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Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Embedded I&C for Extreme Environments

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NEET Program

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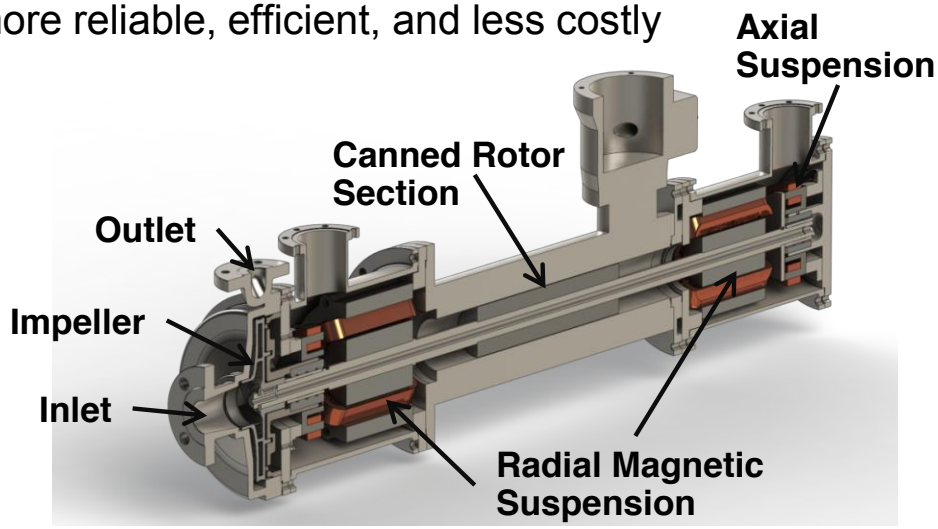
Project Overview

- **Goal, and Objectives**
  - Demonstrate performance gains possible using embedded I&C in extreme environments
    - High temperature, radiation, high pressure, high vibration, and high EMF conditions
  - Demonstrate a magnetically suspended canned-rotor motor using functional embedding
  - Affect nuclear power industry's ability to make more reliable, efficient, and less costly components
- **Participants (FY2016)**
  - R. Kisner
  - A. Melin
  - D. Fugate
  - C. Johnson
  - D. Holcomb
  - R. Vidrio
- **Schedule**
  - Phase I Low Temperature Demonstrations
    - 2015 Bench Test Bed
      - Design and built Bench-scale testbed
      - Achieve stable feedback control of bench-scale active magnetic bearings
    - 2016 Loop Device
      - Design and built loop-scale testbed
    - 2017 Operating in Loop
      - Integrate into loop then test
      - Self-generated position feedback
  - Phase II High Temperature Demonstration
    - 2018 and beyond



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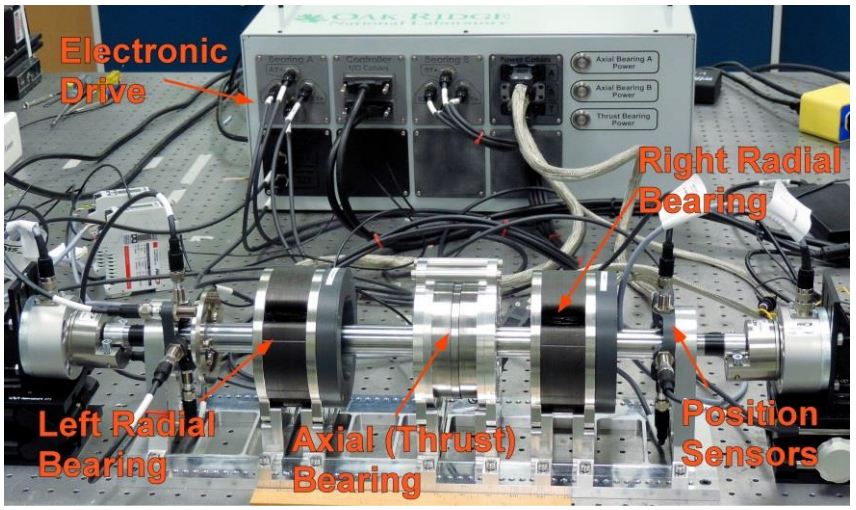
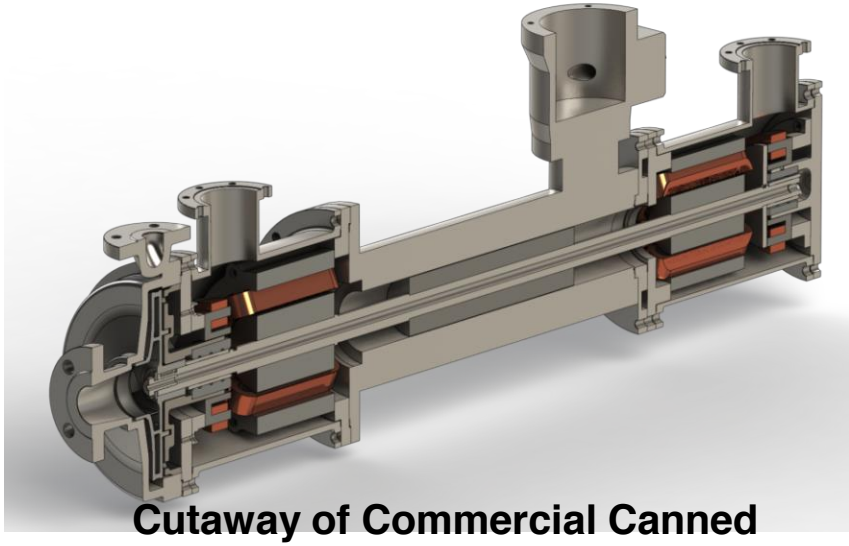
Embedded Instrumentation & Controls Yields Significant Advantages

- Demonstrate performance gains using embedded instrumentation and control (I&C) technologies in extreme environments
  - Enables faster control reaction and increased stability in the event of component failures compared with traditional control
  - Makes stable inherently unstable configurations for smaller, lower mass, lower cost, more reliable components
  - Modern jet engines have experienced a 1000X reliability improvement with embedded I&C
- ORNL is building a magnetically suspended, canned-rotor pump as demonstration platform
  - Pump seals and bearings are maintenance intensive and lead to a good demonstration
  - Demo planned for submerged water loop but technology is extendable to 700 °C in various fluids



Magnetic Suspension Demo Platform



Cutaway of Commercial Canned Rotor Being Outfitted With Magnetic Suspension

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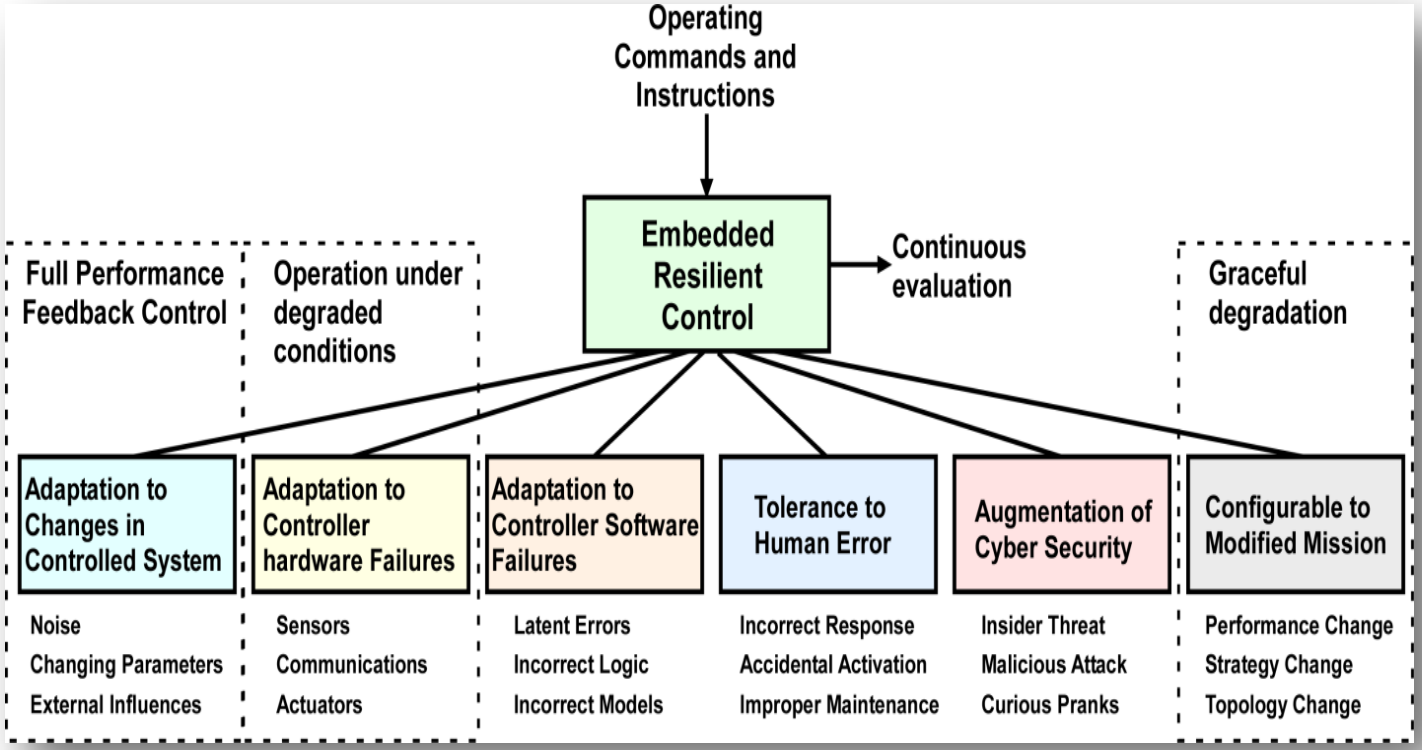
Embedded Systems Are Computational Systems Providing a Dedicated Function within a Larger System

- **Real-time measurement and control**
- **Computer based**
  - Dedicated microprocessor
  - Unique algorithms
- **Physical embedding**
  - Close proximity only when environment is suitable
- **Functional embedding**
  - Harsh environment not suitable to electronics component
- **Minimizes data loading of networks**
  - Eliminates control loops that add data transmission, processing, and actuation time



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Accomplishments FY2016

- **Design Loop-scale motor-pump system — Completed**
  - Modify commercial pump to reduce testbed design and fabrication costs and time—created a solid model of the commercial pump
  - Analyzed impeller forces to establish force requirements for magnetic bearings
  - Designed and optimized the electromagnetic geometry to minimize mass while meeting the force specification
  - Designed and analyzed the mechanical systems for mounting and aligning the magnetic bearing electromagnets
  - Refined the mechanical design and tolerances in consultation with the fabricator to minimize fabrication cost
- **Control system hardware specification — Completed**
  - Increased the forces created by magnetic bearings by 10x using same basic power hardware of the bench-scale system
- **Assembly of loop-scale system — Delayed**
  - Delays in procurement
  - Last minute move of fabricator at request of DOE
  - Will be receiving parts in first quarter of FY2017

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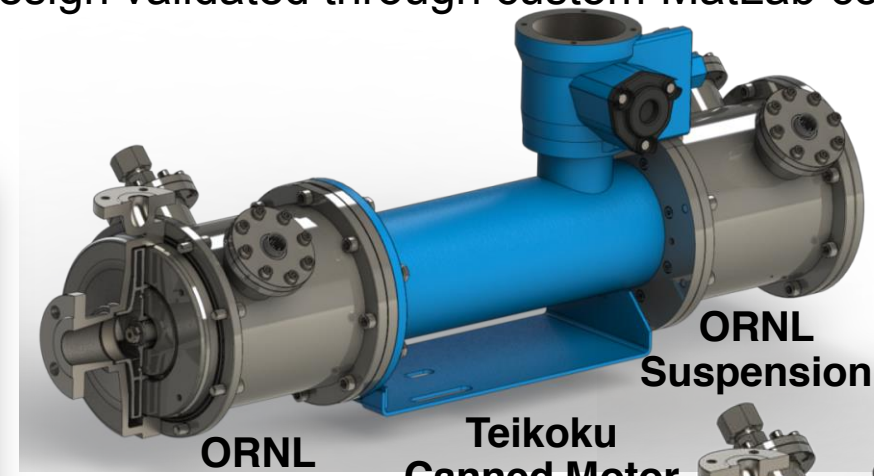
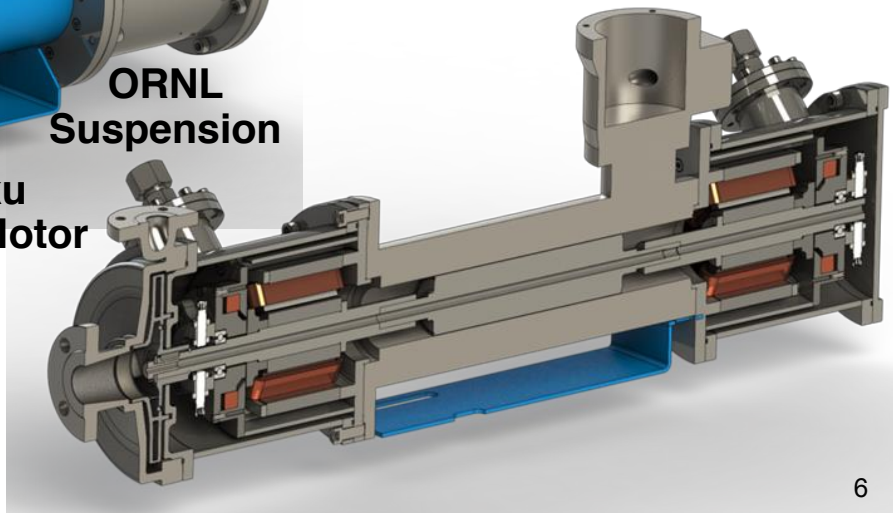
Design Accomplishments

- **Design Loop-scale motor-pump system**
  - Commercial off-the shelf canned rotor pump was purchased to use as a foundation that will be modified to include magnetic bearings—reduces cost and time
  - Shaft fluid force calculations — 1100 N (250 lbf) Radial, 600 N (134 lbf) Axial
  - Axial and radial magnetic bearing electromagnets were designed to achieve 1.5 safety factor
  - Additional FEA calculations (ANSYS) performed to validate structural design
  - Electromagnetic design validated through custom MatLab code

Assembled Teikoku canned rotor pump



Canned Rotor Pump with ORNL Suspension



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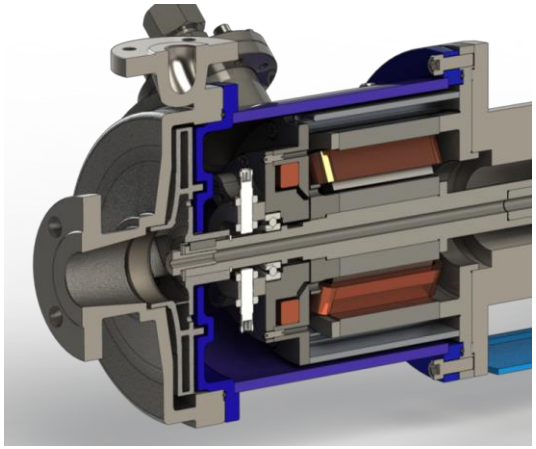
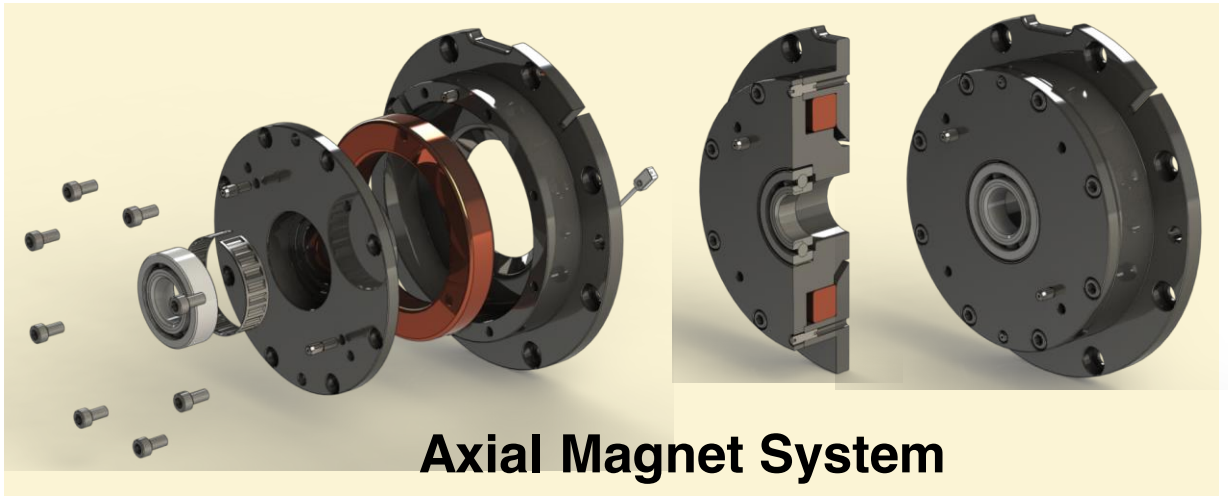
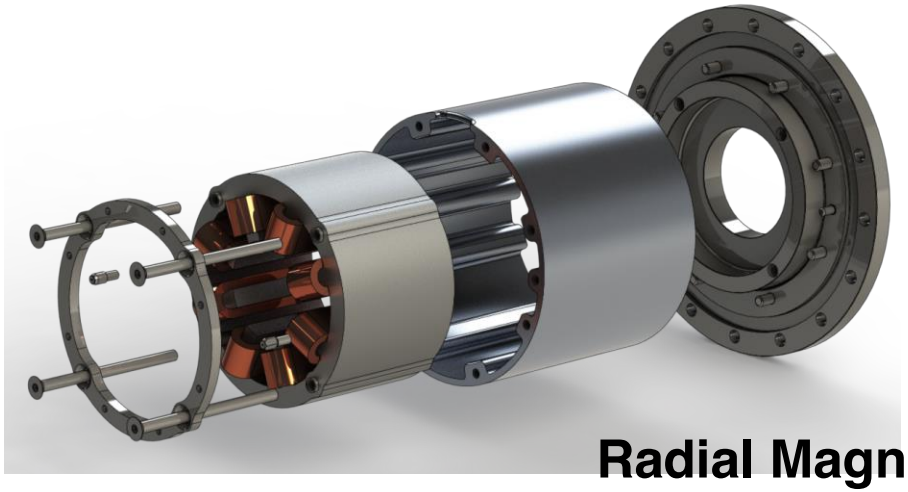
Design Accomplishments

- Section of the radial and axial suspension system shown
- Windings will be water cooled for the water-loop system





Axial Magnet System



Radial Magnet System

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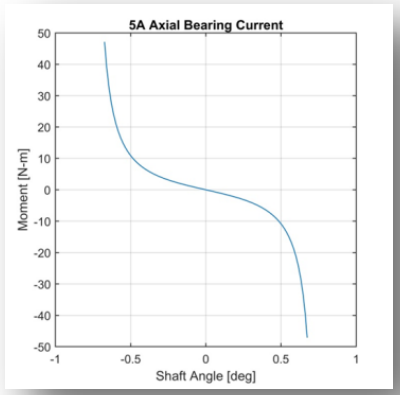
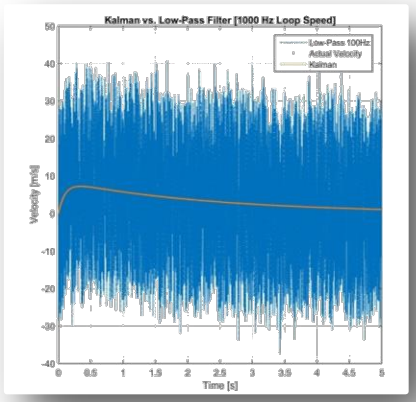
Control System Accomplishments

- **Simultaneous stabilization of radial and axial shaft position is difficult because of nonlinear interaction through shaft angle**
  - Small angular geometry changes airgap which destabilizes
    - Created new decoupled controller—improves axial bearing dynamic response
  - Developed a Kalman filter for position and motor current measurement
  - Developed method for calculating rotor rotational speed using Fourier transforms on the position data from testbed
  - Working on sensorless position measurement
    - Penetration of rotor-stator can by position sensors difficult
    - High temperatures limit position sensor technologies
    - Want to use current and voltage signals from the stator windings as the position sensing mechanism

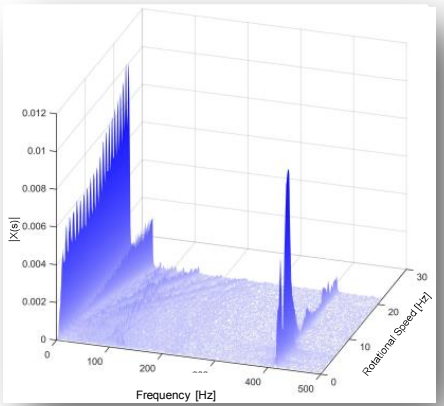
Axial bearing airgap variation from angular shaft rotation



Moment imparted to shaft by thrust bearing as a function of shaft angle



Kalman vs Low-Pass Filter (f_c=100Hz)



Rotor dynamics response

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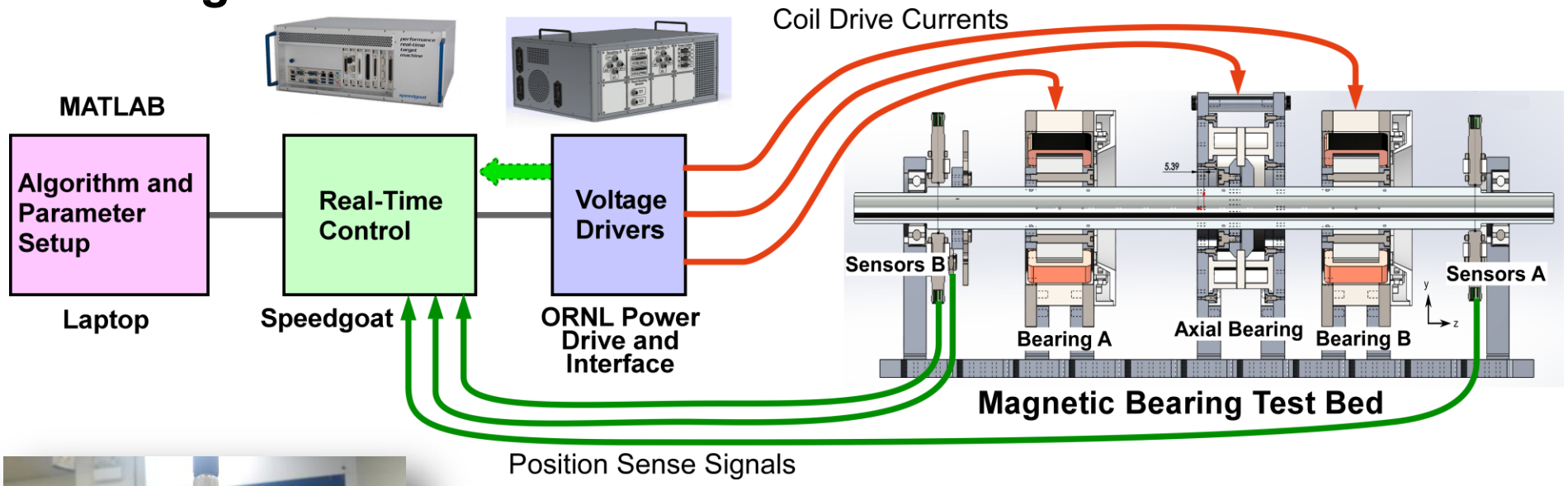
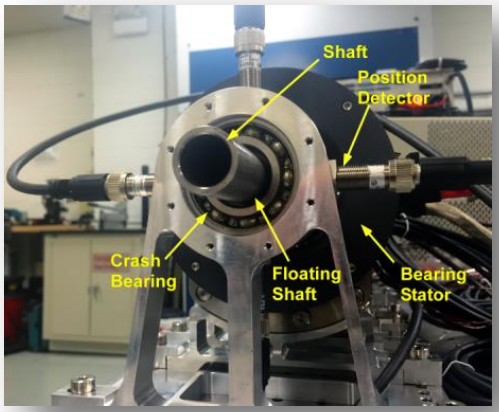
Control System Accomplishments

- **Control system hardware for the bench-top testbed built in FY2015 has worked well for control algorithm development and testing**





Shaft Floating By Magnetic Suspension

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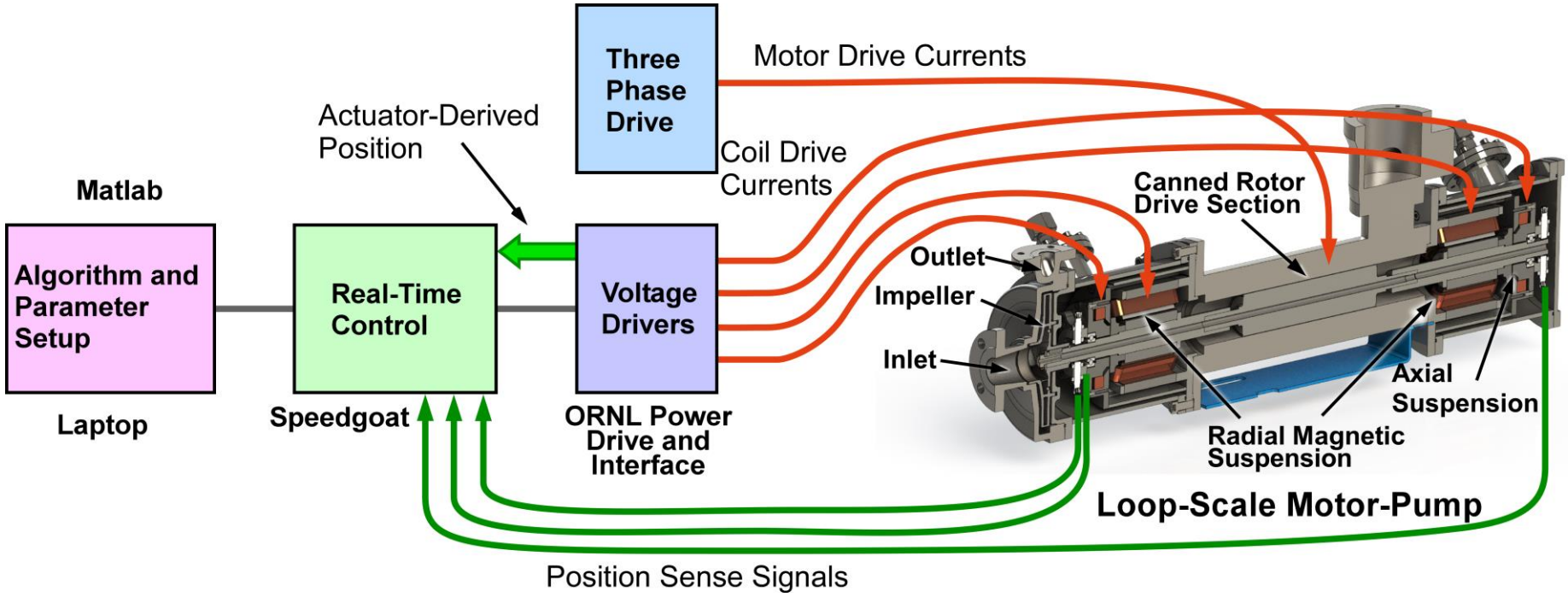
Control System Accomplishments

- A similar configuration with about the same current drive will be used for the loop-scale system in FY2017
- Will build a custom board with currents sensors that have better noise characteristics than the COTS H-Bridge drivers we are using



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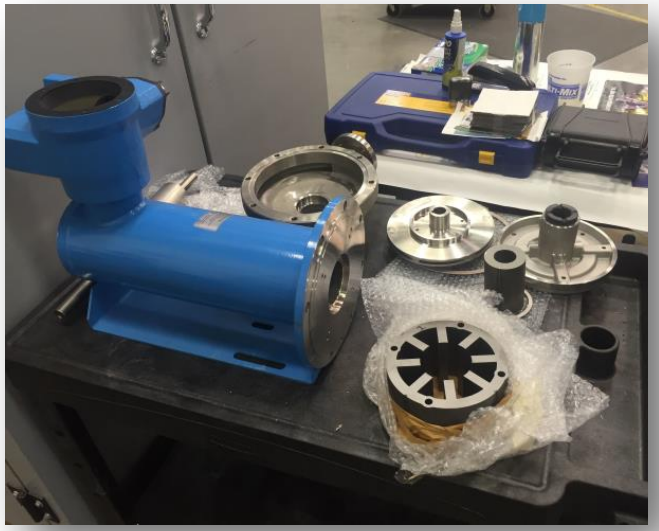
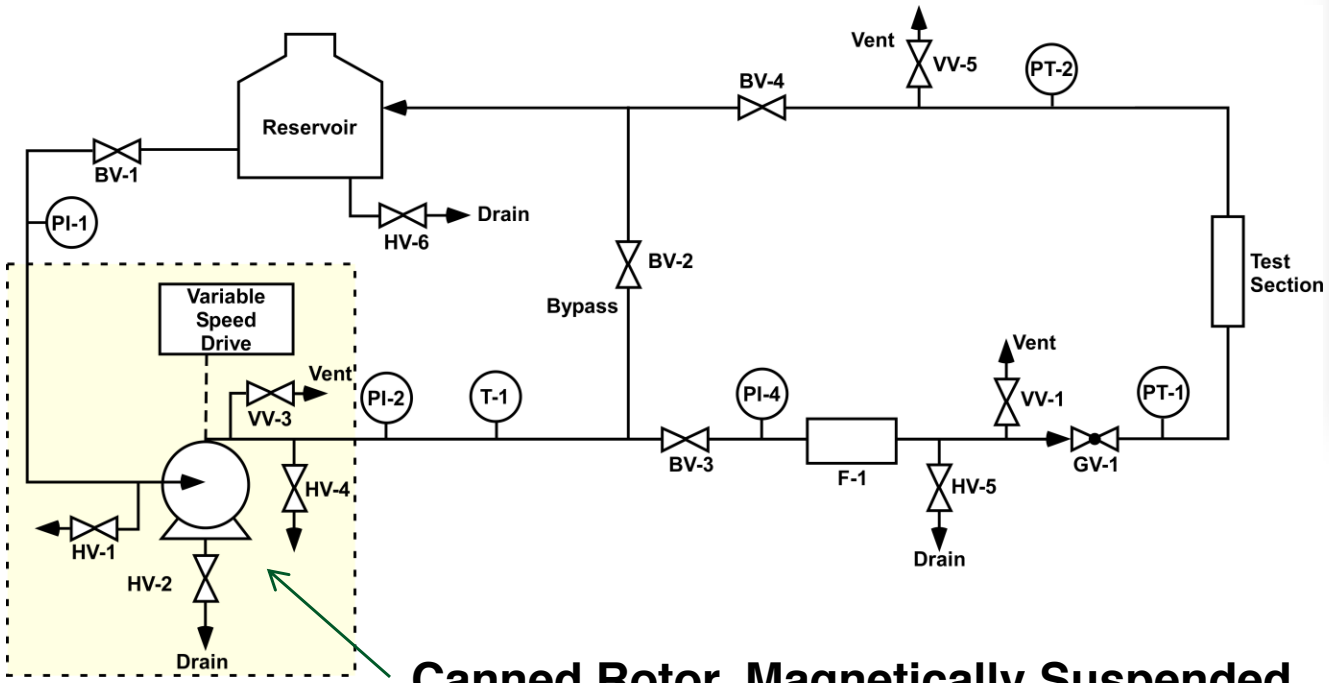
Motor Assembly Accomplishments

- Generated all detailed drawings for component fabrication
- Fabrication was delayed but is now underway at the machine and tooling facility





Canned Rotor, Magnetically Suspended Pump with Embedded I&C Goes Here

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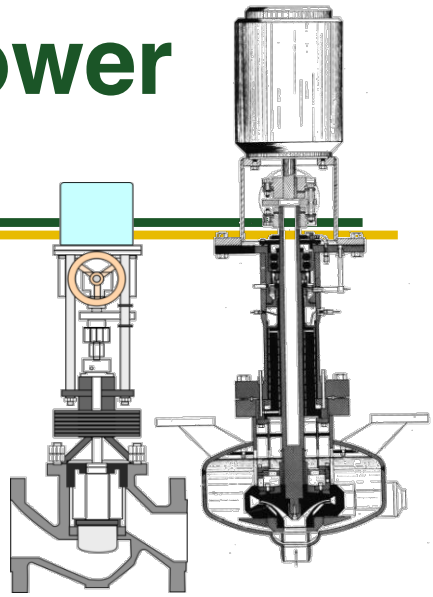
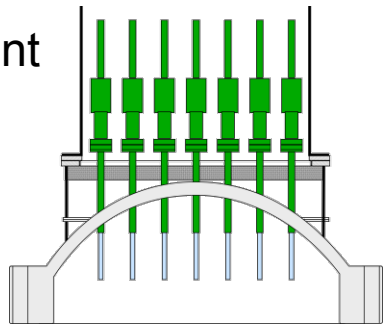
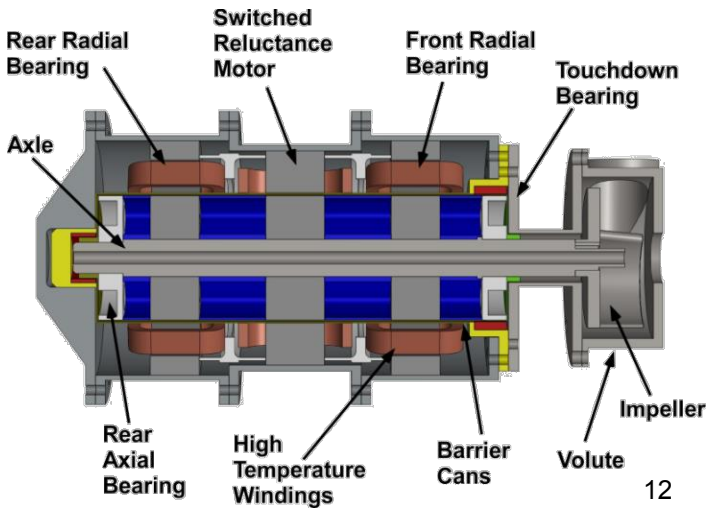
Benefits to Nuclear Power



- **Pump seals and bearings are maintenance intensive**
  - All nuclear power plant classes require coolant pumps
  - 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 damage potential
- **Embedding concept is relevant to many components of a nuclear reactor**
  - Pumps, control rod drives, valves, circuit breakers, robotics …
  - Elevates components (and systems) to new levels of performance, stability, diagnostics, and prognostics
  - Applies to primary systems and BOP components
  - New reactor designs as well as retrofit
- **Resulting pump design is also applicable to solar thermal systems**





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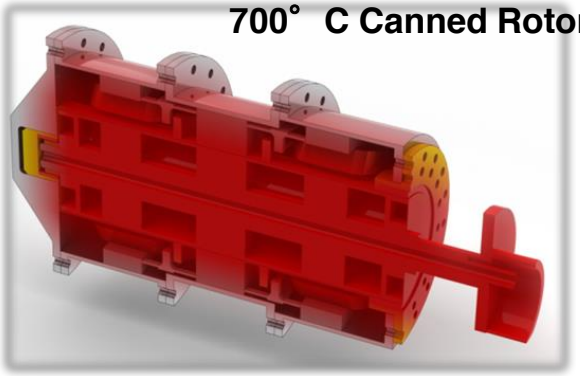
Technology Impact

- 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 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
    - Just out … *Assessment Of Sensor Technologies For Advanced Reactors,* ORNL/TM-2016/337
- New component concepts and designs may be unstable
  - Compact size
  - Less bulk material to absorb transients
  - Continuous high temperature operation
- Embedded I&C stabilizes otherwise unstable configurations
  - Intimate real-time control
  - Monitoring for degradation
  - Appropriate staged responses to failure and degradation events
  - Opportunity for fault-tolerant control
  - Embedded I&C also opens new design and operational capabilities
- Endorsement by nuclear reactor vendor pending (under NDA)
- Endorsement by component manufacturer (Conax)



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Conclusion

- The ORNL team has designed a loop-scale motor-pump system (about 10hp) comprising a commercial canned motor drive and ORNL-designed magnetic suspension
- Controllability studies and test-bench experiments have allowed further technical development of the suspension control system
- Hardware for the water-loop pump system is under construction and will be assembled in early FY2017
- Motor and pump will be fully submerged. This pump design is more flexible for power plant systems than overhanging sump pumps.
- The potential of this design type is high reliability and low maintenance. Eliminates separate lubrication, bearing and rotating seal structures, also makes possible lower cost manufacturing.
- Beyond FY2017, we are envisioning fabrication and demonstration of a magnetic suspension system capable of 700 °C environment
- Advanced reactor community is interested in this innovation

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Published Results

Work featured in DOE/NE NEET ASI Newsletter Issue 5

ORNL/TM-2012/433

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Embedded Sensors and Controls to Improve Component Performance and Reliability Conceptual Design Report

September 2012

Prepared by
R. Kisner
A. Melin,
T. Burress,
D. Fugate,
D. Holcomb,
J. Wilgen,
J. Miller,
D. Wilson,
P. Silva,
L. Whitlow, and
F. Peretz

UT-BATTELLE

ORNL/TM-2013/415

OAK RIDGE NATIONAL LABORATORY
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Embedded Sensors and Controls to Improve Component Performance and Reliability – System Dynamics Modeling and Control System Design

er 2013

Melin

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ORNL/TM-2013/269

OAK RIDGE NATIONAL LABORATORY
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Evaluation of Manufacturability of Embedded Sensors and Controls with Canned Rotor Pump System

July 2013

Prepared by
R. Kisner,
D. Fugate,
A. Melin,
D. Holcomb,
D. Wilson,
P. Silva,
C. Cruz Molina

UT-BATTELLE

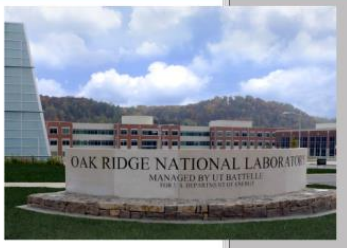
Oak Ridge National Laboratory- Student Undergraduate Laboratory Internship Program

Failure Analysis and Propagation of High Temperature Pump

Lynsie Whitlow
8/10/2012

ORNL/TM-2015/584

Embedded Sensors and Controls to Improve Component Performance and Reliability – Bench-scale Testbed Design Report



Alexander M. Melin
Roger Kisner
Anis Drira
F. Kyle Reed
David L. Fugate
September 2015

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ORNL/TM-2016/563

Embedded Sensors and Controls to Improve Component Performance and Reliability – Loop-scale Testbed Design Report

Alexander M. Melin
Roger A. Kisner
September 2016

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