U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures

Advanced Sensors and Instrumentation Annual Webinar

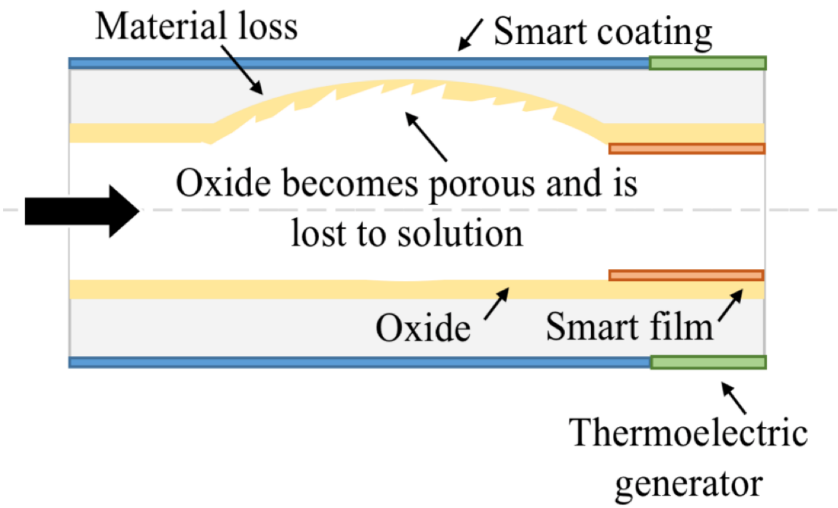
October 31 – November 1, 2018

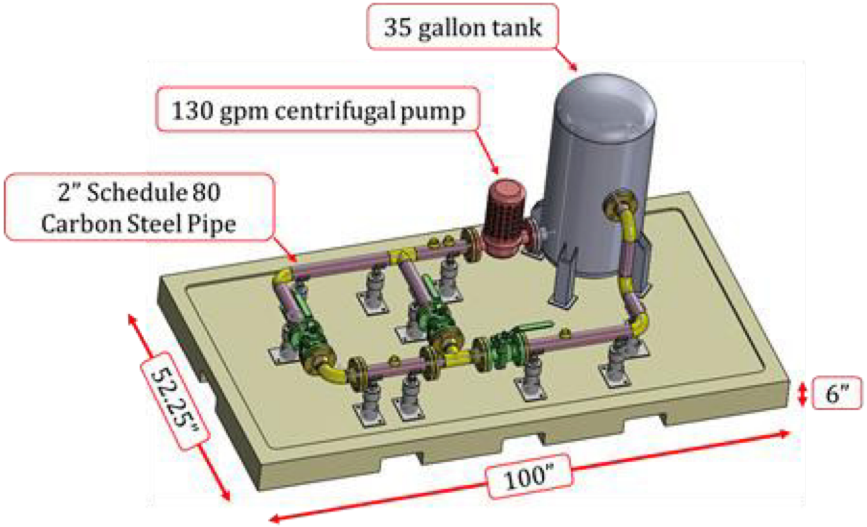
Douglas Adams

Vanderbilt University

Project Overview—Goals and Objectives

- Goal and Objective
  - Develop smart film to sense chemo-mechanical state of inner wall of pipe structure.
  - Utilize vibro-acoustic sensing to detect changes to inner wall of pipe due to material loss.
  - Print multi-physics transducers for power harvesting and sensing on surface of pipe.
  - Map damage inside pipe using a 3-D sensing network on outside.
  - Simulate sensing approach on a subscale cooling circuit testbed.
  - Optimize sensors and algorithms using Bayesian method.





Project Overview—Participants

VANDERBILT School of Engineering

Prof. Doug Adams

Cole Brubaker

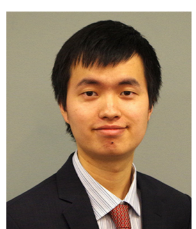
Thomas Stilson

Dave Koester

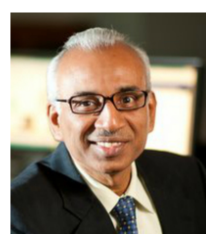
Garrett Thorne

Prof. Kane Jennings

Xuanli (Ricky) Deng



Prof. Sankaran Mahadevan



Prof. Yanliang Zhang

Idaho National Laboratory

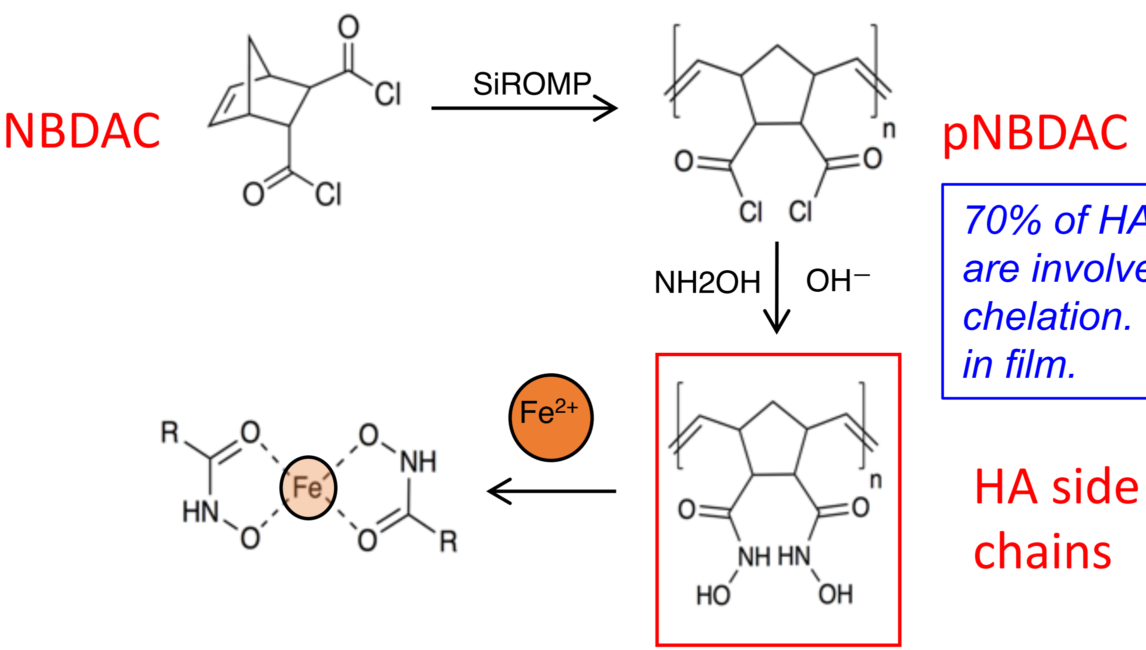
Dr. Vivek Agarwal

Project Overview—Yr 1 Schedule

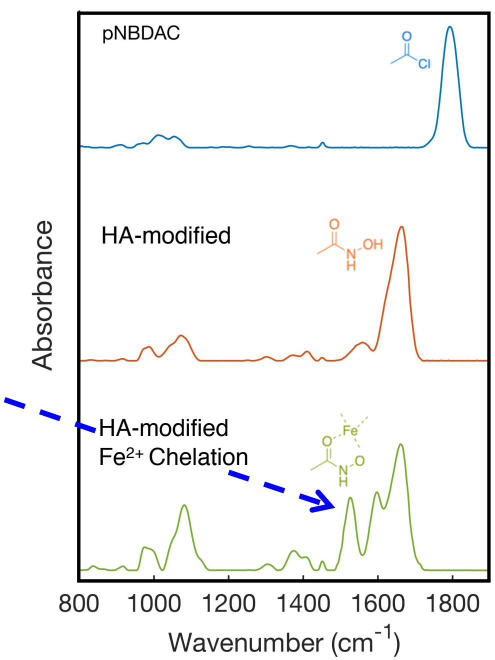
- Schedule
  - **Year 1**
    - **Major Milestone: Operational cooling circuit testbed VU (Adams)**
    - **Minor Milestone: Thermoelectric power harvesters ND (Zhang)**
    - **Minor Milestone: Demonstrate smart layer VU (Jennings)**
  - Year 2
    - Major Milestone: Algorithms for diagnosis in pipe INL (Agarwal)
    - Minor Milestone: Mapping of internal surface damage VU (Adams)
    - Minor Milestone: Smart layer in pipe VU (Jennings)
  - Year 3
    - Major Milestone: Prognosis and optimization of sensor network INL (Agarwal) and VU (Mahadevan)
    - Minor Milestone: Piezo network printed on component ND (Zhang)
    - Minor Milestone: Damage mapping of pipe VU (Adams)

Accomplishments – Smart Film

- Milestone: Demonstrate Smart Layer in Thin Film Laboratory Setting to Detect Corrosive Process Forming Oxide Layer
- Method: Prepare metal-chelating polymer films by the surface-initiated ring opening metathesis polymerization (SiROMP) of norbornene (diacid chloride) (NBDAC) and its modification to contain hydroxamic (HA) side chains.

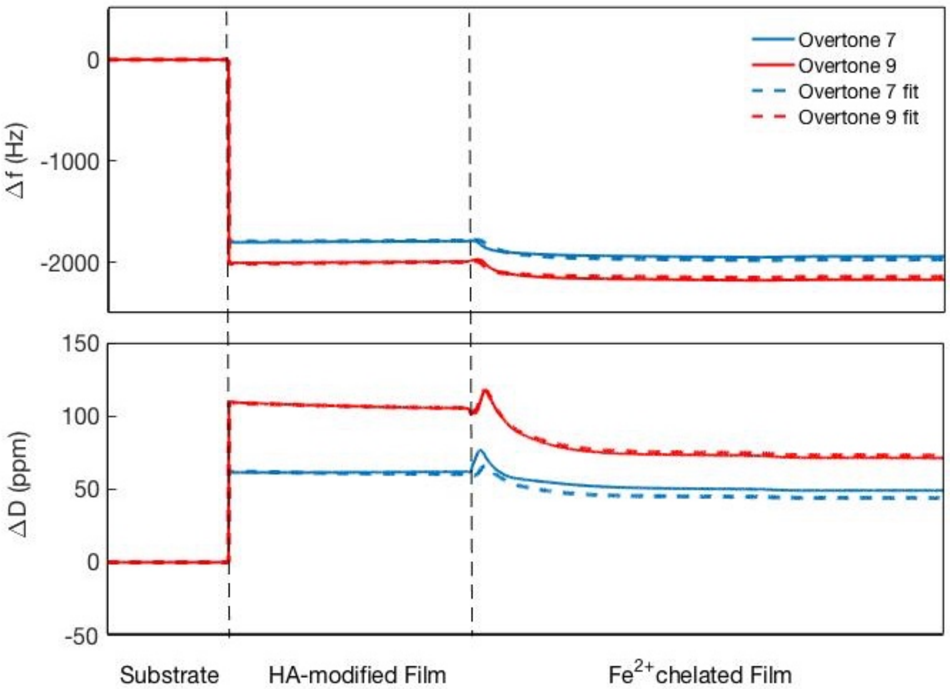


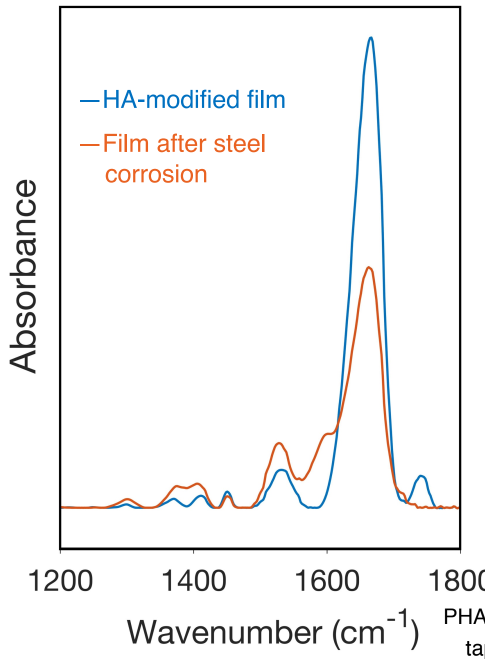
70% of HA chains are involved in Fe chelation. 3 M Fe in film.

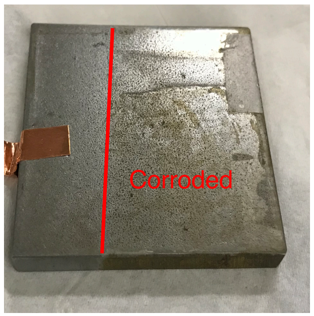


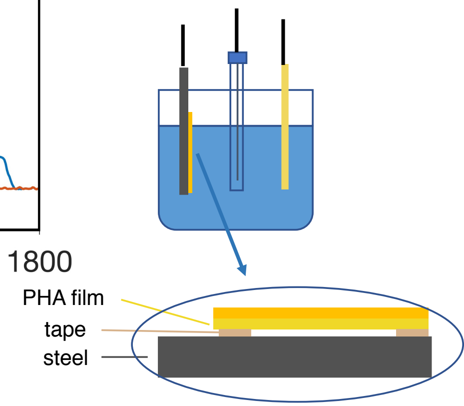
Accomplishments – Smart Film

- Key Results to Support Milestone Completion:









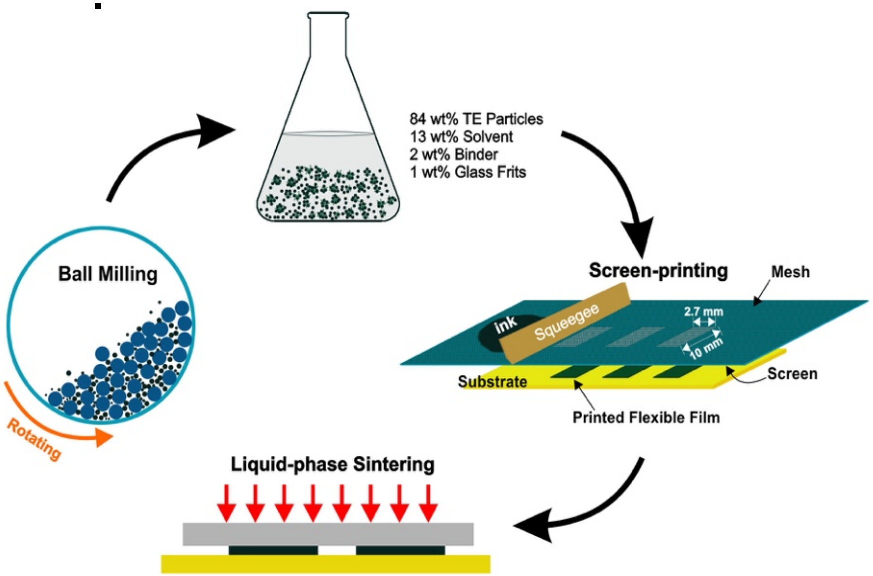
Effects of Fe Chelation

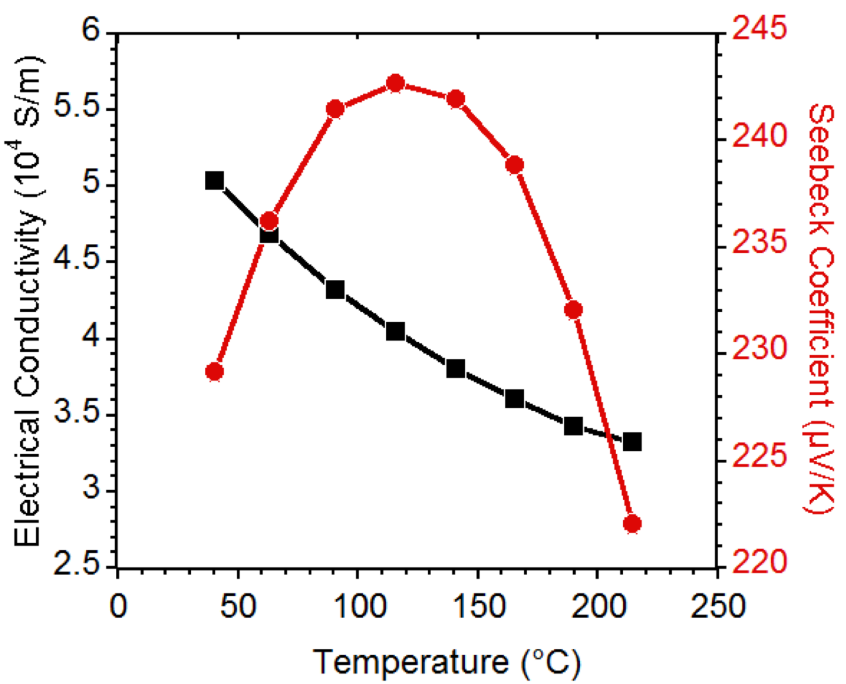
- 65% increase in shear storage modulus
- 50% decrease in shear loss modulus
- >8x increase in ion transfer resistance
- Thermal stability in 80 °C water

Smart film captures metal ions due to corrosion of a nearby carbon steel surface. Detection of copper corrosion also demonstrated.

Accomplishments – Power Harvesting

- Milestone: Demonstrate Thermoelectric Power Harvesters
- Method: Develop a printing process to fabricate flexible thermoelectric (TE) devices for power harvesting. The printed TE films show high electrical conductivity of 5.0×10^4 S/m, and high Seebeck coefficient of 227μV/K at room temperature.
- .

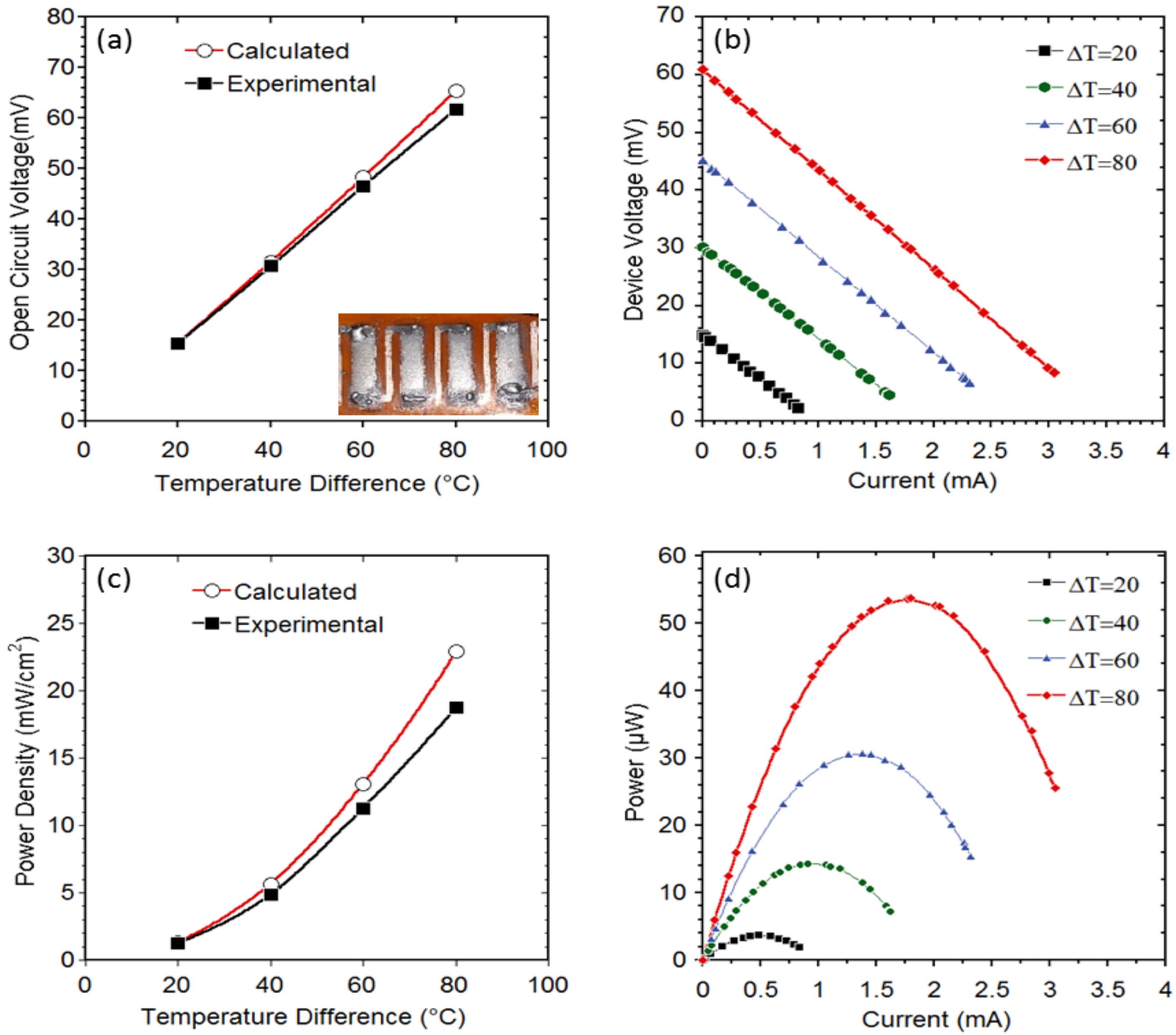




Accomplishments – Power Harvesting

- Key Results to Support Milestone Completion:

- Demonstrated a fully printed flexible thermoelectric generator that produces a maximum electrical power density of 18.8 mW/cm^2 with a temperature gradient of 80 K.

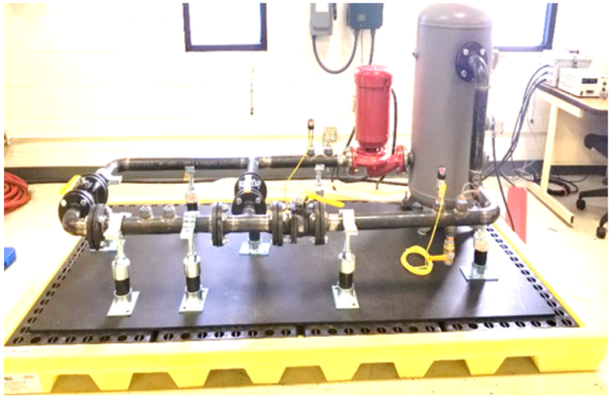


Accomplishments - Testbed

- Milestone: Operational cooling circuit testbed for structural health monitoring, diagnosis and prognosis,
- Method: Utilize fluid flow model to design cooling circuit with replaceable fittings, conduct independent design review, and construct testbed.

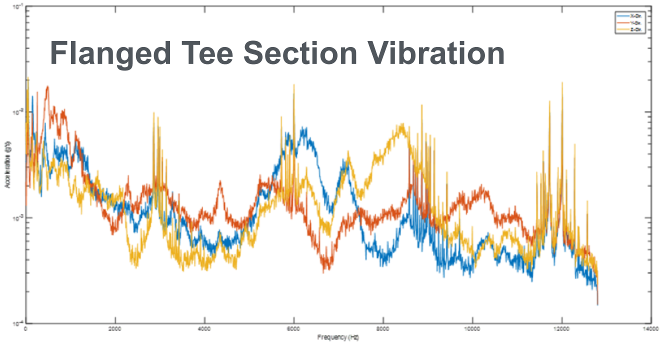
Fluid flow model was developed in Matlab to estimate head loss and fluid flow velocity (pump selected to achieve 2.7 ft/Sec flow)

CAD design developed, INL review.



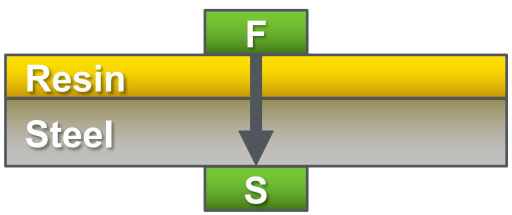
- Key Results to Support Milestone Completion:

Accelerometers mounted on flanged elbow and a flanged tee. Vibration was measured during operation of testbed to show frequency content of flow source.



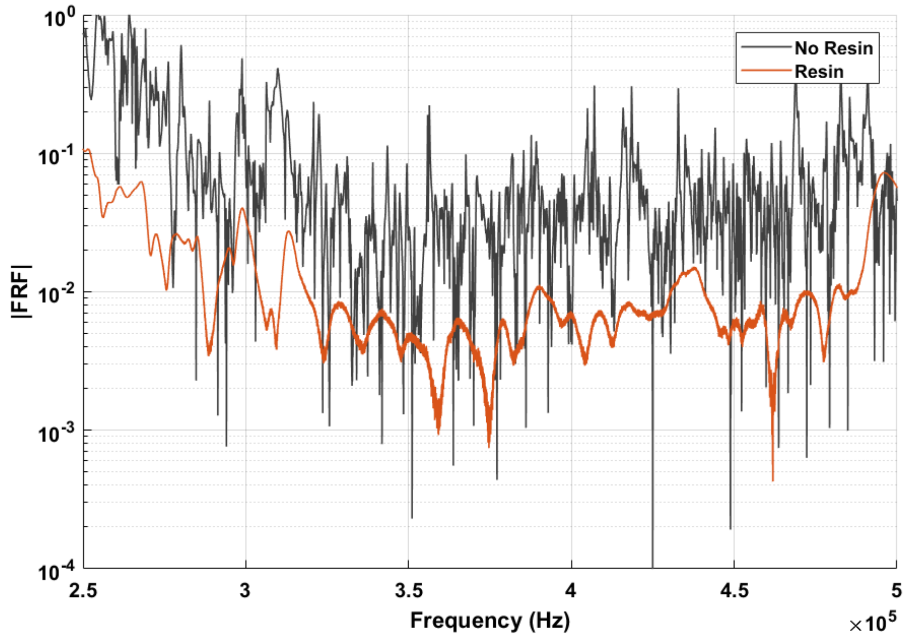
Accomplishments – Mapping of Internal Damage

- Objective: Acquire response measurements on the exterior surface of the pipe as water is pumped through it to map out how the inner surface degrades as it corrodes.
- Method: Analyze effects of changes on inner surface of metal surface on the vibro-acoustic response of external surface.



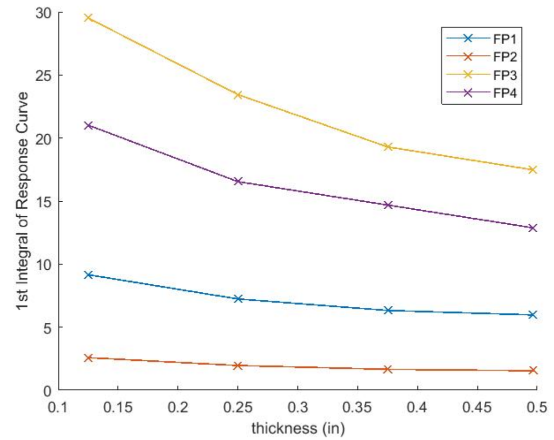
Test Schematic

$$H(j\omega) = \sum_{i=1}^{N} \frac{1/k_i}{1 - \left(\omega/\omega_{n,i}\right)^2 + j2\omega_{n,i}\zeta_i}$$

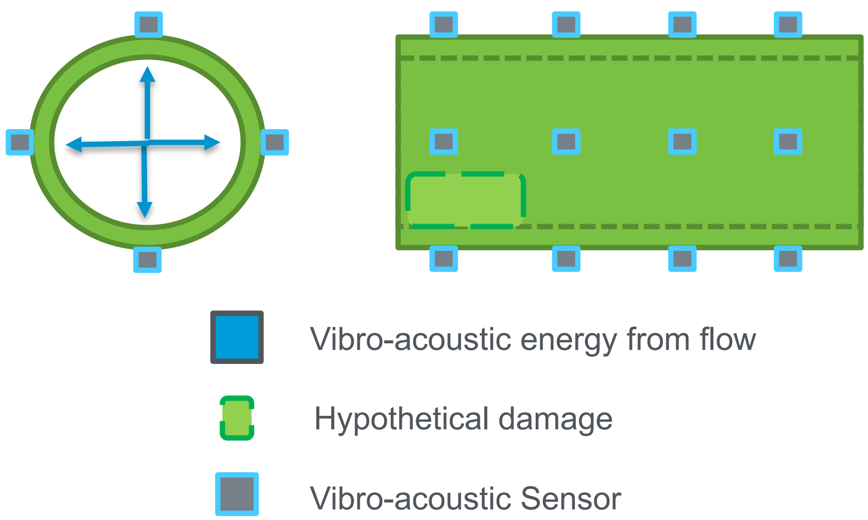


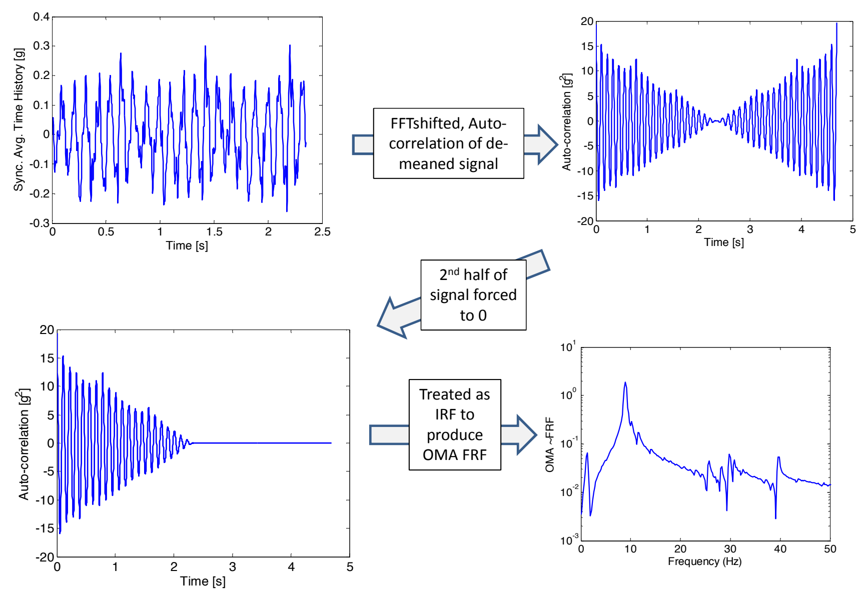
Accomplishments – Mapping of Internal Damage

- **Results:** To realize a 3-D sensing approach to map out damage to the inner surface of pipe structure, a sensing array and spatial correlation analysis will be implemented.



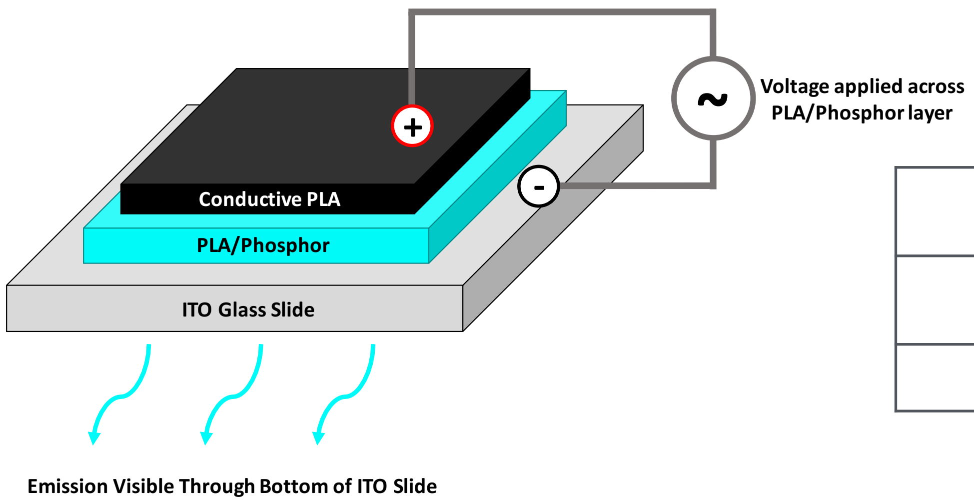
Response magnitude vs. Thickness for metal plate





Accomplishments – Damage Mapping of Pipe

- **Objective:** Print sensors that monitor changes in a pipe in 3-D due to corrosion and are powered by energy from the flow; and demonstrate this in a subscale test bed.
- **Method:** Incorporate phosphorescent materials within the 3D-printing process to manufacture a visually responsive sensing system. ZnS:Cu phosphors were embedded within a polylactic acid (PLA) host matrix and printed using fused deposition modeling to manufacture the sensing system.

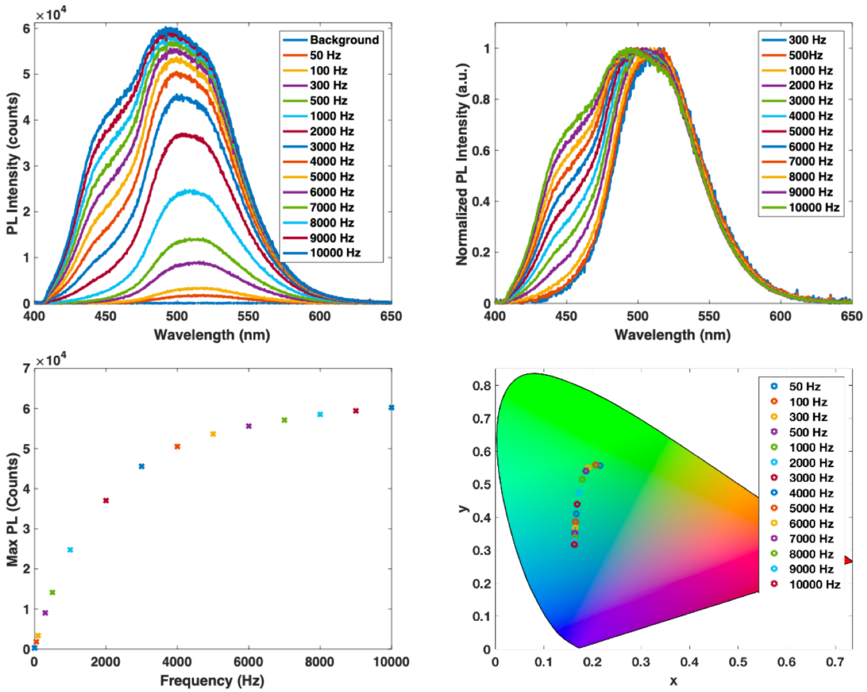


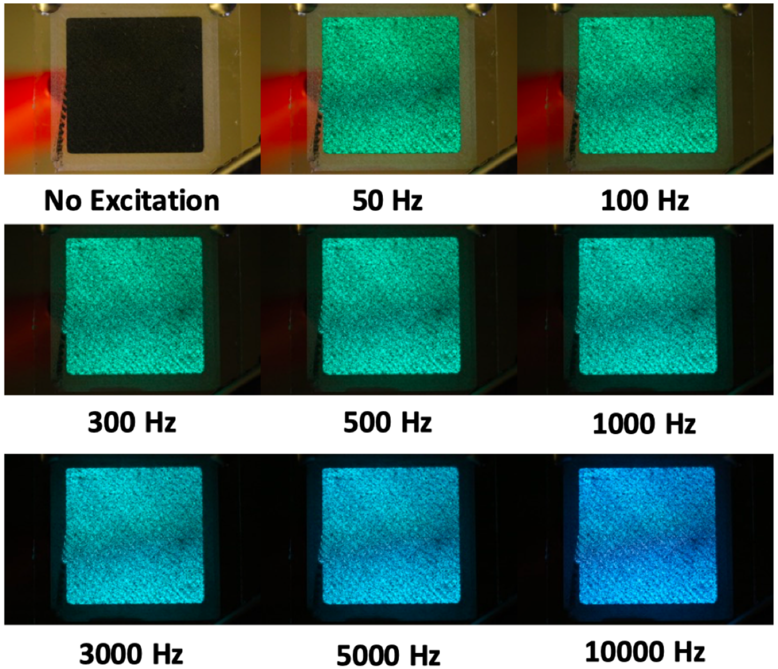
Sample Dimensions

Conductive PLA	18 mm x 18 mm x 0.2 mm
PLA/Phosphor	20 mm x 20 mm x 0.1 mm
ITO Glass Slide	25 mm x 25 mm 1.1 mm

Accomplishments – Damage Mapping of Pipe

- Results





3D-printed films and devices displayed a visual color change from green to blue with increasing frequencies under constant excitation (250 V shown). Overall response and output will be evaluated next for sensing changes in structure.

Technology Impact (1)

Describe how this technology:

- *Advances the state of the art for nuclear application*
  - A suite of smart sensors that provide a solution for monitoring and 3D mapping of damage in secondary piping.
    - E.g., smart film on the inner wall of the pipe could do something that is impossible today, that is, the film could detect minute chemical reactions that signal the earliest stages of corrosion.
- *Supports the DOE-NE research mission*
  - Continuously certify that nuclear power plants are safe to operate with monitoring as an economically efficient approach.
    - Corrosion is very difficult to detect especially in the early stages.
    - Approx. 70 miles of piping in nuclear power plants to inspect.
    - Inspections turn up no damage 99% of the time.
  - Students who are being trained in this project are being exposed to an area of national need.

Technology Impact (2)

Describe how this technology:

- *Impacts the nuclear industry*
  - This kind of health monitoring system for the pipes used in a cooling circuit system for a nuclear power plant can help to reduce maintenance costs and outages saving consumers money.

- *Will be commercialized*
  - Monitoring of much of the cooling circuit can be addressed using guided wave technology so we are focusing on the joints and the regions of the pipe downstream of the joint such as the elbows and T sections to address commercial need.
  - This strategy is scalable to facilitate commercialization because it will focus on the optimization and implementation of the 3D sensor network to specific regions of interest in a large circuit.

Conclusions

Smart film can achieve 10,000x higher concentration of Fe in the film versus Fe^{2+} in solution--signals onset of corrosion.

Mapping internal damage was accomplished on a metal structure using correlation analysis of sensor data.

Devices for damage mapping in pipes were 3-D printed and will be tested in future work.

Printed flexible thermoelectric generator that produces a maximum power density of 18.8 mW/cm^{2}.

A subscale pipe circuit testbed with 130 GPM pump to flow water at 2.7 ft/sec (27 GPM) at 80C through two replaceable fittings at 30 psi was constructed.

Questions

- *douglas.adams@anderbilt.edu any additional questions that may not be answered during the webinar.*

Clean. Reliable. **Nuclear.**