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

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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 29, November 5, November 12 , 2020

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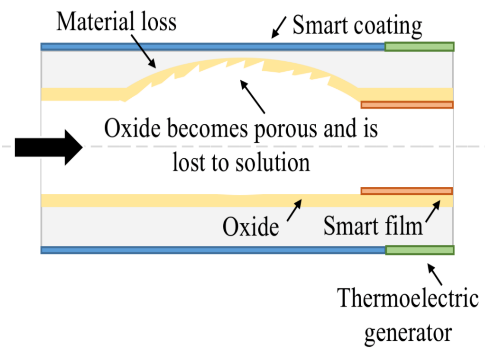
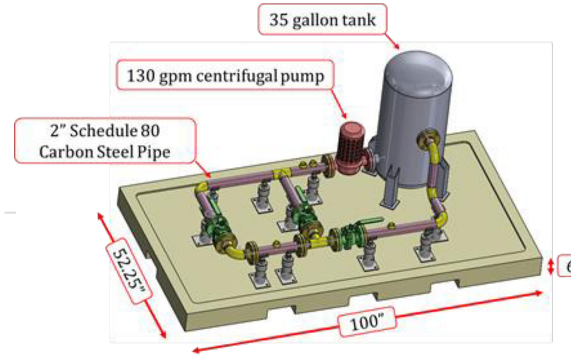
Vanderbilt University

Project Overview

- Goal and Objective
  - Develop smart film
  - Print surface transducers
  - Map damage
  - Optimize sensors and algorithms
  - Simulate on test bed (TRL 3)
- Schedule (Year 3)
  - Major Milestone: Prognosis and optimization of sensor network
  - Minor Milestone: Effects of operational variability on mapping
  - Minor Milestone: Piezo network printed on component





VANDERBILT School of Engineering

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Liudmyla Prozorovska


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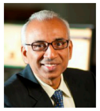

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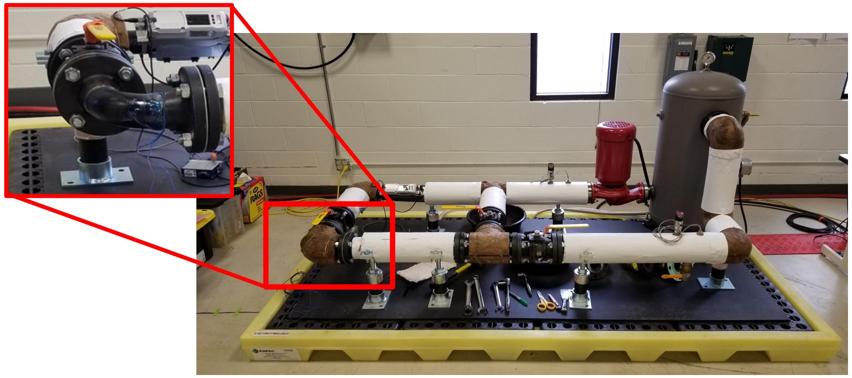
Accomplishments – Prognosis and Optimization

- **Milestone:** Demonstrate Prognosis and Optimization of Sensor Network
- **Method:**
  - Accelerometers and thermocouples
  - Material added and removed in stages
- **Results:**
  - Support vector machine and least absolute shrinkage and selection operator logistic regression; align vibration sensors with the flow.
  - Steady trend in temperature above locations material was removed; promise for prognosis



Cooling circuit test bed with insulation installed.

Test Condition	Average Wall Thickness (mm)	Average Wall Thickness Change (mm)	Normalized Temperature for TC Pair 3	Normalized Temperature for TC Pair 4
Baseline (No material removed)	5.89	0.00	0.9913	0.9866
First Material removal	5.72	0.18	0.9945	0.9894
Second Material Removal	5.08	0.64	0.9951	0.9889
Third Material Removal- Run 1	4.11	0.97	0.9955	0.9909
Third Material Removal- Run 2	4.11	0.97	0.9959	0.9912

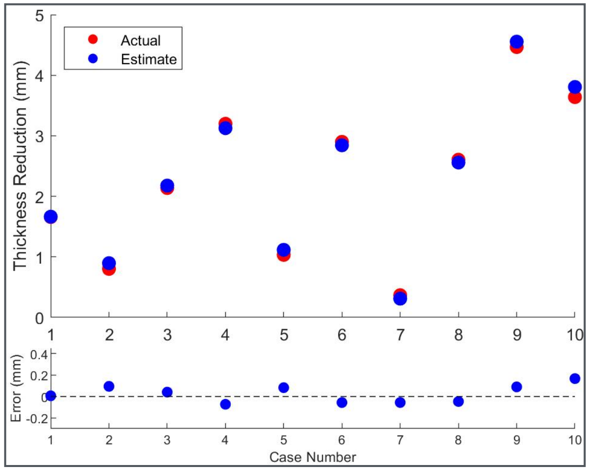
BINOMIAL CLASSIFICATION ACCURACY

Direction	Classifier	Baseline v/s 2.9g	Baseline v/s 23.5g
X	SVM	Baseline: 99.9% 2.9g: 99.9%	Baseline: 99.9% 23.5g: 99.8%
	LASSO	Baseline: 99.7% 2.9g: 99.1%	Baseline: 99.7% 23.5g: 99.9%
Y	SVM	Baseline: 99.9% 2.9g: 99.8%	Baseline: 99.9% 23.5g: 99.9%
	LASSO	Baseline: 98.5% 2.9g: 98.9%	Baseline: 96.2% 23.5g: 97.5%
Z	SVM	Baseline: 99.9% 2.9g: 99.9%	Baseline: 99.9% 23.5g: 99.9%
	LASSO	Baseline: 98.6% 2.9g: 97.5%	Baseline: 99.2% 23.5g: 90.4%

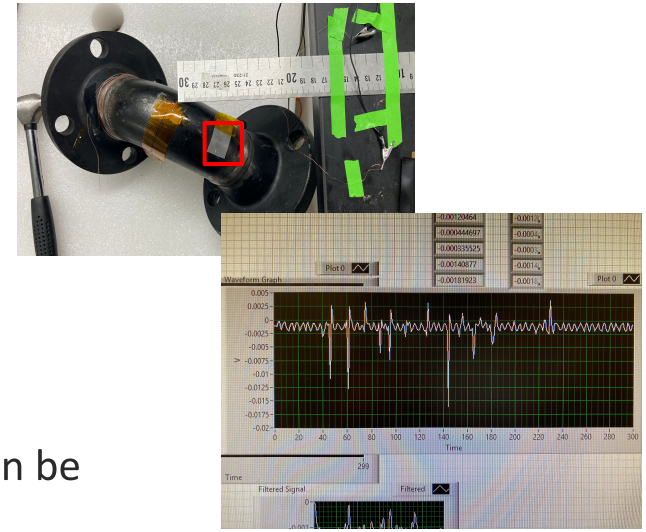
Accomplishments – Operating Variability, Printed Piezos

- **Milestone:** Demonstrate Effects of Variability
- **Method:**
  - Simulations run varying wall thickness, water temperature, thermal conductivity, density, etc.
- **Results:**
  - Simulations run GPM1 produced pipe wall thicknesses less than 9% (below 0.5 mm)
  - GPM2 reduced errors below 0.2 mm (less than 3.6%) by adding measurement of water temperature
- **Milestone:** Demonstrate Printed Piezo Sensor Network
- **Method:**
  - Print piezo sensors directly onto pipe elbow
- **Results:**
  - Sensors demonstrate ability to measure broadband frequency response
  - Combined with previous results, printed sensor array can be used to monitor and map damage to inner wall of pipe.

GPM2: Pipe and water temperature



Errors less than 3.6%



Technology Impact

- *Advances the state of the art for nuclear application*
  – A suite of smart sensors and algorithms to provide **a solution for monitoring and 3D mapping of damage in critical piping areas**.
  – Key findings on effectiveness of sensing modalities
    - effects of non-uniform pipe material loss on vibration signature, heat flow
- *Supports the DOE-NE research mission*
  – Continuously certify that nuclear power plants are safe to operate with monitoring as an **economically efficient approach**.
    - Approx. 70 miles of piping, inspections turn up no damage 99% of time.
- *Impacts the nuclear industry*
  – Help **to reduce inspection/maintenance costs** and outages saving consumers money
- *Commercialization potential*
  – Focus on elbows and T sections
  – Conduct field testing in power plant.

Courtesy: http://www.nbcnews.com/

Conclusions

Demonstrated for the first time ability to sense early stage corrosion with film coating on inner surface of pipe in conjunction with printed piezo sensor network on exterior of pipe for sensing advanced corrosion using both vibration and temperature signatures that exhibit trends for prognosis due to material loss in pipe wall.

Showed how to optimize sensors for monitoring pipe fitting given anticipated variability in operation.

Publications list available in final report

Questions

- *douglas.adams@anderbilt.edu for additional questions*

Publications

Year 2018:

- Vanderbilt University:
  - X. Deng and G. K. Jennings, "Surface-Initiated Polymerization of trans-5-Norbornene-2,3-Dicarbonyl Chloride: A Versatile Platform for Tailored Polymer Film Compositions," 2018, Langmuir

Year 2019:

- Vanderbilt University:
  - X. Deng, L. Prozorovska, and G. K. Jennings "Metal Chelating Polymer Thin Films by Surface-Initiated ROMP and Modification," J. Phys. Chem. C, 2019, 123, 23511-23519.
  - X. Deng, J. L. Livingston, N. J. Spear, and G. K. Jennings "pH-Responsive Copolymer Films Prepared by Surface-Initiated Polymerization and Simple Modification," Langmuir, 2019, submitted.
  - Brubaker C., Newcome, Kailey, Jennings, Kane, Adams, Douglas. "3D-Printed Alternating Current Electroluminescent Devices." 2019, Journal of Materials Chemistry C, DOI: 10.1039/C9TC00619B
- University of Notre Dame:
  - M. Zeng, Y. Zhang, Colloidal Nanoparticle Inks for Printing Functional Devices: Emerging Trends and Future Prospects, *Journal of Materials Chemistry A*, 7, 23301 - 23336, 2019.
  - T. Varghese, C. Dun, N. Kempf, M. Saeidi-Javash, J. Richardson, D. Estrada, Y. Zhang, Flexible Thermoelectric Devices of Ultrahigh Power Factor by Scalable Printing and Interface Engineering, *Advanced Functional Materials*, 1905796, 2019

Year 2020:

- Vanderbilt University:
  - Nash, C., Karve, P., Adams, D., Thorne, G., and Mahadevan, S.," Real-Time Cure Monitoring of Fiber-reinforced Polymer Composites using Infrared Thermography and Recursive Bayesian Filtering," 2020, *Composites B,* accepted (Adams and Mahadevan)
  - L. Prozorovska and G. K. Jennings, "Surface-Initiated Dopamine-Rich Films for Chelation of Metal Ions," Langmuir, to be submitted in 2020
  - L. Prozorovska and G. K. Jennings, "Combining Surface-Initiated Polymerization and Spin Coating to Achieve Thick, Removable Polymer Films for Metal Chelation," ACS Applied Materials & Interfaces, to be submitted in 2020.
- University of Notre Dame
  - M Zeng, W Kuang, I Khan, D Huang, Y Du, M Saeidi-Javash, L Zhang, Z Cheng, A J Hoffman, Y Zhang, Colloidal Nanosurfactants for 3D Conformal Printing of 2D van der Waals Materials, *Advanced Materials*, 2003081, 2020
- INL
  - Manjunatha, K, A., Mack, A., Agarwal, V., Koester, D., & Adams, D. (2020). Diagnosis of a Corrosion Process in Secondary Piping Structures in Nuclear Power Plants. ASME Pressure Vessels and Piping Conference.
  - Manjunatha, K, A., Mack, A., Agarwal, V., Koester, D., & Adams, D. (2020). Time-Series Features driven Diagnosis of Corrosion Process in Nuclear PowerPlants Secondary Piping Structures. Structural Health Monitoring Journal (In review)
  - Manjunatha, K, A., Mack, A., Agarwal, V., (2020). Prognosis of Corrosion Process using Heterogeneous Data Secondary Piping Structures. (In preparation)

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