Additive Manufacturing of Energy Harvesting Material System for Active Wireless MEMS Sensors

DE-FE0027502 Period: 09/2016-08/2019

Luis A. Chavez, Ph.D. student
Victor Elicerio, M.S. student
Jaime Regis, UG student
Bethany Wilburn, UG student
Luis C. Delfin, UG student

Co-PI: Norman Love, Ph.D.
Co-PI: Ryan Wicker, Ph.D.
PI: Yirong Lin, Ph.D.

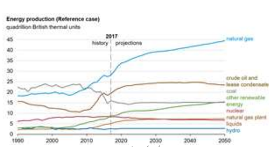
Program Manager: Barbara Carney, NETL

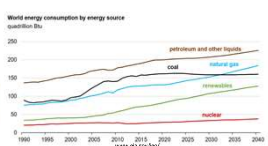
Agenda

- ❑ **Motivation**
- ❑ **Background**
- ❑ **Technical Approach**
- ❑ **Results**
- ❑ **Conclusion**
- ❑ **Future Work**

Motivation

- Highly efficient and environmentally benign power and fuel systems require:
  - Critical sensing in modern power plants and energy systems
  - Higher efficiencies in energy conversion
  - Lower emission for near-zero emission power plants

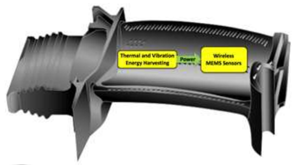




Motivation

- Monitoring/estimating operating conditions in real time is needed for high system performance and reliability
- Energy harvesting and direct sensing using piezoelectric ceramics

Turbines and Gasifiers
- Up to 1200 °C
- Up to 1000 psi
- Oxidative, corrosive, highly reducing



Background

- Energy Harvesting

Environment Energy → Usable Energy

Solar, Wind, Vibration, Thermal → Electrical

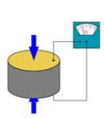
Background

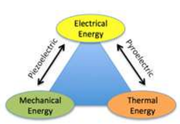
- Both piezoelectric and pyroelectric effects
- Harvest energy by coupling both effects in a single material

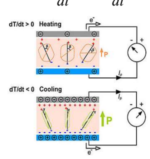
$$S = s^E \cdot T + [d]^t \cdot E$$

$$D = d \cdot T + \varepsilon^T \cdot E$$

$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

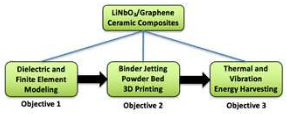






Objective

- $LiNbO_3$/Graphene Ceramic Composites
- Modeling
- Binder Jetting Powder Bed 3D printing
- Thermal and Vibration Energy Harvesting

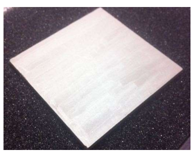


The University of Texas at El Paso

4/11/18 2018 Annual Review Meeting for Crosscutting Research – Pittsburgh, PA 7/34

Materials

Material	Curie Temperature (°C)	Pyroelectric Coefficient ($10^{-8}CK^{-1}m^{-2}$)
Barium Titanate, $BaTiO_3$	135	1.9
Lead Titanate, $PbTiO_3$	492	2.7
Lithium Niobate, $LiNbO_3$	1210	0.9
Lithium Tantalate, $LiTaO_3$	618	2.3
Lead Zirconate Titanate, PZT	365	4.7
Polyvinyl Chloride, PVC	100-266 (Melting Point)	0.01
Polyvinylidene Fluoride, PVDF	177 (Melting Point)	0.3
Zinc Oxide, ZnO	1975 (Melting point)	0.1

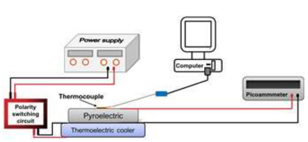


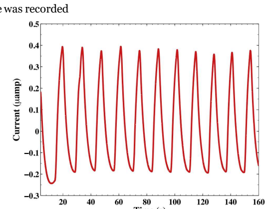
The University of Texas at El Paso

4/11/18 2018 Annual Review Meeting for Crosscutting Research – Pittsburgh, PA 8/34

Energy Harvesting - Current Characterization

- Sample was cycled in a temperature range of 45℃ to 55℃
- Current generated as a function of temperature change was recorded



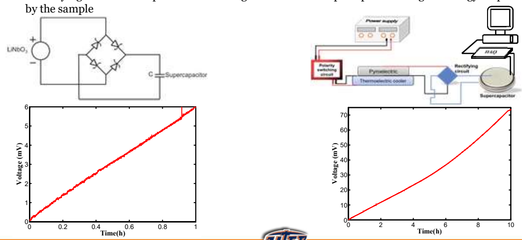


The University of Texas at El Paso

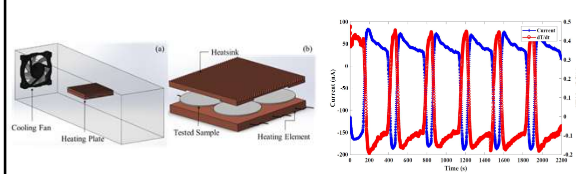
4/11/18 2018 Annual Review Meeting for Crosscutting Research – Pittsburgh, PA 9/34

Energy Harvesting

- A rectifying circuit was implemented to charge a commercial supercapacitor using the energy outputted by the sample



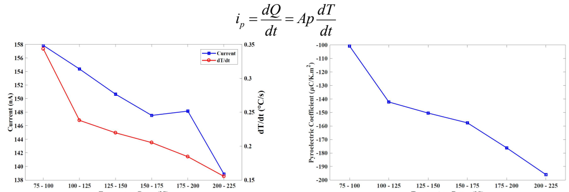
Energy Harvesting at Elevated Temperatures



Energy Harvesting at Elevated Temperatures

- Thermal loads at different temperature ranges were applied
- Characterized pyroelectric coefficient of $LiNbO_3$ as these ranges

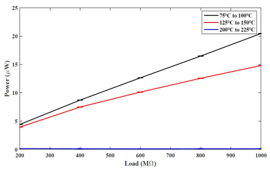
$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

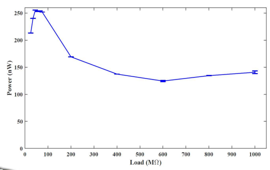


Energy Harvesting at Elevated Temperatures

- Electrical resistors were introduced to calculate the power output at three different temperature ranges
- Power decreases as temperature increases

$$P = I^2 \, x \, R = \frac{V^2}{R}$$

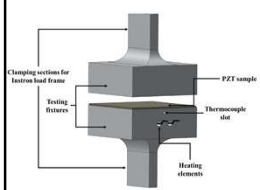




The University of Texas at El Paso

Hybrid Energy Harvesting

- Mechanical, thermal, and simultaneous loads were applied to the sample

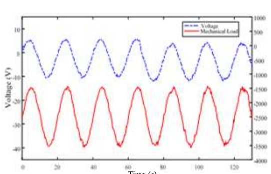


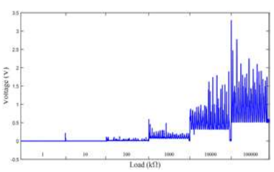
Test	Initial Mechanical Conditions	Initial Thermal Conditions	Mechanical Cycling load	Thermal Cycling Load
Pure Mechanical	2500 N Compression	Room Temperature	1000 N Amplitude at 0.05 Hz	No Thermal Cycling
Pure Thermal	2500 N Compression	Room Temperature	No Cycling Load Applied	Temperature cycled at 50 to 60 °C
Mechanical at 50	2500 N Compression	50 °C	1000 N Amplitude at 0.05 Hz	Constant Temperature
Mechanical at 60	2500 N Compression	60 °C	1000 N Amplitude at 0.05 Hz	Constant Temperature
Combined	2500 N Compression	Room Temperature	1000 N Amplitude at 0.05 Hz	Temperature cycled at 50 to 60 °C

The University of Texas at El Paso

Hybrid Energy Harvesting

- A full bridge rectifying circuit was implemented to rectify the voltage output from the sample



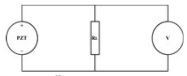


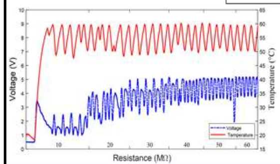
$$D = d \cdot T$$

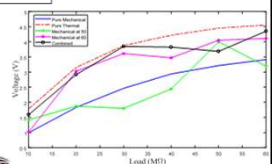
The University of Texas at El Paso

Hybrid Energy Harvesting

- Average voltage output across different resistors was measured under all testing conditions





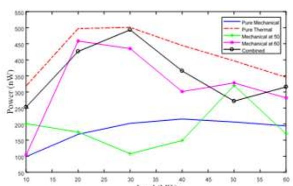


The University of Texas at El Paso

Hybrid Energy Harvesting

- Peak power at each loading condition was determined
- Maximum power observed under pure thermal conditions

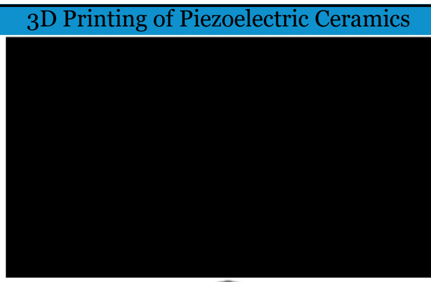
$$P = I^2 \, x \, R = \frac{V^2}{R}$$



Test	Peak power (nW)	Load at peak power (MΩ)	Lowest power (nW)	Load at lowest power (MΩ)
Pure Mechanical	216	40	98.6	10
Pure Thermal	501	30	319	10
Mechanical at 50	320	50	108	30
Mechanical at 60	458	20	103	10
Combined	494	30	253	10

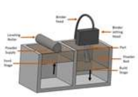
The University of Texas at El Paso

3D Printing of Piezoelectric Ceramics



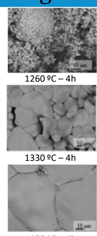
The University of Texas at El Paso

3D Printing of Piezoelectric Ceramics



ExOne M-Lab

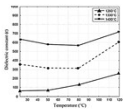
d_{33} meter



1260 ºC – 4h — d_{33} = 13.23 pC/N

1330 ºC – 4h — d_{33} = 41.73 pC/N

1400 ºC – 4h — d_{33} = 74.1 pC/N



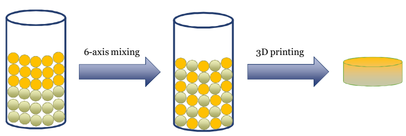
Density values obtained for specimens fabricated with 60% binder saturation.

Material	Sintering temperature (°C)	Sintering time (h)	Density (g/cm³)/(%)	Porosity (%)
BTO	1260	4	2.49/41.4	31
	1330		3.65/60.6	18
	1400		3.93/65.2	7

Gaytan, Lin, Wicker et al, *Ceramics International*, 2014

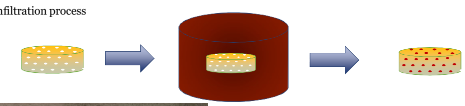
3D Printing of Piezoelectric Ceramics

- Have successfully been able to 3D print Barium Titanate using binder jetting technologies
- Print using Barium Titanate as the matrix for Lithium Niobate and PZT



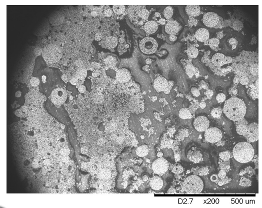
3D Printing of Piezoelectric Ceramics

- Infiltration process



3D Printing of Piezoelectric Ceramics

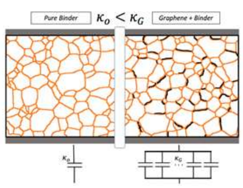
- Poling process
- DC field of 1.2 kV/mm was applied
- 2 hours
- 120 °C



The University of Texas at El Paso

4/11/18 2018 Annual Review Meeting for Crosscutting Research – Pittsburgh, PA 22/34

3D Printing of Piezoelectric Composites



$$K_e = K\left(1+\frac{3(\alpha-1)}{[\alpha+2-(\alpha-1)\varphi]}\{\varphi+f(\alpha)\varphi^2\}\right.$$

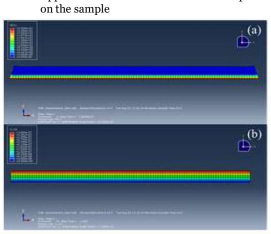
$$d_{33} = k_3^T \varepsilon^0 g_{33}$$

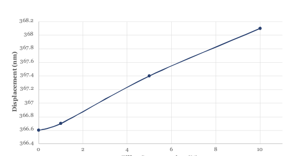
The University of Texas at El Paso

4/11/18 2018 Annual Review Meeting for Crosscutting Research – Pittsburgh, PA 23/34

3D Printing of Piezoelectric Composites

- Applied thermal stresses to the different piezoelectric composites to obtain the displacements generated on the sample



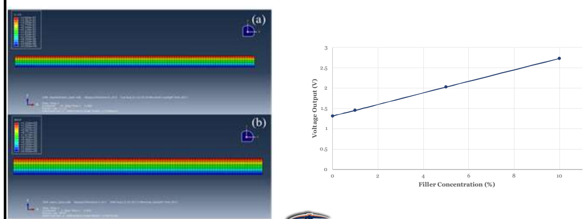


The University of Texas at El Paso

4/11/18 2018 Annual Review Meeting for Crosscutting Research – Pittsburgh, PA 24/34

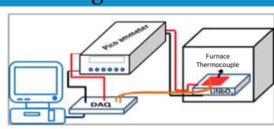
3D Printing of Piezoelectric Composites

- Used generated displacement from previous calculation as input for piezoelectric simulations



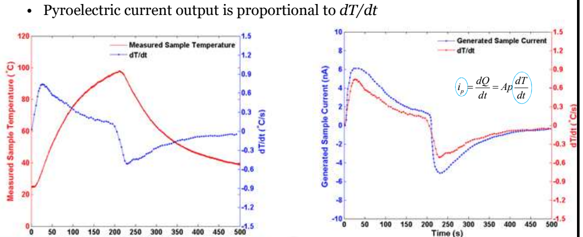
Direct Sensing

- $LiNbO_3$ placed inside a tube furnace with controlled temperature
- Picoammeter used for current measurement
- DAQ and Labview used for data processing



Results – Direct Sensing

- Pyroelectric current output is proportional to *dT/dt*

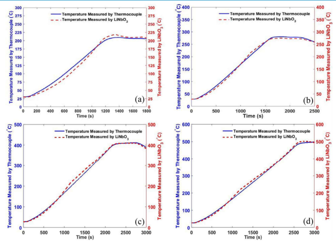


Results – Direct Sensing

- Demonstrated temperature sensing capabilities of piezoelectric ceramics up to 500℃

$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

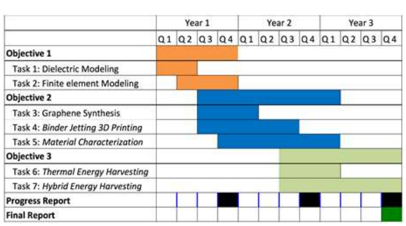
$$T_f = -\frac{1}{pA}\int_{t_i}^{t_f} I dt + T_i$$



Conclusions

- Pyroelectric energy harvesting using a lead free material was demonstrated
- Current and pyroelectric power were characterized at elevated temperatures
- Hybrid energy harvesting was also performed
- It's possible to improve the amount of energy harvested by improving the harvesting circuit design and circuit elements
- Direct sensing under high temperature conditions was demonstrated
- Currently working on the development of piezoelectric ceramic composites using additive manufacturing technologies

Schedule



Future Work

- Improve density of 3D printed ceramics
  - Bimodal particle size distribution
  - Surface modification
  - Design of experiments for printing parameters
- Energy harvesting characterization of 3D printed ceramics

The University of Texas at El Paso

Acknowledgement

- Funding support by the U.S. DOE NETL (DOE) Grant DE-FE0027502
- Program Manager: **Barbara Carney**, NETL

The University of Texas at El Paso

Student Involvement

MSME, Spring 2018
Manufacturing Engineer, LMC

BSME, Fall 2018
Summer Intern, Sandia National Lab

BSME, Spring 2018
Summer Intern, UCSB

BSME, Fall 2019
Summer Intern, Freeport McMoran

Publications

- Karim, H., Sarker, M. R. H., Shahriar, S., Shuvo, M. A. I., Delfin, D., Hodges, D., Tseng, T. L. B., Roberson, D., Love, N., & Lin, Y. (2016). Feasibility study of thermal energy harvesting using lead free pyroelectrics. *Smart Materials and Structures*, 25(5), 055022.
- Chavez, L. A.,Zayas Jimenez, F. O., Wilburn, B. R., Delfin, L. C., Kim, H., Love, N., and Lin, Y. (2018) Characterization of Thermal Energy Harvesting Using Pyroelectric Ceramics at Elevated Temperatures. Energy Harvesting and Systems, *In Press*.
- Chavez, L. A., Elicerio, V. F., Regis, J. E., Garcia Rosales, C. A., Kim, H., Love, N., and Lin, Y. (2018) Thermal and Mechanical Energy Harvesting Using Piezoelectric Ceramics. *Submitted*.
- Chavez, L. A., Elicerio, V. F., Lin, Y. (2018). Energy Harvesting Characterization of Piezoelectric Ceramics under Thermal, Mechanical, and Combined Loads. Materials Research Society, Spring 2018 Meeting.

The University of Texas at El Paso

Thank you

Questions?

The University of Texas at El Paso

4/11/18 2018 Annual Review Meeting for Crosscutting Research – Pittsburgh, PA 34/34