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Nuclear Energy Enabling Technologies (NEET)

Advanced Sensors and Instrumentation (ASI) Annual Project Review

Embedded I&C for Extreme Environments

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Project Overview

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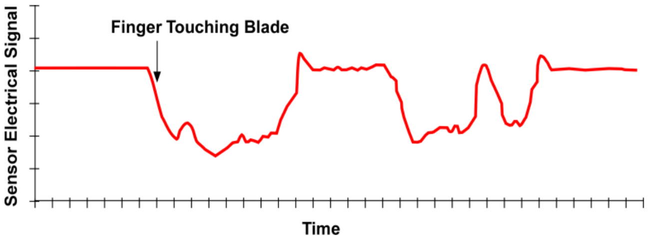
Goal and Objectives

- The overall goal is to demonstrate performance and reliability improvements possible in major **power reactor system** components when sensors and controls are deeply integrated
- Challenge: make desirable functions possible using embedded I&C
  - Railroad — AC traction drive locomotives enables 50% thrust increase
  - Industrial tools— Sawstop® prevents saw blade amputations
  - Aircraft/Aerospace — stabilizing fundamentally unstable wing configuration
- The project will design, fabricate, and demonstrate a reactor coolant pump employing embedded I&C (for multiple reactor types ~700°C)
- This demonstration of prototypic high-temperature cooling pump, useful in its own right, shows a path for future embedded design efforts

Locomotive AC Traction Motors



Sawstop® Blade Current Signal

Delta Wing Aircraft

Project Overview (2)

- **Participants — Work performed using ORNL staff and facilities**
  - Principle Investigator: Roger Kisner
  - Control Systems: Alex Melin, David Fugate, Roger Kisner
  - Sensor Systems: Roger Kisner, David Holcomb, Tim Burress
  - Motor Design: John Miller, Tim Burress
  - Mechanical/Hydraulic Systems: Alex Melin
  - Magnetic Design: John Wilgen
  - Electronics Design: Roger Kisner, David Fugate, Tim Burress
  - Material Science: Dane Wilson, David Holcomb
  - Summer Interns: Electrical Engineering, Mechanical Engineering
- **LWRS, SMR, ARC, NGNP, and FCT programs will benefit from this work**

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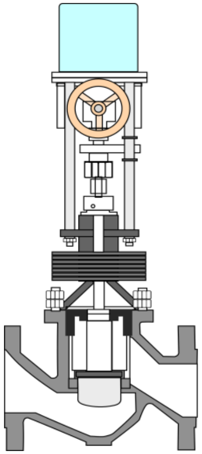
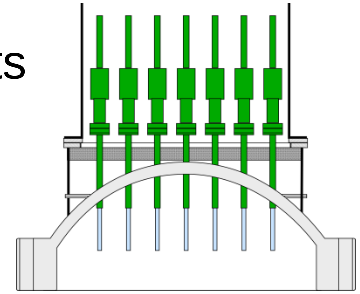
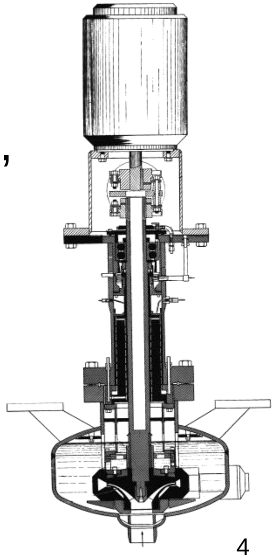
Crosscutting Benefits

- **Research directly benefits DOE-NE R&D programs and initiatives**
  - SMRs, Na reactors, gas reactors, and fluoride salt reactors
  - LWR Life Extension
  - Advanced Reactors (high temperatures)
  - Space Power Systems
- **Embedding concept is relevant to many components of a nuclear reactor**
  - Pumps, control rod drives, valves, circuit breakers, …
  - Elevates components (and systems) to new levels of performance, stability, diagnostics, and prognostics
  - Applies to primary systems and BOP components
  - New reactor designs and retrofit







Crosscutting Benefits (2)

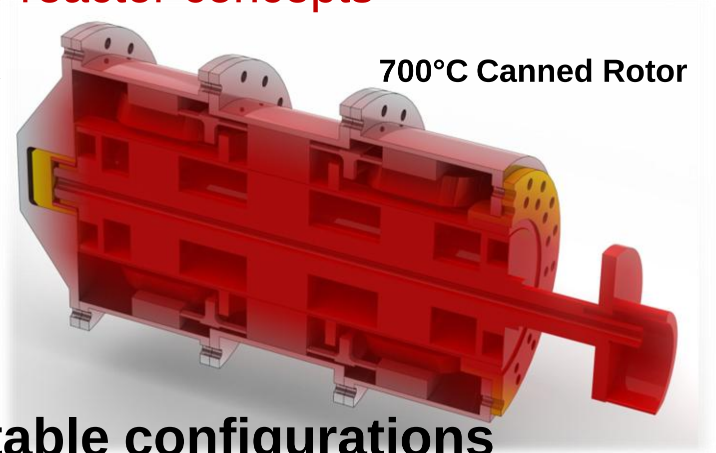
- **Benefits of embedding are being validated and coordinated**
  - All nuclear power plant classes require coolant pumps
  - Highly relevant demonstration in a representative environment
- **Pump seals and bearings are maintenance intensive**
  - Pump seals and bearings are have been historic source of problems in nuclear power applications
  - Helium circulator seal leaks were a significant source of problems at Fort St. Vrain
  - Pump seal leaks were root cause of Simi Valley sodium reactor accident
  - Pumps possess large kinetic energy with potential for causing damage
- **What are the outcomes and measures of success**
  - Demonstration in a coolant loop system
  - Future demonstration of embedded I&C in other reactor systems
  - Demonstration that embedded I&C makes otherwise unattainable performance in nuclear power components possible

Crosscutting Benefits (3)

- **The Light Water Reactor Sustainability (LWRS) will benefit from this R&D through**
  - Retrofit of components having embedded I&C for extended life, high reliability, and efficiency
- **The Advanced Small Modular Reactor (SMR) Program will benefit from this R&D through**
  - Design of components that are cost effective, low maintenance, and reliable
- **Advanced Reactor Concepts (ARC) and Next Generation Nuclear Plant (NGNP) programs will benefit from this R&D through**
  - Design of components that operate efficiently and reliably in extreme environments
- **The Fuel Cycle Technologies (FCT) program could indirectly benefit from this R&D through**
  - Design of components that are low maintenance and long lived in harsh environments

Technology Impact

- **Sensors and controls have not typically been embedded in nuclear power reactor components (compared with other industries)**
  - Advanced I&C technologies were not available in the first nuclear era
  - Requires multi-disciplinary design effort — I&C, mechanical and electrical engineering, materials science, and systems engineering
  - Existing components have limitations for new reactor concepts
- **Required new component concepts may be inherently unstable**
  - Compact size
  - Less bulk material to absorb transients
  - Continuous high temperature operation



- **Embedded I&C stabilizes otherwise unstable configurations**
  - Intimate real-time control
  - Reporting of degradation
  - Appropriate responses to failure and degradation events
  - Opportunity for fault-tolerant control

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Technology Impact (2)

- **Advancing the state-of-the-art in nuclear systems**
  - Traditional approach to large component design is to include mass, large margins, and tolerate inefficiency as cost of doing business
  - Close coupling of I&C with electromechanical system components permits design with minimal mass and appropriate margins leading to lower cost, higher performance, and improved reliability (modern jet engines have experienced a **1000X reliability improvement** with embedded I&C)
- **Embedded I&C can help DOE-NE meet three of four primary research objectives from R&D Roadmap**

✓1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors

✓2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals

✓3. Develop sustainable nuclear fuel cycles

4. Understand and minimize the risks of nuclear proliferation and terrorism

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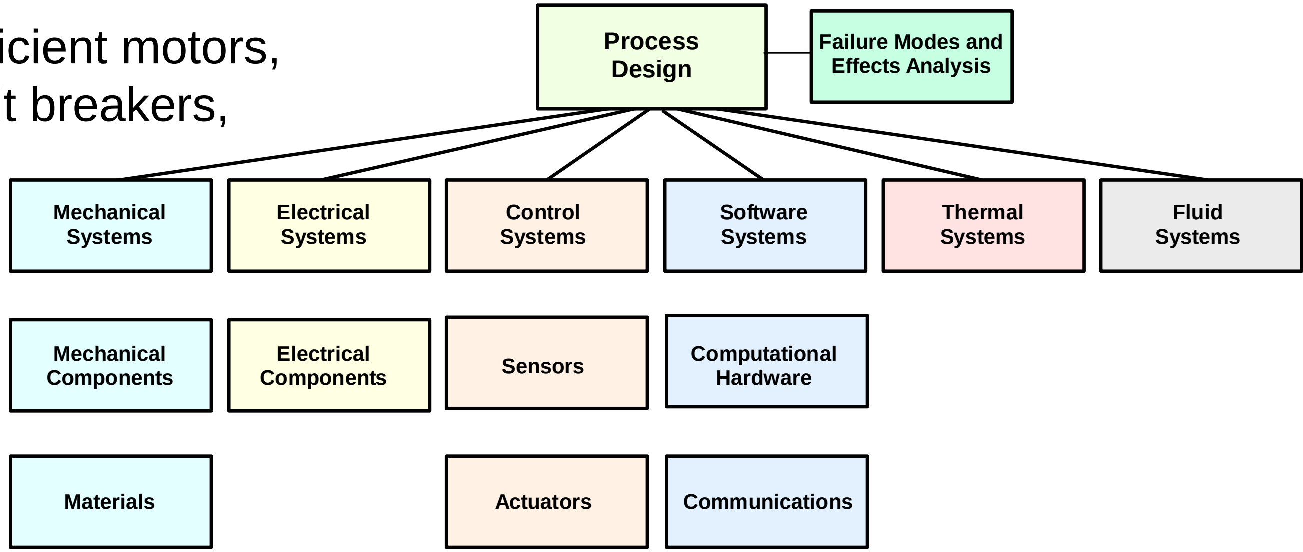
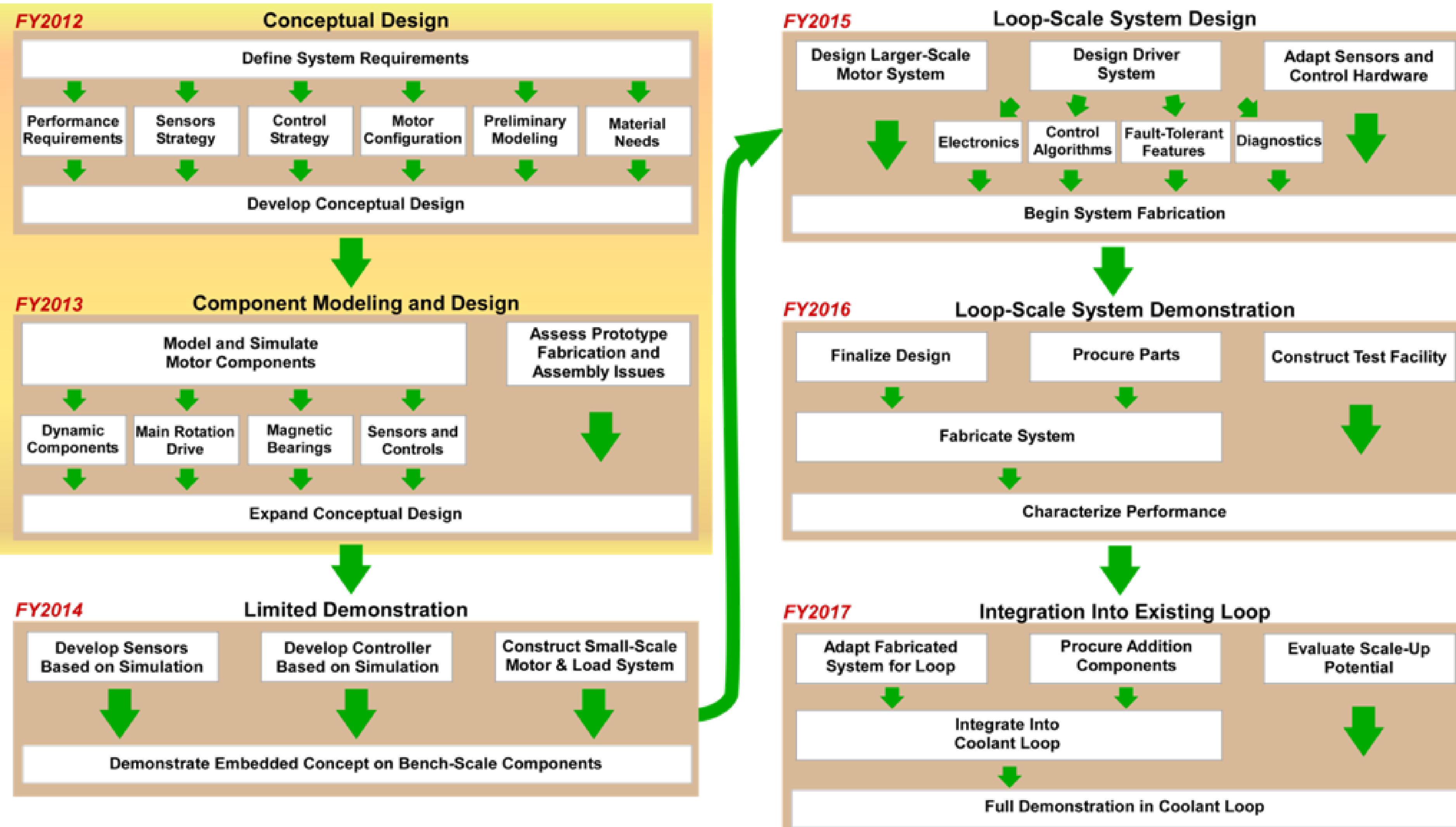
Technology Impact (3)

Technology affects the nuclear industry

- Working system demonstration provides needed confidence to allow designers to rely on integrated measurements and controls to provide robustness and efficiency
- Embedding I&C where they have not been before in major components of a nuclear power plant changes capabilities and takes I&C to new level
- Integrated measurement and controls practices can be applied to many component types
- More reliable and efficient motors, pumps, valves, circuit breakers, control rod drives, …



Planned Progress



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Research Plan (Original Proposal)

- **FY2012 - $500 K**
  - Create implementation plan
  - Identify performance requirements for nuclear plant operation
  - Model preliminary system and its performance
  - Investigate material requirements
  - Develop conceptual design
- **FY2013 - $270 K**
  - Model and simulate motor components
    - dynamic components (rotor assembly)
    - main rotation drive
    - magnetic bearings
    - sensors and controls to simulate the embedded characteristics
  - Assess fabrication and assembly issues that apply to prototype construction

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Research Plan (2)

- **FY2014 - $400 K (original plan)**
  - Develop sensors and controller concept based on simulation results including sensorless position measurement capability
  - Construct small-scale (table-top) motor/load
  - Demonstrate embedded concept on the small-scale motor
- **FY2015 - $490 K (original plan)**
  - Design larger-scale motor system (~10 kW motor)
  - Design driver electronics and control algorithms with fault-tolerant features
  - Adapt sensors and controller developed previously to larger system
  - Begin system fabrication
- **FY2016 - $500 K (original plan)**
  - Finalize design and fabricate larger demo system
  - Construct testing facility that generates 700°C environment
  - Characterize performance of mechanical, sensing, and control systems
- **FY2017 - $430 K (original plan)**
  - Integrate demo into coolant loop test facility
  - Perform scale-up evaluation

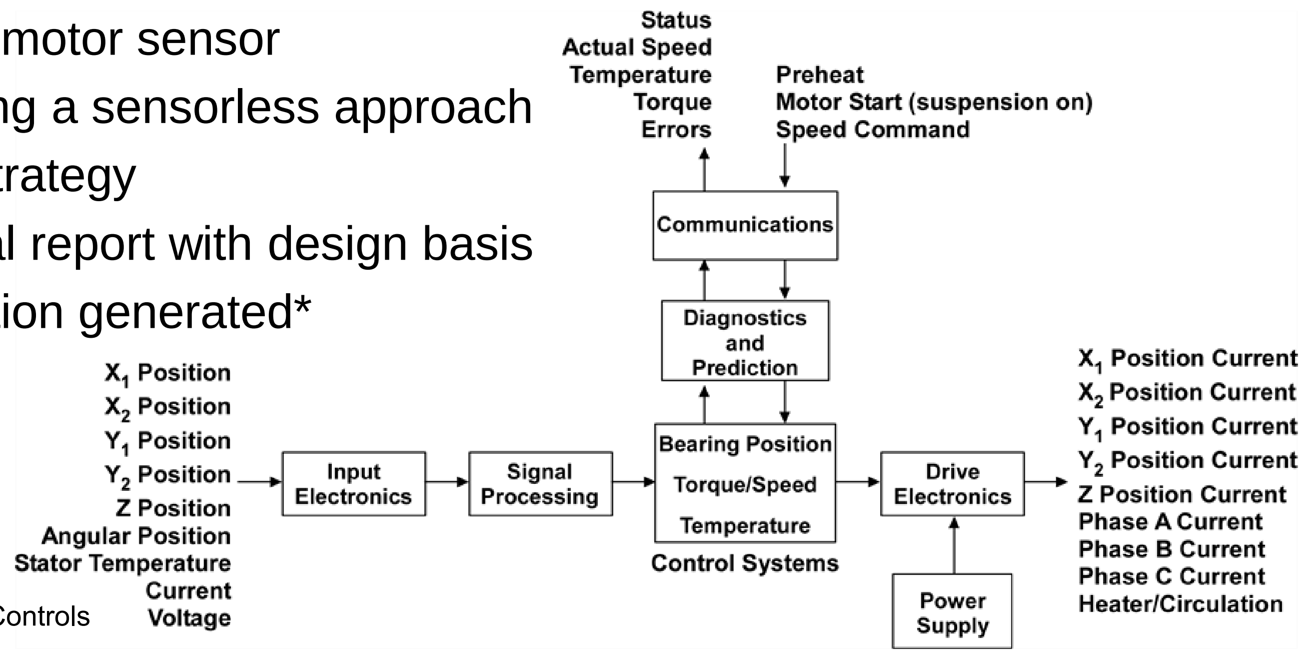
FY-2012 Accomplishments

Established motor performance requirements

- Motor drive configuration determined — reluctance drive
- Failure modes and effects analysis was conducted
- Preliminary engineering calculations and modeling performed

Conceptual design for embedded I&C components

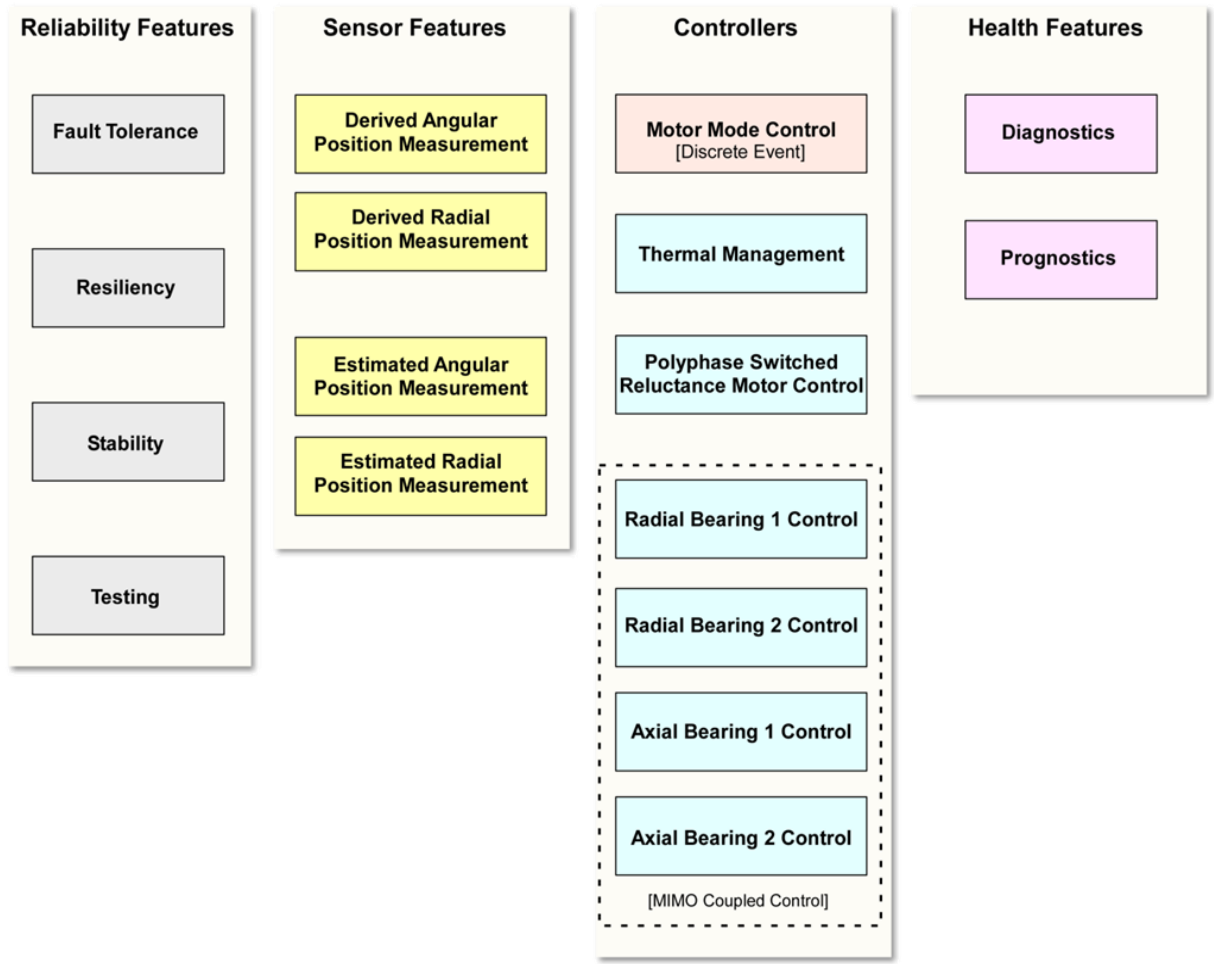
- Identified significant motor sensor technologies including a sensorless approach
- Developed control strategy
- Produced conceptual report with design basis and backup information generated*



* R. Kisner et al., “Embedded Sensors and Controls to Improve Component Performance and Reliability,” ORNL/TM-2012/433, Sept. 2012

FY-2012 Accomplishments (2)

- **Identified engineering issues in embedded concept**
  - Control of coupled response between motor torque and forces on magnetic bearings
  - Control of natural oscillatory modes and frequency response of S&C
  - Magnetic materials for high temperature environment
  - Design for minimizing magnetic gap
  - Insulation at high temperatures



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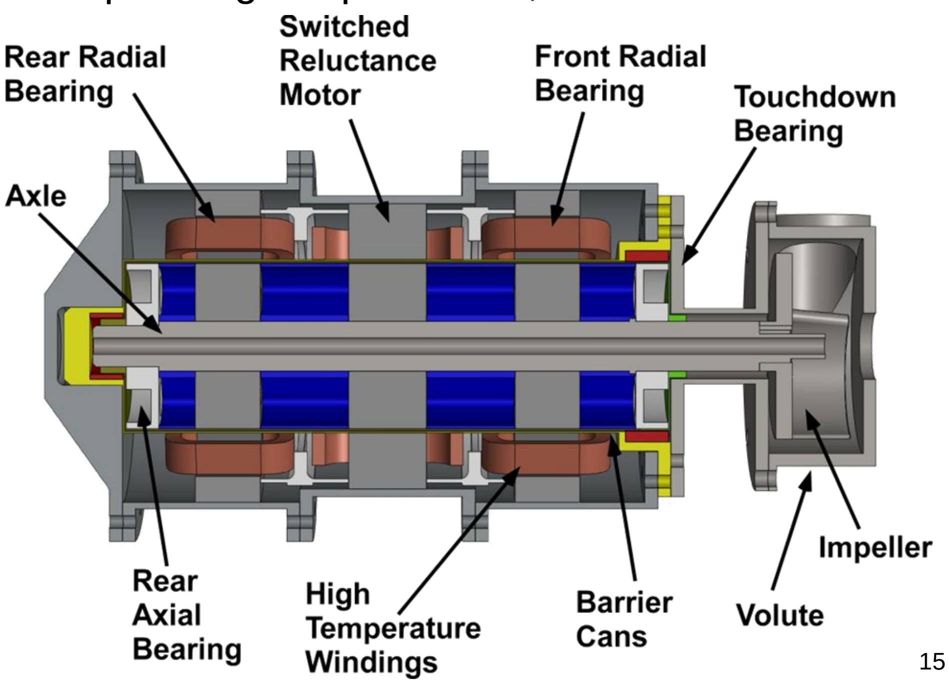
FY-2012 Accomplishments (3)

- **Motor/Pump prototype demonstrates the following**
  - Coupled, multi-axis, high-speed position control
  - Intrinsic sensing in support of operations and maintenance
  - Embedded high-temperature sensors
  - Fault-tolerant computing and controls including graceful degradation, and
  - High-temperature magnetic actuators
- **Canned rotor design has no rotating fluid seals**
- **Unstable without continuous stream of control signals**

- **Challenging measurements**
  - No penetrations (eliminates virtually all conventional sensing methods)
  - High temperatures (limits material selection)
  - Harsh environment — FliNaK (LiF 46.5%, NaF 11.5%, and KF 42%), melt = 459C, operating temp. = 700C, corrosive



FY-2013 Activities

- **Model sensors and controls for canned rotor magnetic system**
  - **PURPOSE:** Gain a sufficient understanding of the dynamic mechanical system functioning and potential degradation to create detailed sensor, actuator, and control system
  - **WORK PRODUCT/DELIVERABLE:** Models and simulation results of sensors and controls for the magnetic suspension and drive system
  - **MILESTONE:** September 30, 2013, report
- **Assess methods of fabrication and assembly**
  - **PURPOSE:** Gain sufficient understanding of materials, methods of fabrication, and methods of system assembly to apply to the creation of detailed sensors, actuators, and control systems as well as machine design
  - **WORK PRODUCT/DELIVERABLE:** Evaluation of effective methods to fabricate motor components and assemble as a working unit
  - **MILESTONE:** July 29, 2013, report

FY-2013 Activities (2)

- **Working concurrently with ORNL research group investigating reluctance motors for transportation applications**
  - Hardware is being adapted for bench scale testing
  - Investigating the effect of gap and rotor can material (Alloy N)
- **Invited paper for IEEE I&M Magazine***
  - Appearing as a feature article in the June 2013 edition
  - Discusses challenges of harsh environments for a canned rotor motor with embedded control

* A. Melin, R. Kisner, and D. Fugate, "Advanced Instrumentation for Extreme Environments," IEEE I&M Magazine, Vol.16, No. 3, June 2013.

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Planned Accomplishments

- **FY2014**
  - Sensorless position measurement capability designed and tested
    - Uses actuation magnetics to supplement perhaps replace independent sensors
    - Based on simulation results
  - Small-scale (table-top) motor/load constructed
    - Less than 1 kW, not to full operating temperature
    - Main rotation drive with magnetic bearings
    - Capable of modifying motor parameters for simulation results comparison (gap)
    - Electronic drive consisting of IGBJT electronics package and computer for implementing control algorithms
    - Variable load to simulate fluid pumping effects (mechanical motion, fluid dynamics, …)
  - Demonstration of embedded concept on the small-scale motor
    - Sensor and sensorless measurements
    - Steady-state and dynamic behavior
    - Component failures and malfunction

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Planned Accomplishments (2)

- **FY2015**
  - Larger-scale motor system designed (~10 kW motor)
    - Scaled-up from laboratory scale experiments using lessons learned and simulation results
    - Fault tolerant embedded control and driver electronics developed
    - Sensors and controller developed previously to the larger system adapted
  - Begin system fabrication
- **FY2016**
  - Final design completed
  - Larger demonstration system fabricated
  - Test facility that generates 700°C environment constructed
  - Characterized performance of mechanical, sensing, and control systems
- **FY2017**
  - Motor/pump with embedded control are installed in a coolant loop facility for demonstration
  - Perform scale-up evaluation

Transition to Competitive Research

- **The project "Embedded Instrumentation and controls for extreme environments" leads to demonstrations showing that embedding I&C in large components is technically possible, achieves desired benefits, and has commercialization potential**
  - The challenge is building components with embedded I&C in harsh environments
  - Multidisciplinary process integrates sensors, controls, software, materials, mechanical and electrical design
- **FY2014-2016**
  - A bench-scale and a loop-scale pump with embedded control is constructed and characterized
  - Fault-tolerant control, high efficiency, reliability are demonstrated
- **FY2017-2019**
  - The demonstration pump system is installed in a high-temperature coolant loop
  - Results of the loop experiments become the basis for scaling up the design to power reactor size
  - Partner with equipment manufacturers for up-scaling and demonstration
  - Additional plant components identified for application of the embedding process

Transition to Competitive Research (2)

- **High value for components in future power plants**
- **Component lifetime and reliability issues have been a contributor to maintenance costs and failure events since the beginning of nuclear power**
- **Outcome of this project adds significant value to the nuclear industry**
- **Project generates significant industry interest to continue**
  - Detailed reports made available
  - Key papers
  - Utilities and manufacturers are shown the features and benefits of embedded I&C

Conclusion

- **By successfully demonstrating the performance, reliability, and cost benefits of embedded I&C on a relevant prototypic reactor component, confidence is realized that can lead to major improvements in reactor system components for future plants**
  - Improve the reliability, sustain the safety, and extend the life of current reactors
  - Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals