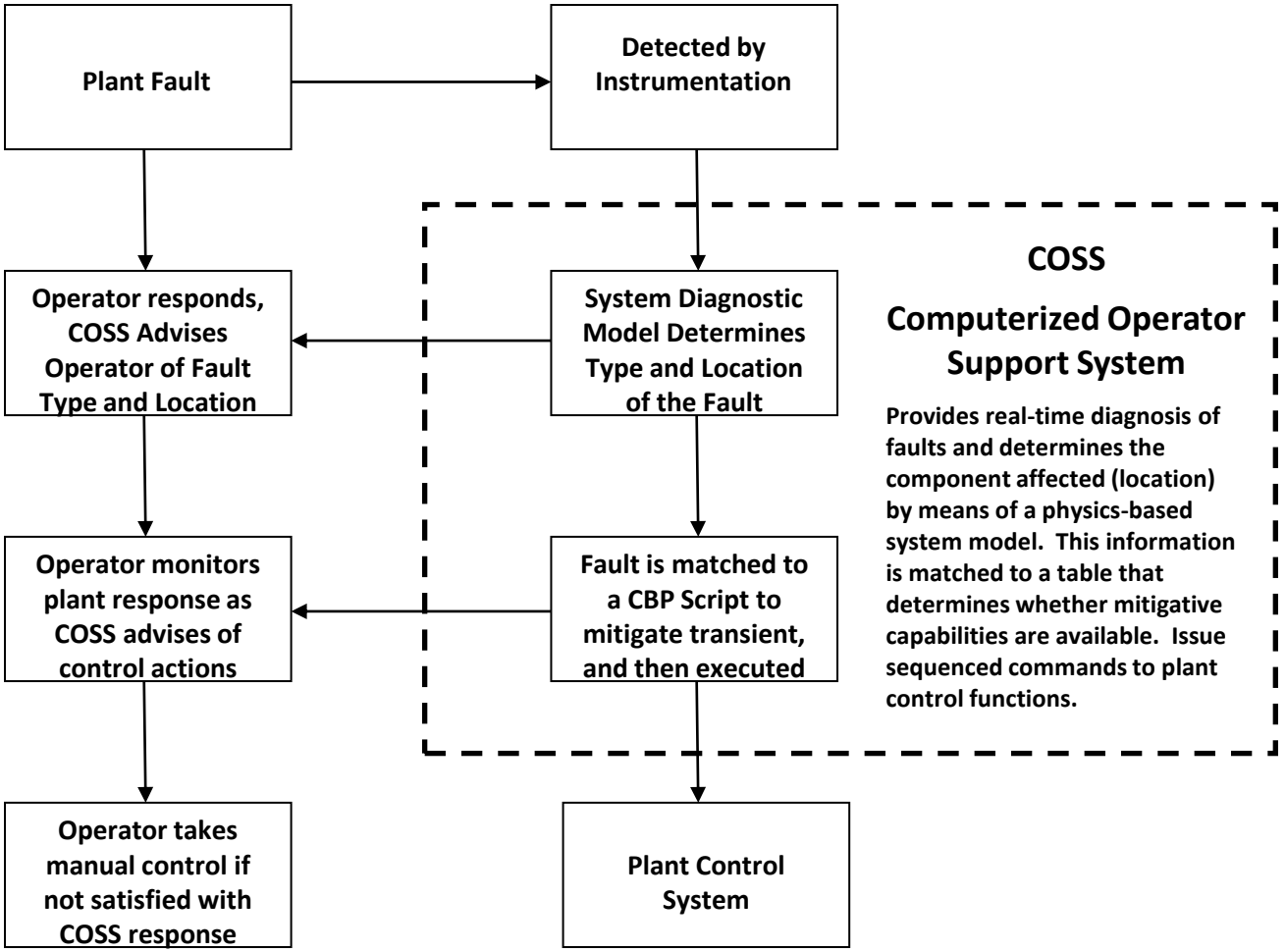
FY 2013 Activities

Operator Support Technology for Fault Diagnosis and Mitigation



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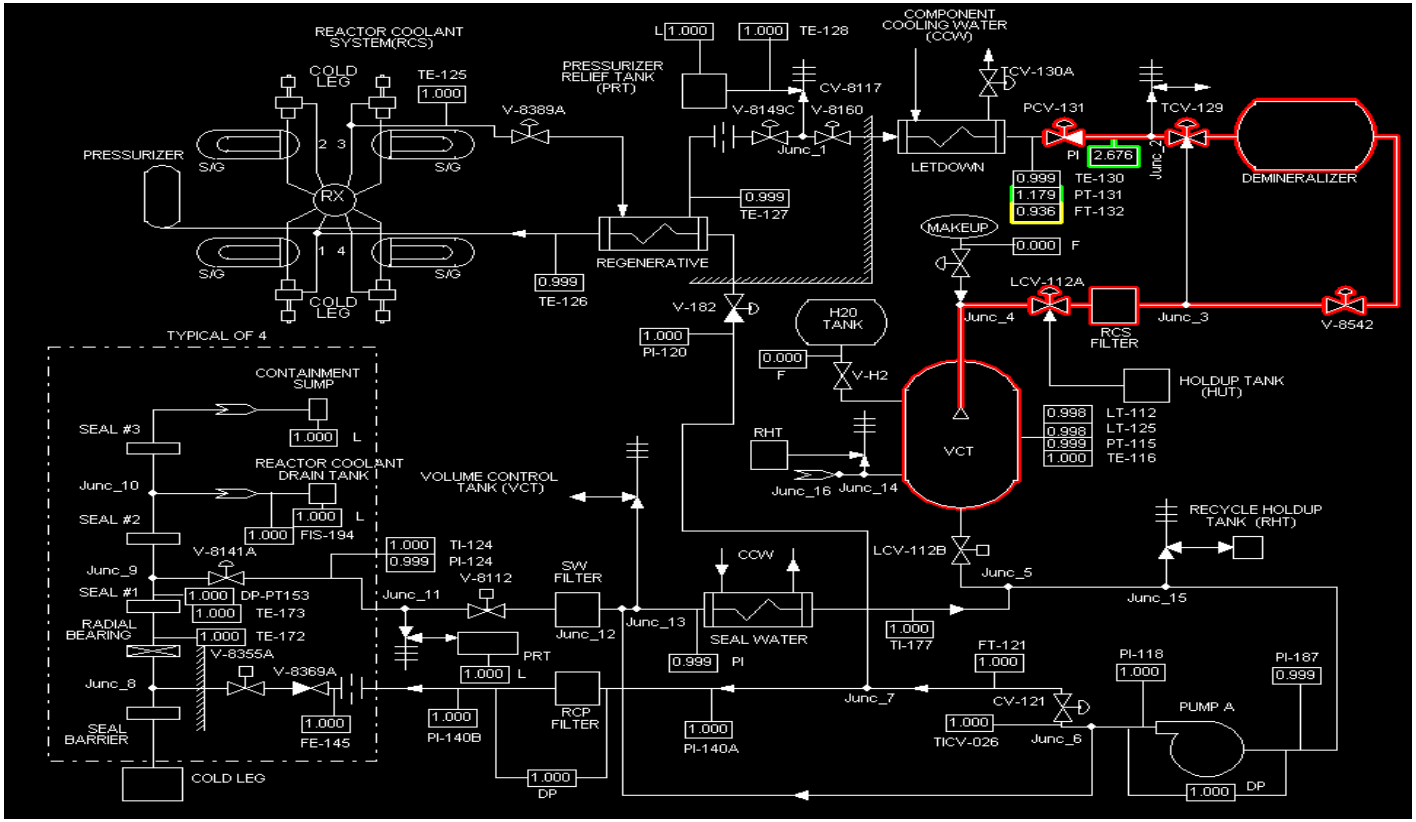
FY 2013 Activities

- **Equipment Fault Diagnosis – Detected before Operator Sees It**



GUI Highlighting Location of Fault in CVCS

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FY 2013 Activities

- **Development Path**
  - Leading up to eventual integration of ANL and INL technologies
  - Focusing on faults in the Chemical and Volume Control System
    - Leak rate larger than make-up capability
    - Today operator trips the reactor if leak exceeds make-up capability
    - New Operator Support Technology determines leak location, alerts the operator, and directs the control system to isolate the leak
    - Benefits
      - No reactor trip, No challenge to safety and shut-down systems, No thermal cycling of virtually all plant components, Continued electric generation, No regulatory impact
- **Algorithms and Integration (ANL)**
  - Complete automated reasoning engine in fault diagnosis code
  - Conduct comprehensive tests of fault diagnosis on CVCS

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FY 2013 Activities

Operator Support Technology (INL)

- Program the CVCS fault including the simulated diagnostic technology
- Define and develop the operator alarm display
- Develop and demonstrate the fault scenario

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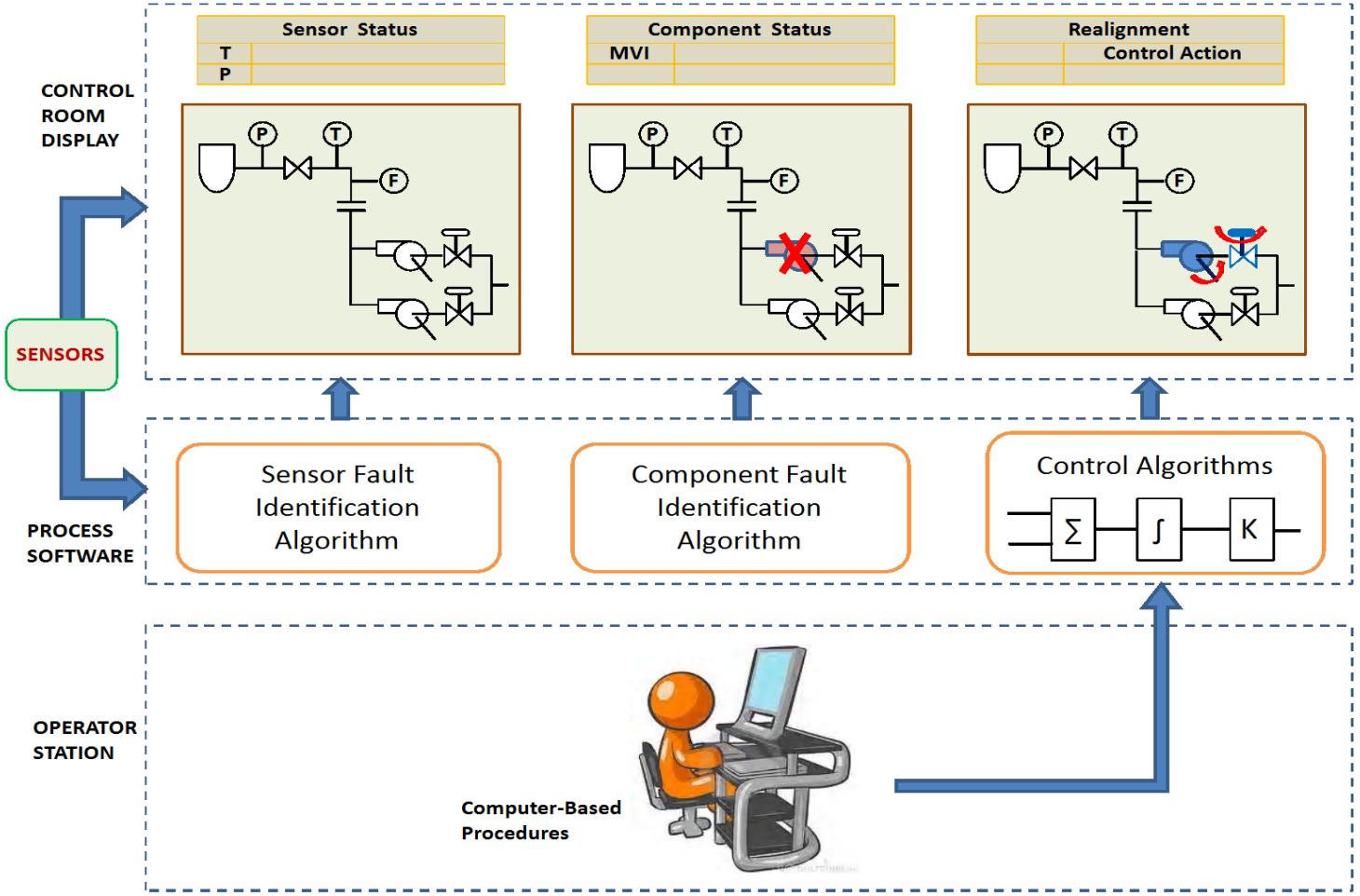
Planned Accomplishments



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Planned Accomplishments

- **FY14**
  - Algorithms and Integration
    - Complete current generation component fault-diagnosis algorithm development and testing
    - Identify technology extensions for next generation component fault-diagnosis algorithms
  - Simulator and Human Factors
    - Write wrappers for porting fault-detection and diagnosis software to full-scale simulator
    - Develop computer-enabled implementation of control algorithms for simulator
- **FY15**
  - Algorithms and Integration
    - Develop extensions for next-generation component fault-diagnosis algorithms
  - Simulator and Human Factors
    - Develop fully-integrated operator-support system for demonstration including fault detection, fault diagnosis, and control actions to mitigate fault
    - Develop script-based operator prompting
    - Conduct human factors assessment of the operator-support technology
- **FY16**
  - Integrated Demonstration
    - Perform full-scale simulator shakedown tests of integrated fault diagnosis and automated control for a representative spectrum of faults
    - Develop technical requirements for broad application of the operator support technology across multiple plant systems

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Crosscutting Benefits

- **Light Water Reactor Sustainability (LWRS) Program**
  - Enhancing plant reliability and reducing human error through plant control automation is a key aspect of the LWRS Advanced I&C
  - Opportunity for early testing of prototype and path to technology maturation
- **Small Modular Reactor (SMR) Program**
  - SMRs will require significant reductions in staffing to be economical
  - Reduction in operator workload by automating control for upset recovery
- **Advanced Reactor Concepts (ARC) Program**
  - ARC designs will likely have advanced digital control systems providing a platform to host automated control capabilities
- **Utilities**
  - Engaged a utility with an interest in long-term deliverable of the project

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Transition to Competitive Research

- **Enables Next-Generation Advanced Control Capabilities for Plant Operation Under Digital I&C System**
  - Apply across plant-wide systems
  - Integrate into plant procedures
- **Anticipated Hand-Off to Industry to Occur Upon Successful Utility Demonstration**
  - Transfer of intellectual property
- **Industry Commercialization Tasks**
  - Shrink-wrap and bullet-proof software
  - Operator interface for use by non-experts
  - Vendor for distribution and training

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Conclusion

- **Next-Generation Operator Support Technology**
  - Improves operational reliability
  - Improves nuclear safety
  - Reduces human error through the development of advance NPP control automation in lieu of procedure-based operator actions.
- **Directly supports upcoming development work in the LWRS II&C pathway**
- **Enables advanced concepts of operation for new reactor types, including SMRs, and particularly facilitates control of multiple reactors by operators**
- **Represents a natural outgrowth of the advanced distributed control systems now being implemented in many of the current operating plants**