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

Investigators: Norman Love, Ph.D.
Ryan Wicker, Ph.D.
Yirong Lin, Ph.D.

Program Manager: Sydni Credle, Ph.D.

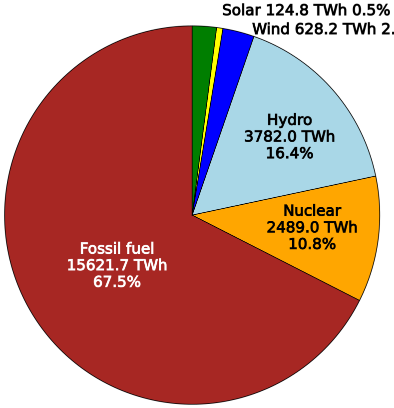
THE UNIVERSITY OF TEXAS
AT EL PASO

Agenda

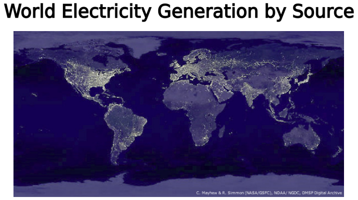
- Project Overview and Rationale
- Project Objectives
- Technical Tasks
- Schedule
- Cost plan & Risk management
- Student involvement
- Q&A

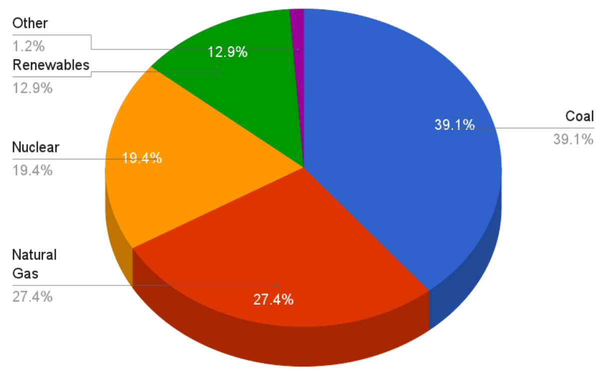
Motivation

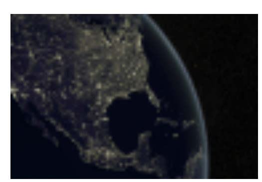
- Highly efficient and environmentally benign power and fuel systems require:
  - Critical Sensing in modern power plants and energy systems
  - Higher efficiencies in energy conversion
  - Lower emission for near-zero emission power plants
  - Enhanced material systems safety



World Electricity Generation by Source (2013)

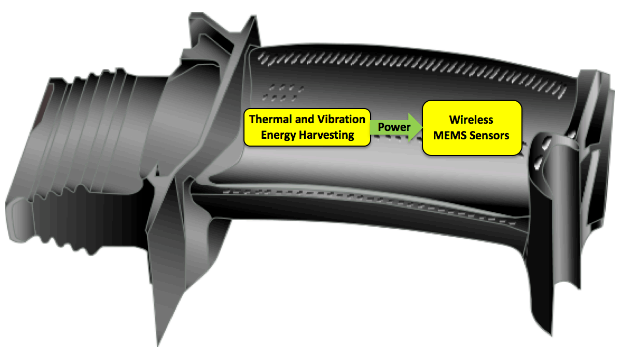


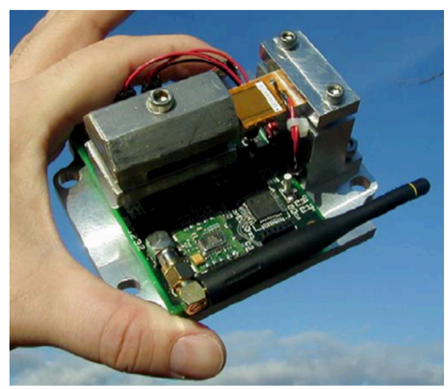


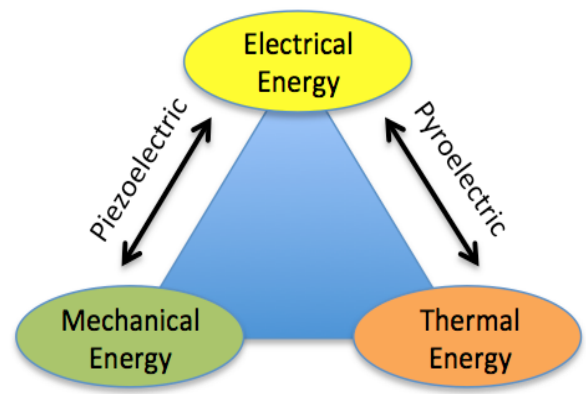


Background

- Energy Harvesting to Power Wireless Sensors
  - Vibration based: bulky, fatigue
  - Thermoelectric: hot end – cold end, temperature gradient needed
  - Pyroelectric: Absolute temperature change vs relative temperature
  - Feasibility of combined vibration and thermal energy harvesting
  - Realized by 3D printing technology



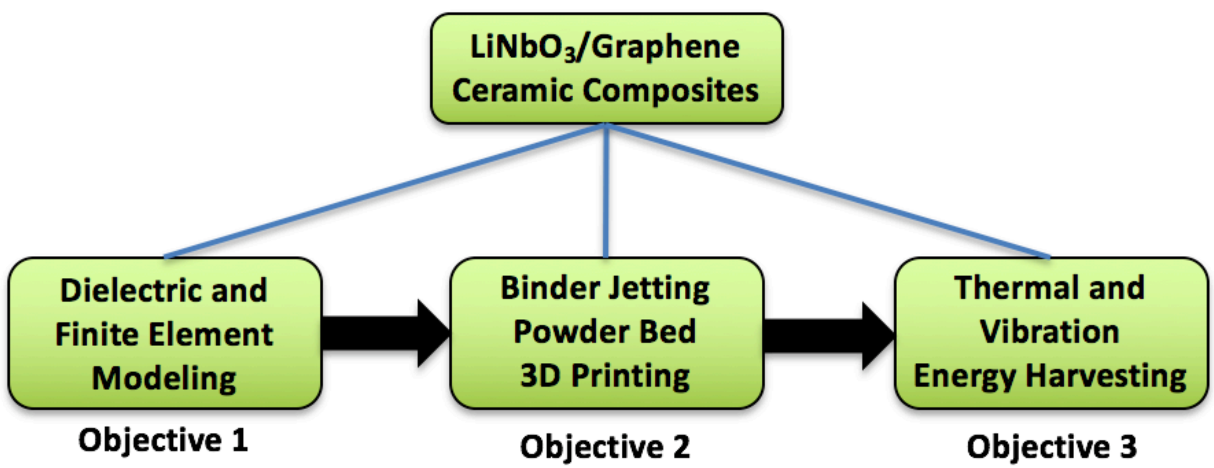




$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

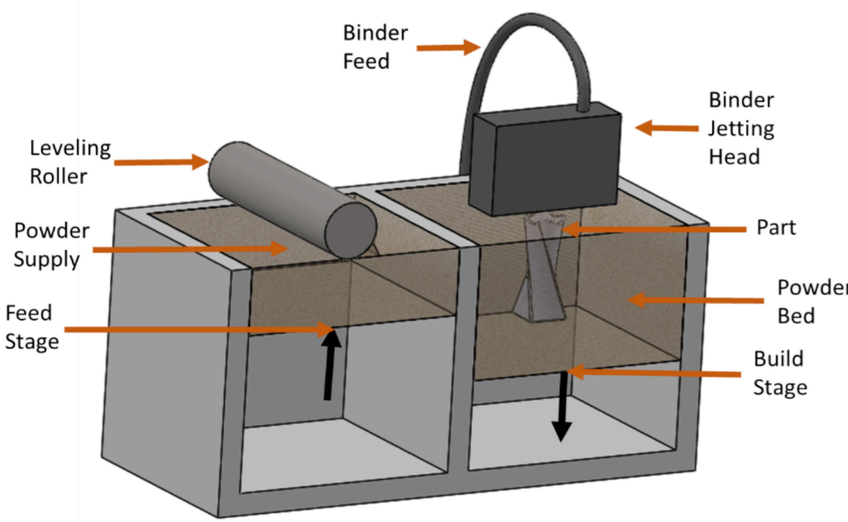
Objective/Vision

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

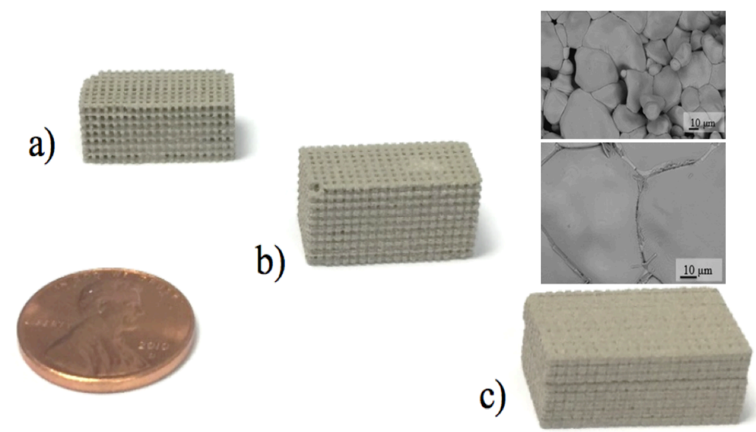


Background

- Powder bed binder jetting technique
- Binder jetting with layer by layer fabrication process
- Aqueous based binder can be modified

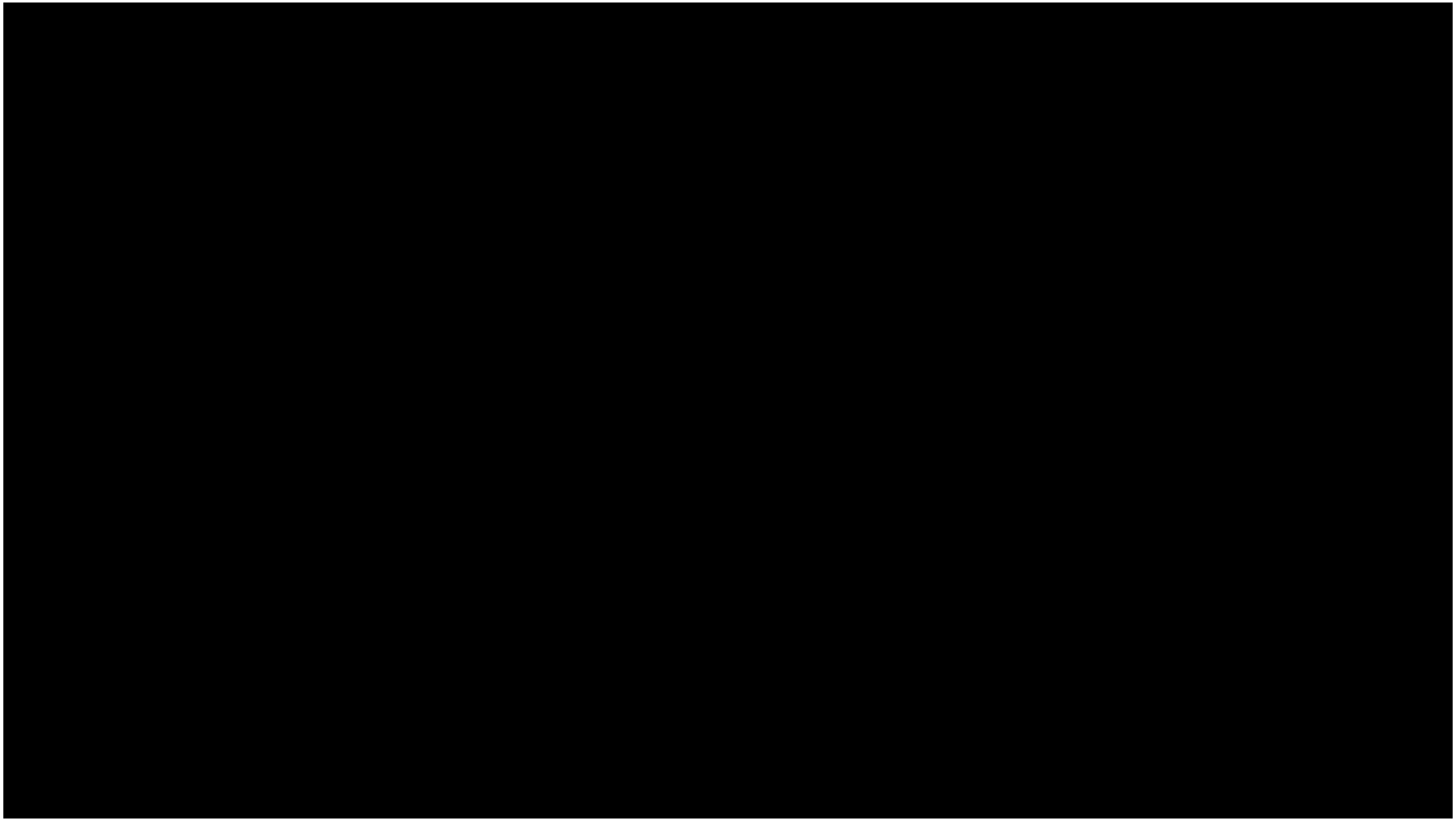


Schematic representation of binder jetting additive manufacturing technology.



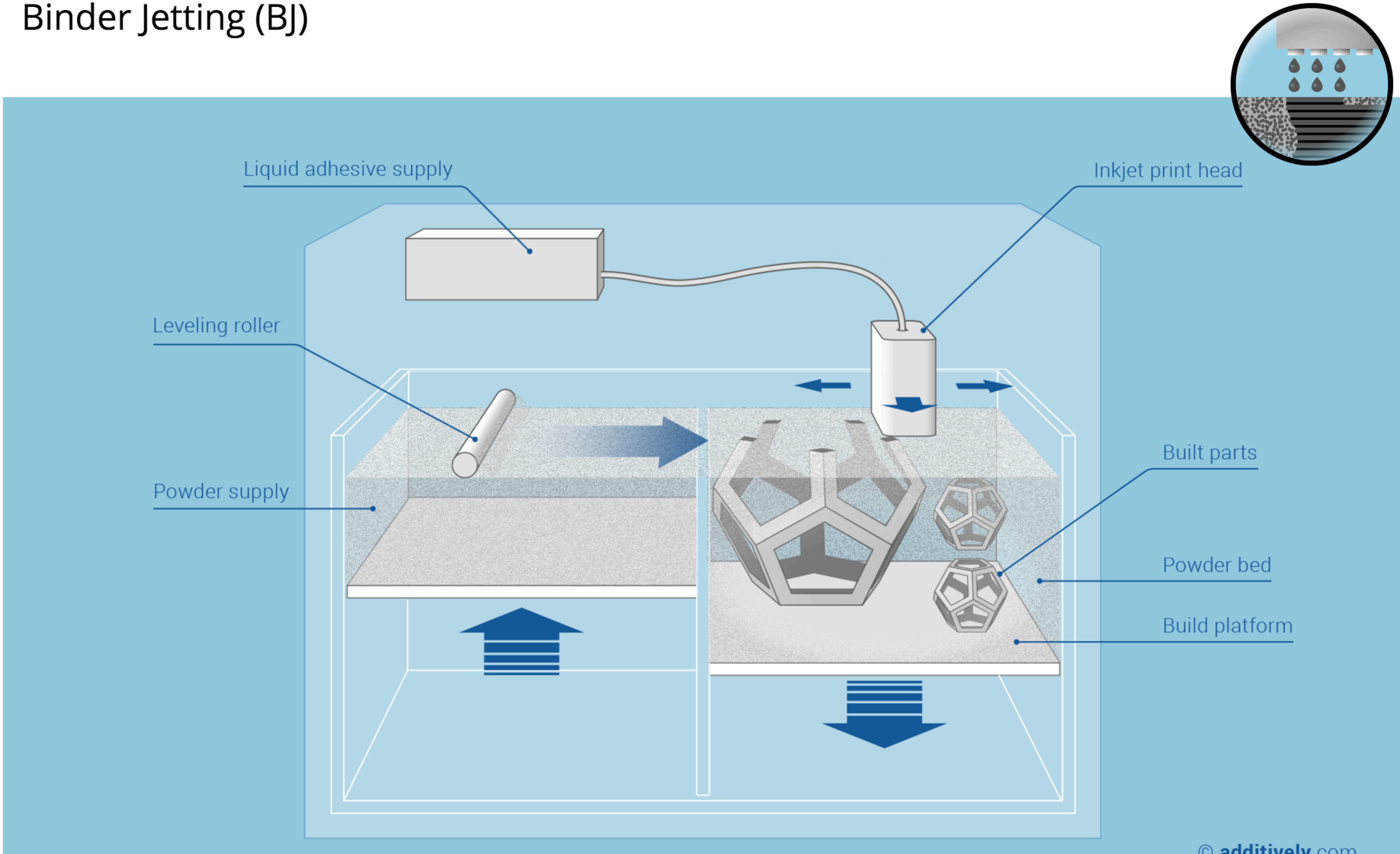
Al_2O_3 manufacture red via binder jetting with tailored density of (a) 25%, (b), 50%, and (c) 75%.

Binder Jetting 3D printing



Binder Jetting 3D printing

Binder Jetting (BJ)

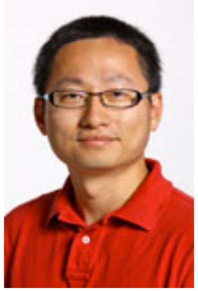


https://www.additively.com/en/learn-about/binder-jetting

Team Description and Assignment

- Norman Love
  - Energy harvesting finite element modeling (Objective 1)
  - High temperature energy harvesting (Objective 3)

- Ryan Wicker
  - 3D printing (Objective 2)



- Yirong Lin
  - Energy harvesting modeling (Objective 1)
  - Materials synthesis and characterization (Objective 2)
  - High temperature energy harvesting (Objective 3)

Task Description

- **Objective 1: Establish theoretical models to predict the effective material property**
  - Finite element modeling for dielectric and energy harvesting
  - Guide the fabrication of ceramic nanocomposites

- **Objective 2: Fabricate the ceramic-graphene nanocomposites using binder jetting 3D printing technique**
  - Synthesis of graphene oxide
  - Graphene oxide modified aqueous binder for 3D printing
  - Graphene reduction and ceramic sintering
  - Material characterization

- **Objective 3: Determine energy harvesting properties**
  - Mechanical energy harvesting
  - Thermal energy harvesting at high temperature
  - Simultaneous energy harvesting

Task Description - Objective 1

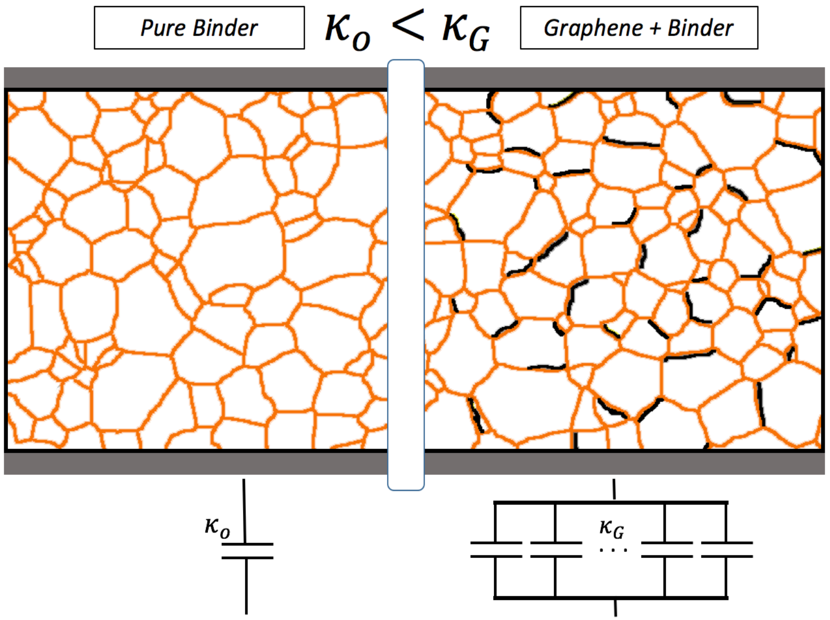
- **Task 1.1: Modeling to predict dielectric property of nanocomposites**

- Enhanced dielectric could lead to increase of energy harvesting efficiency

- Thermal conductivity modeling of Graphene could lead to higher thermal conductivity in ceramics

- Percolation threshold is the theoretical limit

- Finite element modeling will be performed to predict the dielectric and thermal conductivities



$$\kappa \propto \kappa_m |f - f_c|^{-s}$$

Task Description - Objective 1

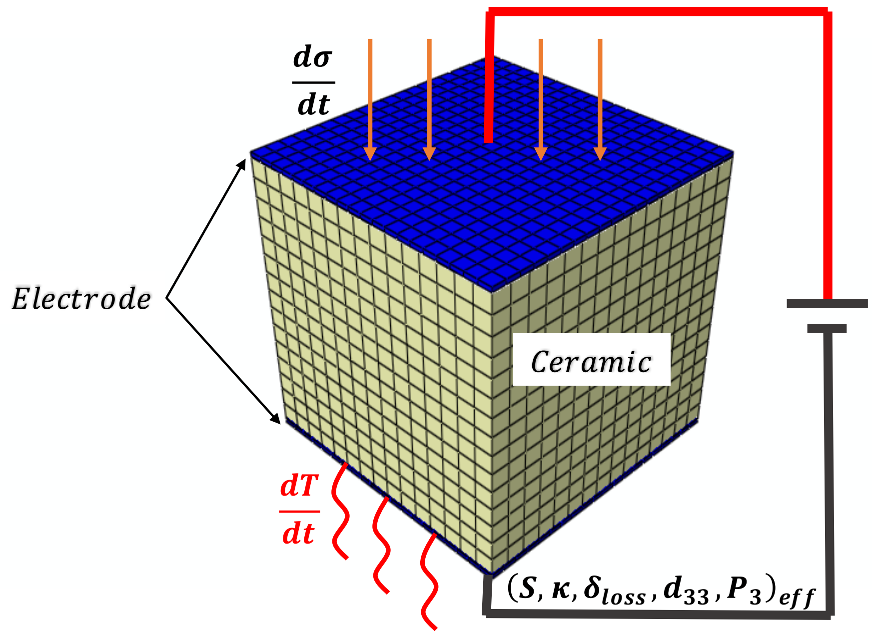
- **Task 1.2: Finite Element Modeling to predict dielectric property of nanocomposites**

- Commercial finite element ABAQUS will be used for finite element analysis

- Both piezoelectric and pyroelectric property will be investigated

- Effective dielectric constant, effective pyroelectric constant, effective piezoelectric constant will be predicted

- Modeling results will guide the fabrication but validated by experimental testing



Task Description - Objective 2

- **Task 2.1: Synthesis of graphene oxide**

- Modified Hummer's method will be used for large scale synthesis of graphene oxide

- Surface functionalization can be controlled in processing

- Graphene oxide can be uniformly dissolved in water, which is the 90% content in binder solution

- Graphene oxide can be reduced to graphene in final ceramic for enhanced mechanical, thermal, and dielectric properties

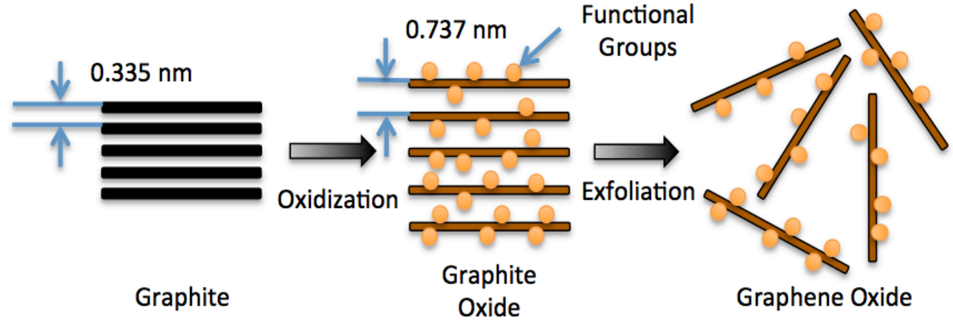


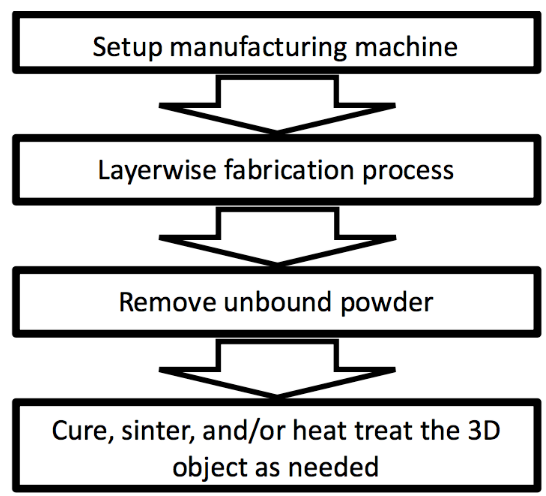
Illustration of fabrication process for graphene oxide sheets

Task Description - Objective 2

- **Task 2.2: Modified binder for ceramic-graphene composites fabrication**

- Only ceramic will be used for binder jetting fabrication first to characterize the fabrication of $LiNbO_3$

- Fabrication parameters such as layer thickness, powder disperse speed, and binder saturation level will be modified to optimize fabrication

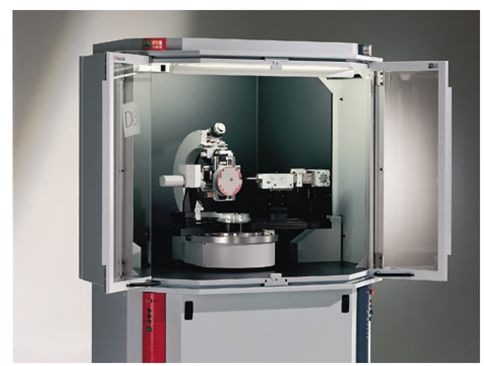


- Binder solution will be modified with graphene oxide

- Functional gradient can be achieve by binder saturation level during the layer by layer fabrication process

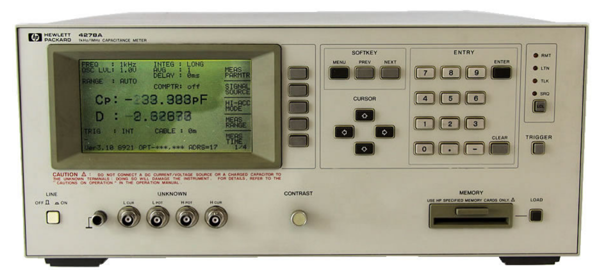
Task Description - Objective 2

- **Task 2.3: Post processing**
- **Heat treatment:** Two stage sintering profile will be used, binder burning out and full sintering
- **Sintering:** Tube furnace with controlled atmosphere to reduce graphene oxide to graphene
- **Poling process:** High voltage at elevated temperature
- **Surface Morphology**: SEM
- **Density**: ASTM standard
- **Crystal structure**: XRD



Task Description - Objective 2

- **Task 2.3: Material characterization**
- **Piezoelectric** property: d_{33} meter
- **Pyroelectric** property: furnace and pico-ammeter
- **Weight percentage:** Both Graphene and $LiNbO_3$: TGA
- **Dielectric property**: LCR meter
- **Material interface**: FTIR



Task Description - Objective 3

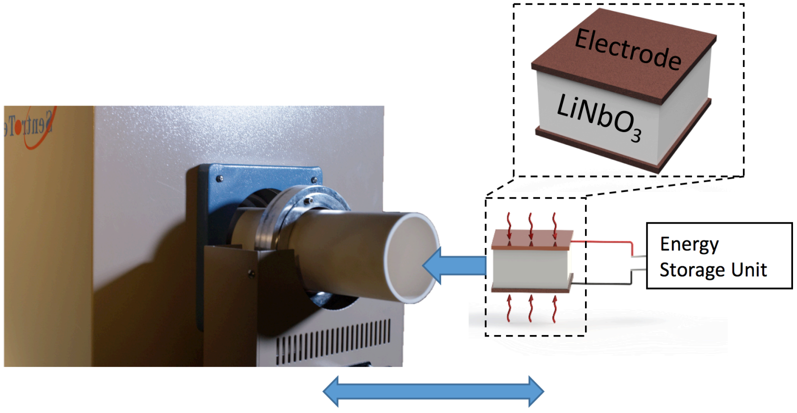
- **Task 3.1: Thermal Energy Harvesting Characterization**

- A tube furnace will be used to quantify the thermal energy harvesting property of the fabricated ceramic composites

- Temperature fluctuation at different temperature baseline will be investigated for the nonlinear energy harvesting property

- A resistive load will be used the quantify energy can be harvested

- Direct energy storage in supercapacitor will be investigated

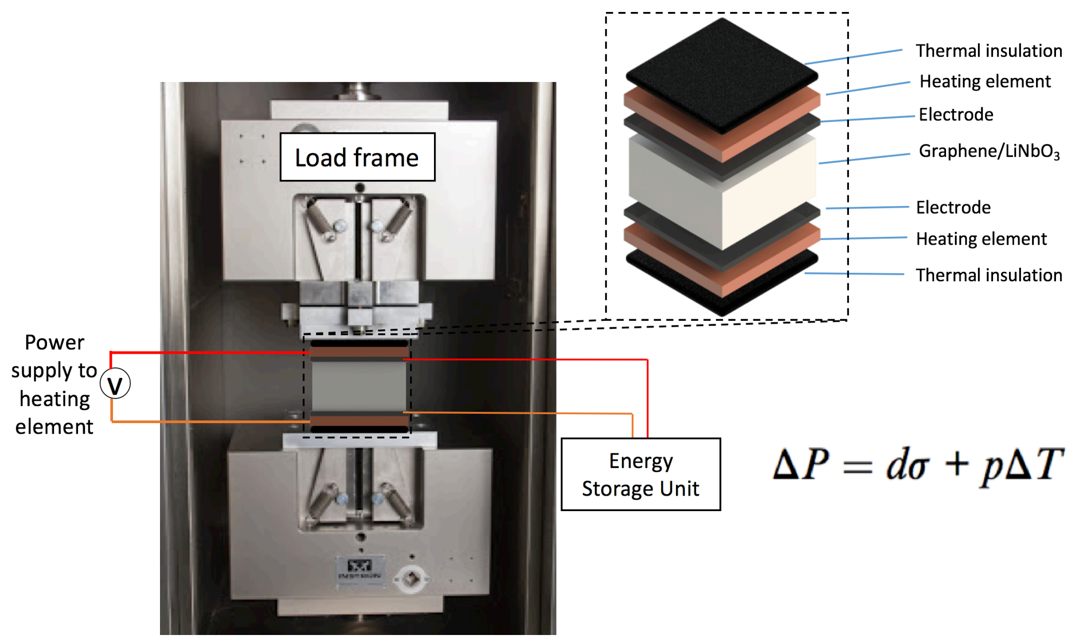


Task Description - Objective 3

- **Task 3.2: Hybrid Energy Harvesting Characterization**

- A parallel and series synchronized switch harvesting on inductor (SSHI) method will be used to synchronize the piezoelectric and pyroelectric energy

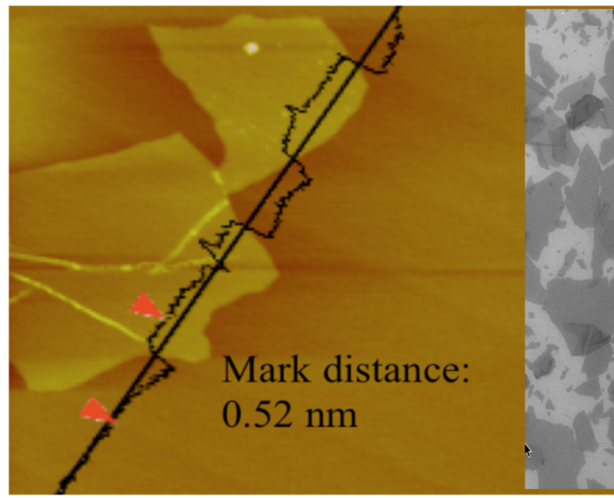
- A load frame with heating element will be developed for combinded mechanical and thermal loading

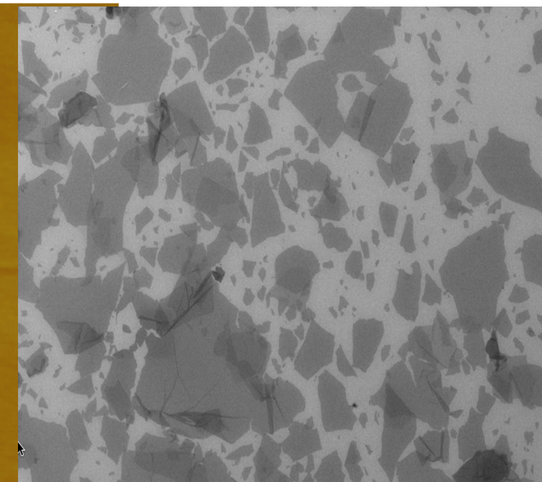


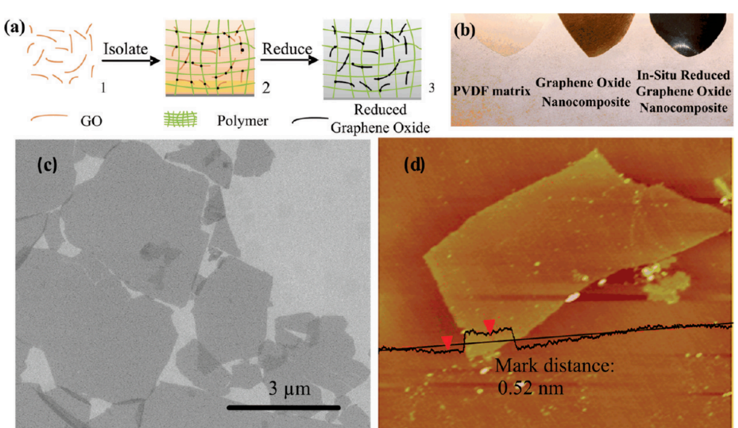
$$\Delta P = d\sigma + p\Delta T$$

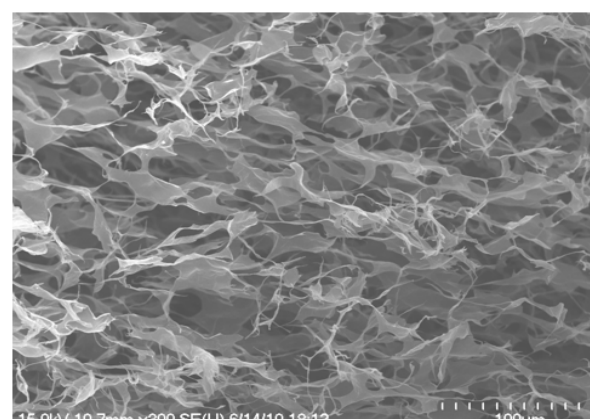
Preliminary Result

- Fabrication of Graphene and Graphene Oxide
- The synthesized graphene is single layer with large size
- Graphene oxide can be dispersed in various solution for casting composites
- Three dimensional porous material provides light weight and high surface area



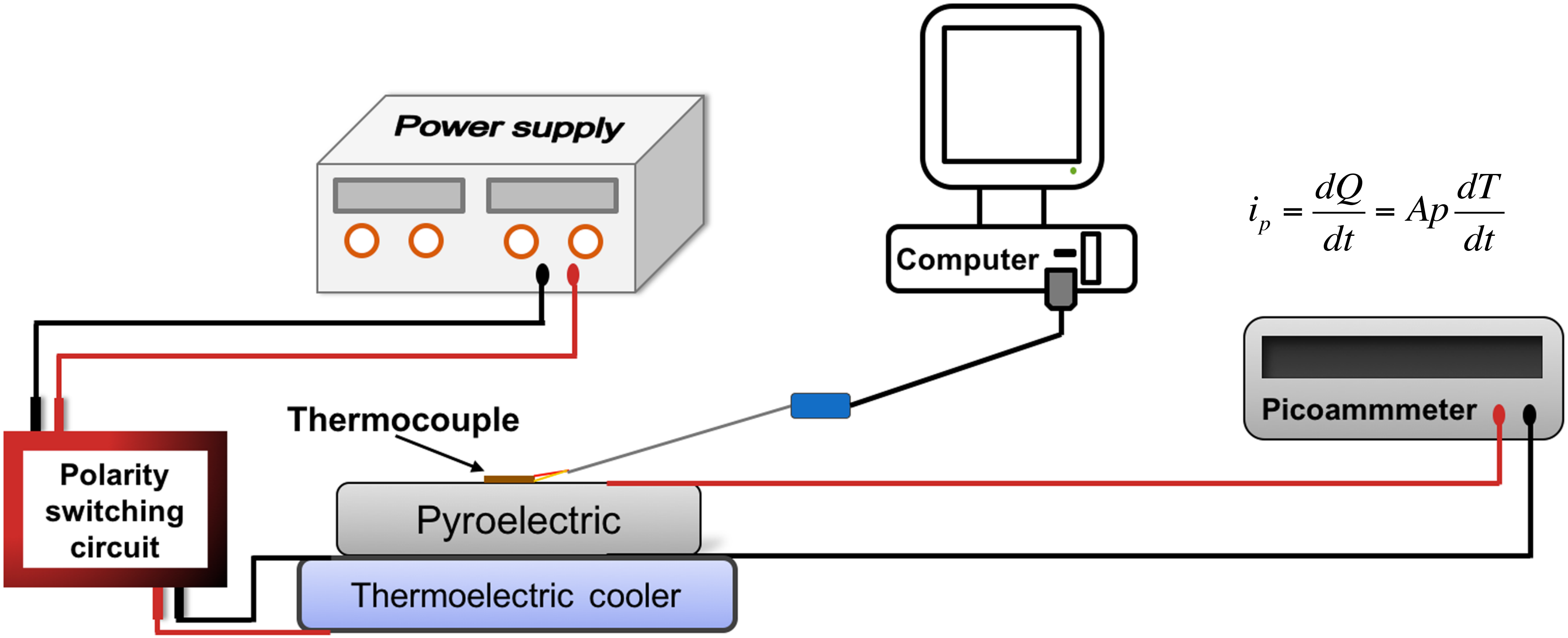






Preliminary Result

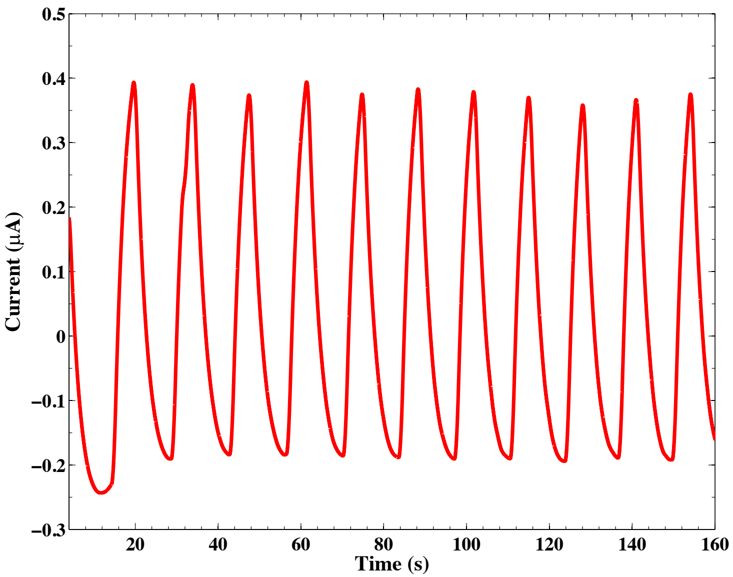
- Thermal Energy Harvesting Setup



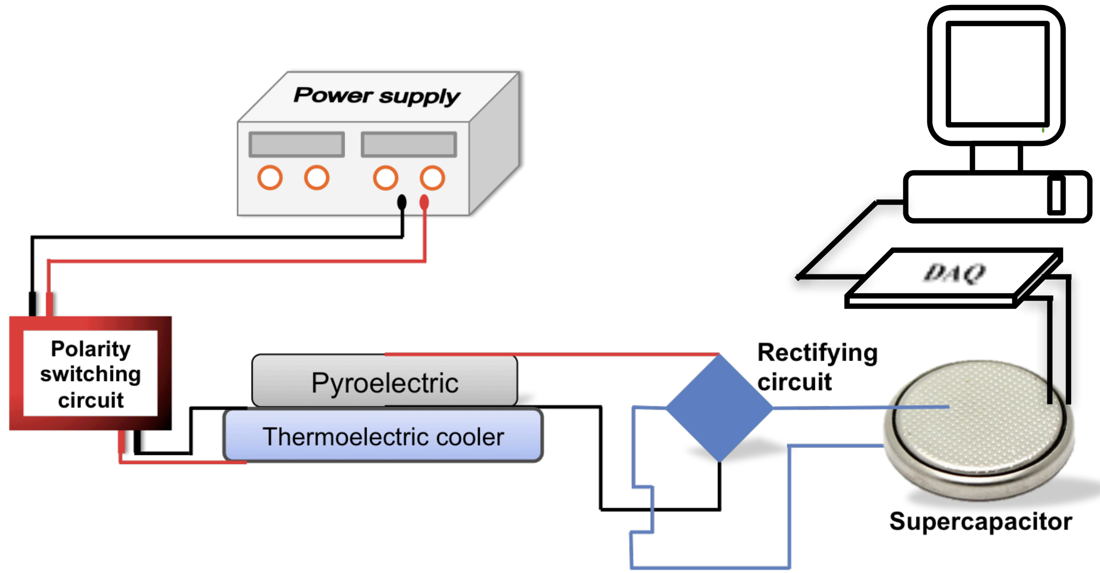
$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

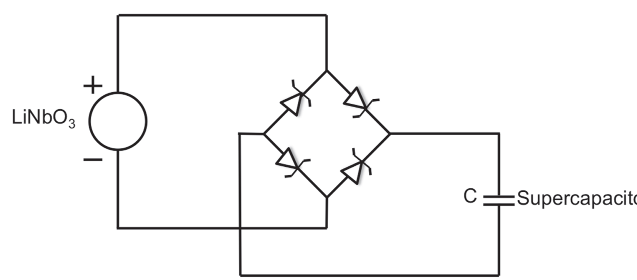
Preliminary Results

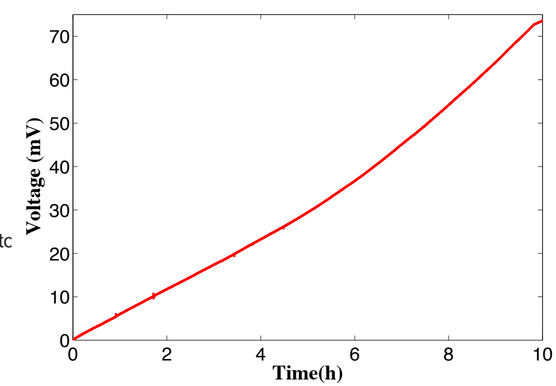
- Current generated and storage from $LiNbO_3$ with heating and cooling



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





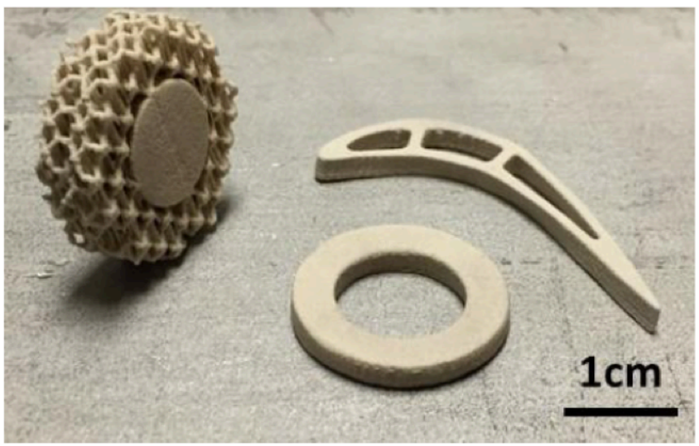


Preliminary Results

- 3D printed ceramics

▪ Ceramics enabled by binder jetting technology

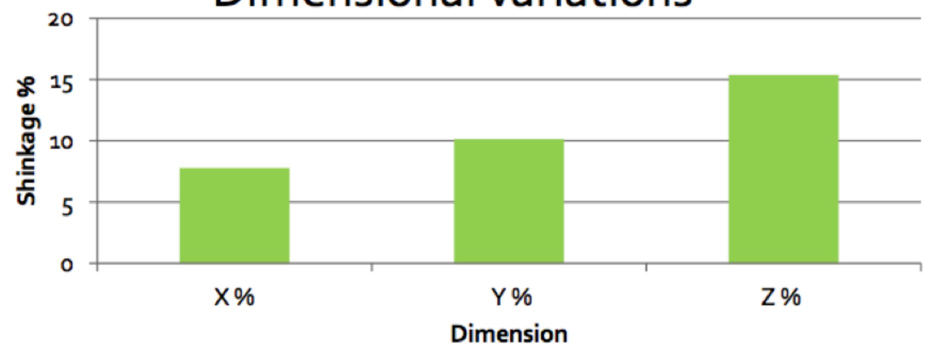
Fabrication of complex shapes



Density results

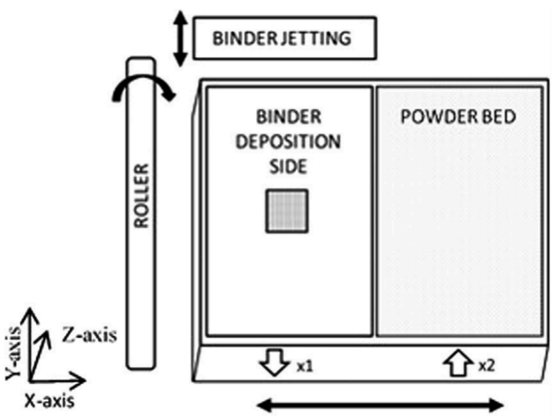
Layer Thickness (µm)	Sintered Profile (hrs)	% Rel ρ
106	2	91.10
45	2	92.72
106	16	94.04
45	16	96.51

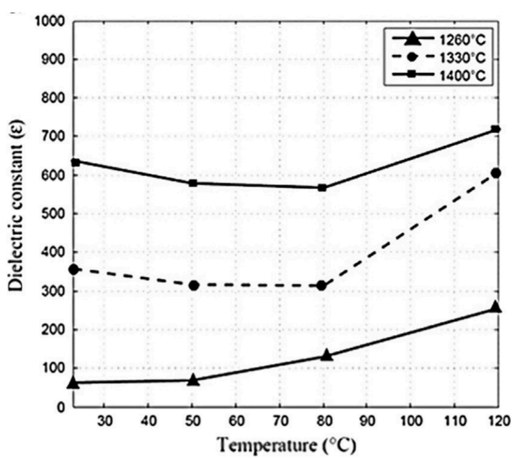
Dimensional variations

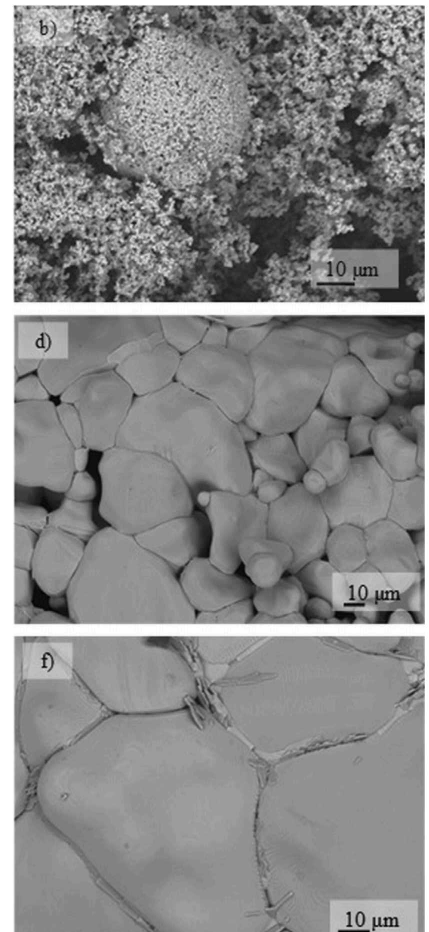


Preliminary Results

- $BaTiO_3$ was 3D printed using powder bed binder jetting technologies
- 60% density was achieved
- 80% of theoretical piezoelectric coupling was achieved

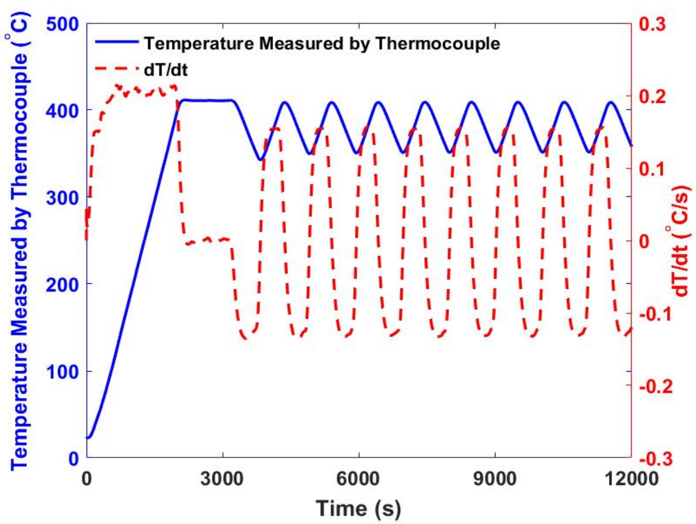


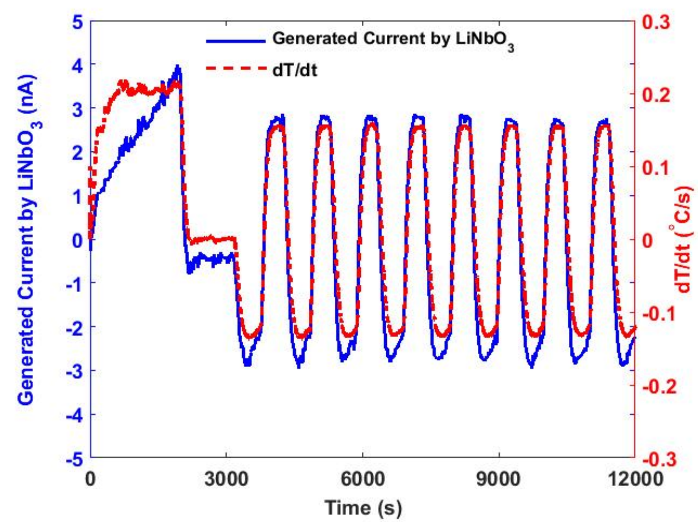




Preliminary Results

- The nonlinear pyroelectric property of $LiNbO_3$ was characterized
- Pyroelectric current is proportional to temperature change dT/dt
- At higher temperature, the pyroelectric coefficient is higher, better for thermal energy harvesting



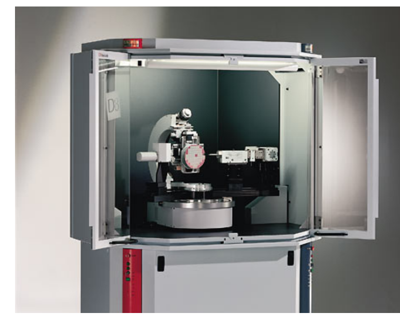


Temperature Range (°C)	Pyroelectric Coefficient, 10^{-5}, (C/m² °C)	Measurement Method
25-218	-8.5	Manufacturer Value
218-240	-14.85	Dynamic Test
257-292	-18.74	Dynamic Test
343-392	-21.81	Dynamic Test
350-410	-23.70	Dynamic Test
410-500	-23.70	Dynamic Test

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

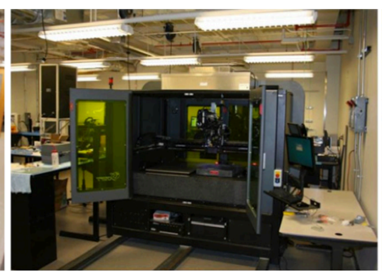
Resources and Facilities

- Challenger-Columbia Structures and Materials Research Facility
  - Class 100 Clean Room Facility
  - Pulsed Laser Deposition System
  - Electron Beam Deposition System
  - RF Magnetron Sputtering System
  - High Temperature Induction Furnaces
  - Thermal Cycling Systems
  - Planetary Ball Mill
  - Scanning Electron Microscopy
  - Energy Dispersive X-Ray Spectroscopy
  - X-Ray Photoelectron Spectroscopy
  - Nano-Indentation System
  - Fatigue and Impact Testing Systems



Resources and Facilities

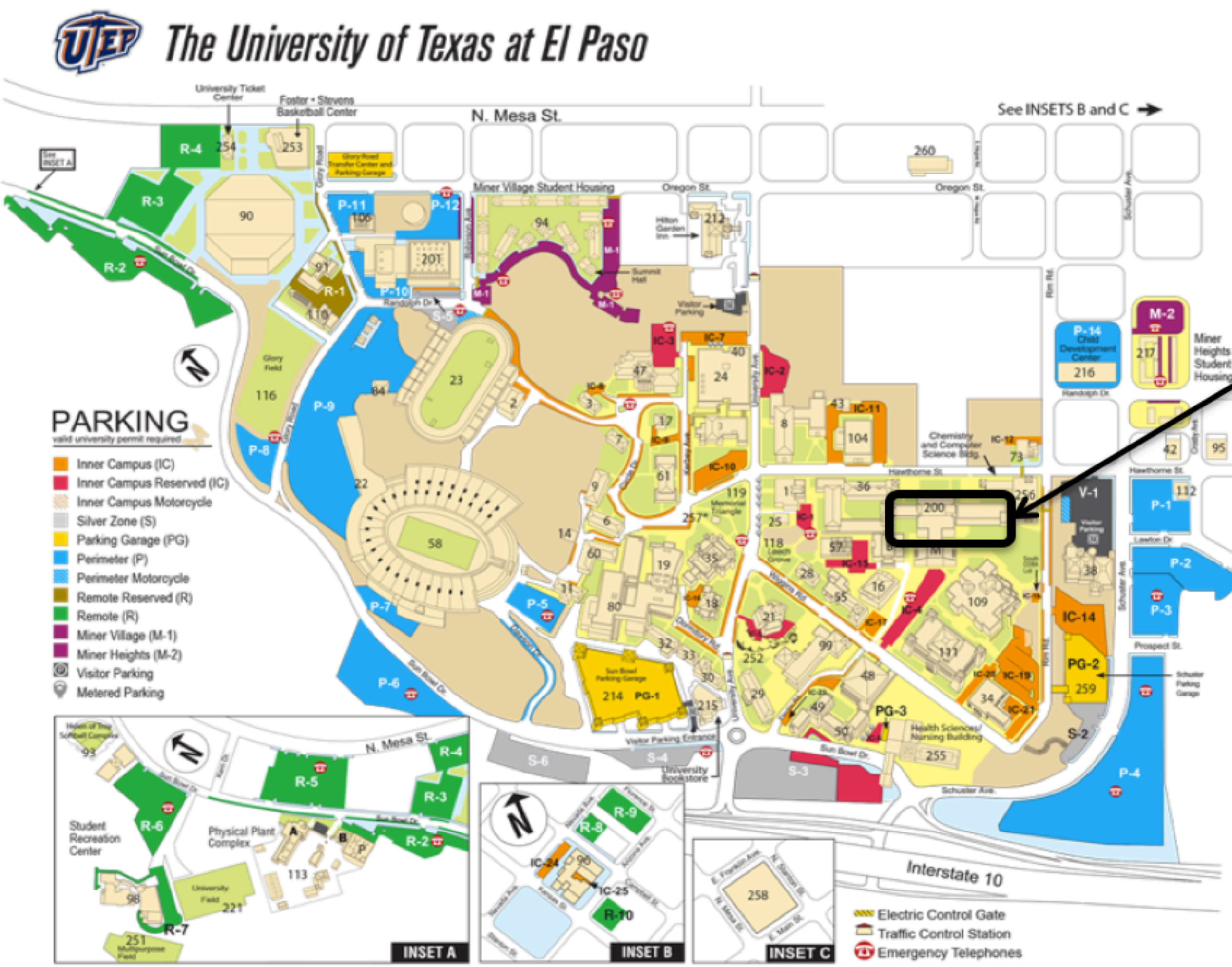
- Additive Manufacturing Equipment:
  - 2, Arcam Electron Beam Melting Machine (2, Arcam A2 EBM machine,Arcam S12 EBM Hot machine).
  - 11, Stratasys Fused Deposition Modeling Machines (1, Fortus 900mc; 1, Fortus 400mc; 1, FDM Titan; 7, FDM 2000/3000 – used as multi-axis deposition systems and FDM materials research machines; 1, UPrint)
  - 11, 3D Systems Stereolithography Machines (3, Viper si2 high resolution systems; 1, SLA 500/5000; 7, SLA 250s – used primarily as research machines
  - Custom Micro-Stereolithography Machine (with 2-micron resolution and multiple material capabilities).
  - 1, Objet PolyJet Machine (1, Objet Eden 333)
  - 1, DTM Selective Laser Sintering Machine (1, DTM, now 3D Systems, Sinterstation 2000)
  - 1, ZCorp 3D Color Printer (1, Z510)
  - 1, EnvisionTec DLP Machine (1, Vanquish)
  - 2, nScrypt Micro-Dispensing
  - 3, Desktop 3D Printers (1, VFlash; 1, Fab@Home; 1, Solido SD300 Pro)





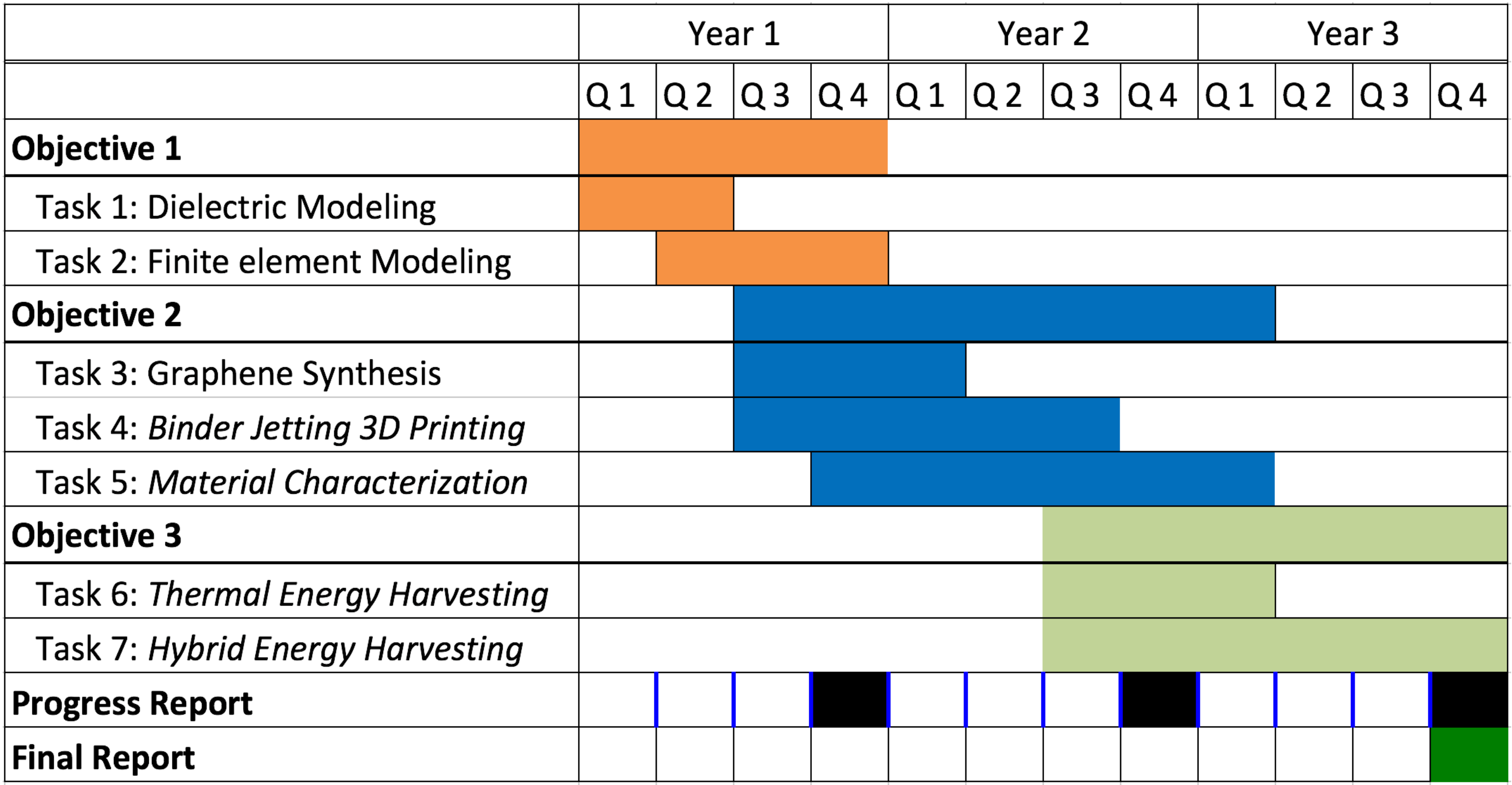
Site Plan Map



Location of the building where proposed work will be performed

(Engineering &Sciences Complex)

Schedule

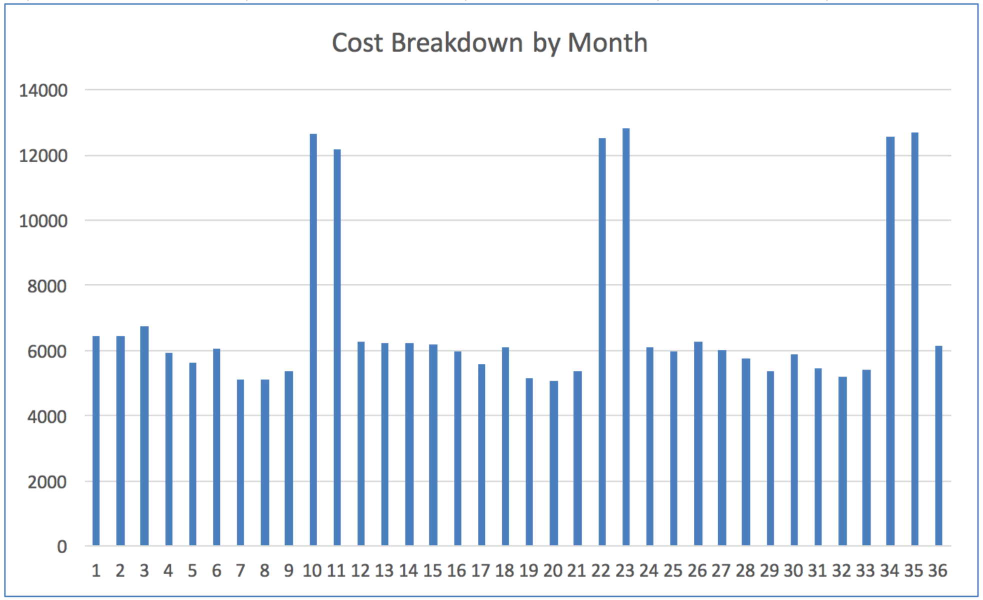

Year 1
Year 2
Year 3
Q 1
Q 2
Q 3
Q 4
Q 1
Q 2
Q 3
Q 4
Q 1
Q 2
Q 3
Q 4
Objective 1
Task 1: Dielectric Modeling
Task 2: Finite element Modeling
Objective 2
Task 3: Graphene Synthesis
Task 4: *Binder Jetting 3D Printing*
Task 5: *Material Characterization*
Objective 3
Task 6: *Thermal Energy Harvesting*
Task 7: *Hybrid Energy Harvesting*
Progress Report
Final Report

Cost Breakdown

SUMMARY OF BUDGET CATEGORY COSTS PROPOSED

(Note: The values in this summary table are from entries made in each budget category sheet.)

CATEGORY	Budget Period 1 Costs	Budget Period 2 Costs	Budget Period 3 Costs	Total Costs	Project Costs %	Comments (Add comments as needed)
a. Personnel	$34,737	$35,782	$36,851	$107,370	42.9%	
b. Fringe Benefits	$6,549	$6,679	$6,815	$20,043	8.0%	
c. Travel	$2,000	$2,000	$2,000	$6,000	2.4%	
d. Equipment	$0	$0	$0	$0	0.0%	
e. Supplies	$6,642	$5,508	$5,000	$17,150	6.9%	
f. Contractual						
Sub-recipient	$0	$0	$0	$0	0.0%	
Vendor	$0	$0	$0	$0	0.0%	
FFRDC	$0	$0	$0	$0	0.0%	
Total Contractual	$0	$0	$0	$0	0.0%	
g. Construction	$0	$0	$0	$0	0.0%	
h. Other Direct Costs	$5,000	$5,000	$5,000	$15,000	6.0%	
Total Direct Costs	$54,928	$54,969	$55,667	$165,563	66.2%	
i. Indirect Charges	$28,013	$28,033	$28,391	$84,437	33.8%	
Total Project Costs	$82,941	$83,002	$84,058	$250,000	100.0%	



Decision Points

Decision Points:

Decision Point 1

Parameter: Predicting energy harvesting property of graphene/$LiNbO_3$ ceramic by modeling
Components: All efforts under Task 1 and 2
Bearing: Ensure material properties and feasibility of energy harvesting
Criteria: Reliability and integrity of data
Planned Assessment: 06/30/17
Successor: Fabrication of ceramic according to modeling effort

Decision Point 2

Parameter: Fabrication of graphene/$LiNbO_3$ ceramic
Components: All efforts under Task 3 through Task 5
Bearing: Ensure high fidelity measurement and characterizations
Criteria: Reliability and integrity of data
Planned Assessment: 06/30/18
Successor: Energy harvesting evaluation of graphene/$LiNbO_3$ ceramic

Decision Point 3

Parameter: Test and determine energy harvesting property
Components: All efforts under task 6 through task 7
Bearing: Ensure high fidelity measurements and characterizations
Criteria: Reliability and integrity of data
Planned Assessment: 06/30/19
Successor: NA

Milestones

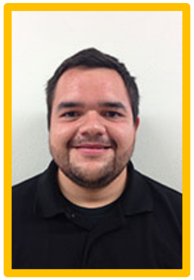
TABLE 1: MILESTONE LIST

	Mile-stone	Title	Description	Relation	Validation	Date
Budget Period 1						
	M1	Updated Project Management Plan	Complete plans for Facility, Resources, Quality, Safety, Documentation Management, etc.	Predecessor of all following tasks	Report Plan delivered to DOE PM	12/31/16
	M2	Kickoff Meeting	Review of objectives, technical and managerial approach and other facets of	Predecessor for tasks	Presentation delivered to DOE PM	12/31/16
	M3	Modeling results to predict energy harvesting property	Volume fraction of graphene for optimized energy harvesting, thermal and vibrational energy harvesting feasibility	Data set for 1st Decision Point	Summarized in nearest Quarterly Report	06/30/17
Budget Period 2						
	M4	Synthesis of graphene	Material property of graphene, large scale synthesis	Predecessor for subsequent tasks	Summarize results in Quarterly Report	10/31/17
	M5	Fabrication of ceramic using binder jetting 3D printing	Fabrication parameter optimization, post-processing parameters	Predecessor for subsequent tasks	Summarize results in Quarterly Report	01/31/18
	M6	Material property characterization	Materials geometry, microstructure, piezoelectric and pyroelectric property	Data set for 2nd Decision Point	Summarize results in Quarterly Report	06/30/18
Budget Period 3						
	M7	Thermal energy harvesting	Demonstration of energy harvesting property at high temperature (1000 °C)	Predecessor for subsequent tasks	Summarize results in Quarterly Report	10/31/18
	M8	Hybrid energy harvesting	Determine the energy harvesting property using combined vibrational and thermal energy	Data set for 3rd Decision Point	Summarized in Quarterly Report	03/31/19
Outside Budget Periods						
	M9	Final Report	Summary of experimentation, findings, and data set	Final	Report	07/31/19

Students Involvement

Total students will be supported by this project

- Graduate students: 2 for 36 months (20% DOE, 80% UTEP)
- Undergraduate students: 2 (100% UTEP)
- All minority students involved



Jorge Mireles

Jose Gonzalez

Mariana Castanéda

Fernando Torres

Acknowledgment

- Funding support from DOE-NETL, Grant DE-FE0027502

- Sydni Credle
  - Federal Project Manager

- Robert Romanosky
  - Deputy Director



NavAir

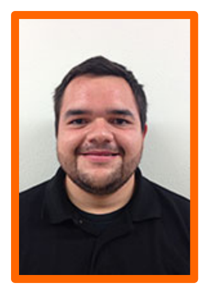
Exxon


Intel

Intel

Intel





Thank you

Questions?

Center for Space Exploration and Technology Research
W.M. Keck Center for 3D innovation

Department of Mechanical Engineering
The University of Texas at El Paso