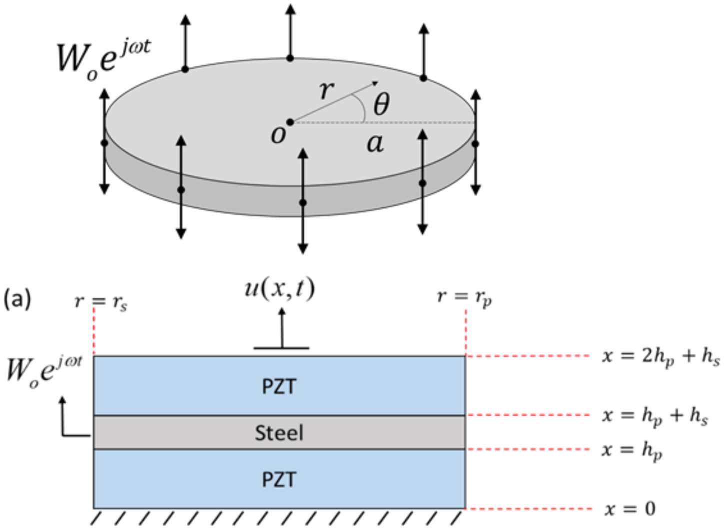
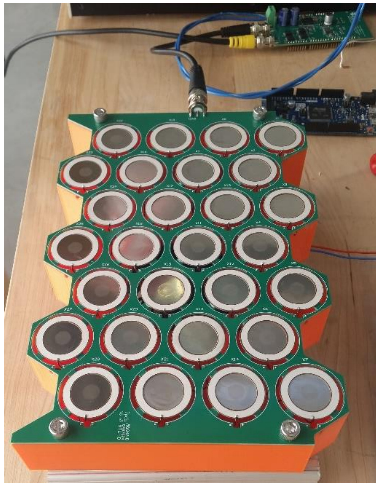




Ultrasonic Clothes Dryer

Oak Ridge National Laboratory, GE Appliances

Viral K. Patel, R&D Associate Staff

patelvk@ornl.gov

Project Summary

Timeline:

Start date: 07/12/2017

Planned end date: 07/12/2020

Key Milestones

1. Specification for full-scale dryer prototype, 12/31/2018 (complete)
2. Full dryer design with parts ordered, 06/30/2019
3. Functioning prototype ultrasonic dryer with the ability to measure drying performance as well as energy advantage, 12/31/2019

Budget:

Total Project $ to Date:

- DOE: $1,900K
- Cost Share: $800K

Total Project $:

- DOE: $1,900K
- Cost Share: $1,300K

Key Partners:

GE Appliances	Cooperative research and development agreement (CRADA) partner
Virginia Polytechnic Institute and State University	Academic partner (subcontract)

Project Outcome:

- This project will develop the world's first precommercial ultrasonic clothes dryer prototype with an equivalent energy factor (EF) higher than 5.4 lb/kWh without increasing drying time by more than 20% over a baseline unit
- The primary energy savings technical potential will be 280 TBtu for the 2030 energy market in all climate zones
- This project supports the 2030 Multi-Year Program Plan (MYPP) goal to develop cost-effective technologies capable of reducing a building's energy use per square foot by 45%, relative to 2010

Team

Oak Ridge National Laboratory

Viral K. Patel, R&D Staff, Project PI
- Experimental prototype development and testing
- Project management
- Research plan development

Ayyoub Momen, R&D Staff
- Wide range of ultrasonics expertise
- Dynamic system modeling

Kyle Reed, Pos-masters Staff
- Power electronics expertise
- Amplifier fabrication and testing
- Prototype testing

GE APPLIANCES

Quentin Pollett, Director, Advanced Systems Clothes Care Technology
- Integration of ultrasonic technology into dryer prototype
- Subsystem design
- Guidance on testing and cycle parameters

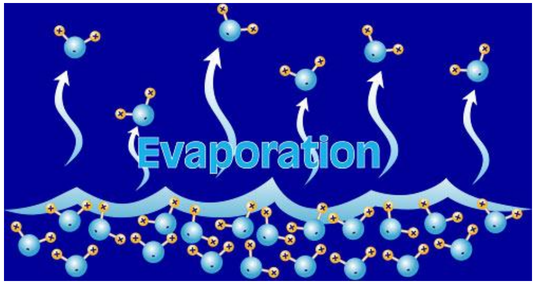
VIRGINIA TECH

Shima Shahab, Professor
- Contactless acoustic energy transfer
- Acoustofluidics
- Piezoelectric actuation

Eric Dupuis, PhD student
- Ultrasonic transducer modeling and simulation
- Experimental validation

Challenge

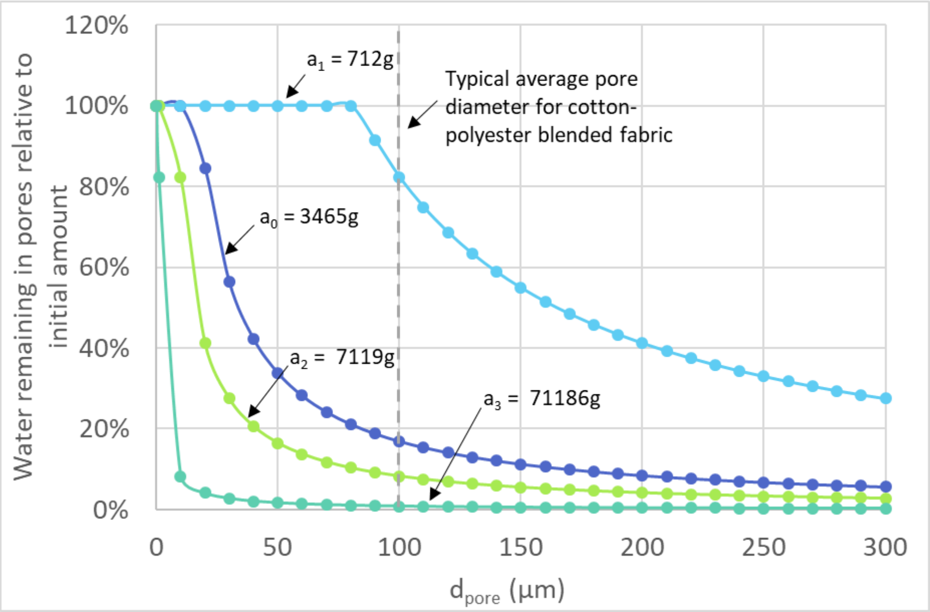
- **Electric clothes dryers consume about 4% of total annual residential electricity use (60 TWh) and are one of the largest energy-consuming appliances in US households**

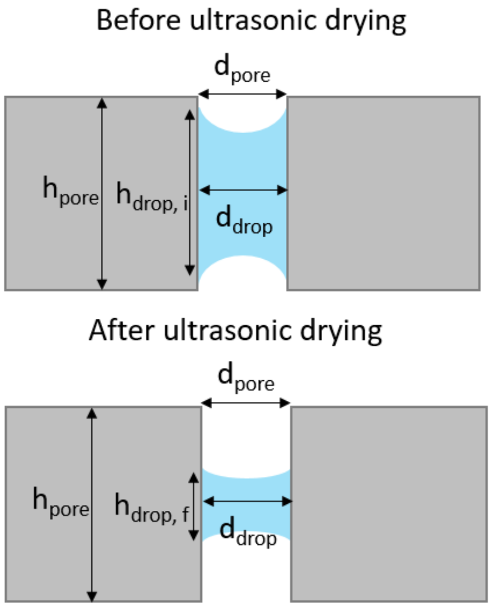


- **Heat-based drying in conventional clothes dryers is inefficient:**
  - Conventional evaporation-based dryers must overcome the latent heat of evaporation and thus ideally need about 2453–2257 kJ/kg_{water}
  - Considering the losses, existing dryers perform at 54–66% of their theoretical maximum efficiency
- **Conventional electric-resistive dryers have an EF of ~3.73 (lb/kWh) and a drying time of ~30–45 minutes**

Approach

- **Ultrasonic drying technology uses piezoelectric elements to shake (vibrate) the fabric at high frequency, resulting in moisture removal**
  - This results in mechanical drying through vibration instead of thermal drying
  - Equilibrium scale analysis for a single microscopic pore where we assume:
    - Simple harmonic motion of the form: $y = A sin(\omega t)$
    - The driving force is mainly inertia of water: $F_{vib} \sim m_{drop} A \omega^2$
    - The main resistive force is capillary action: $F_{cap} \sim \sigma \pi d_{pore} cos\theta$



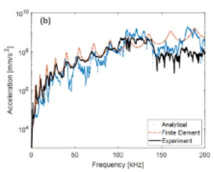


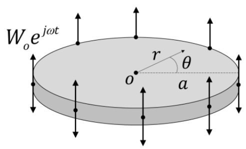
Approach

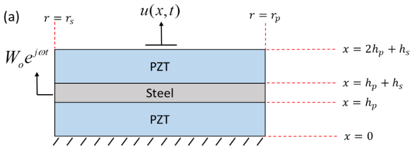
- CRADA project began 07/2017 and builds on previous work on a mid-scale prototype ultrasonic clothes dryer
- High-level approach:

FY18	FY19	FY20

Detailed ultrasonic transducer modeling







High-efficiency amplifier development

Experimental testing of compact printed circuit board (PCB) ultrasonic modules

Prototype design

Prototype fabrication and testing

Performance testing and demonstration of significant improvement over state of the art

Impact

- **This project can potentially revolutionize the clothes drying industry with the world's first precommercial ultrasonic clothes dryer prototype with an equivalent EF higher than 5.4 lb/kWh**
  - This improvement can result in primary energy savings technical potential of 280 TBtu for the 2030 energy market in all climate zones
- **Eliminating the need for a high flow rate of high-temperature air will minimize issues with lint in the air processing system and will allow clothes to last longer**
- **The technology is branching into many other areas: (a) dehumidification, (b) desalination, (c) heat exchanger performance enhancement, and (d) noncontact ultrasonic drying**

Impact

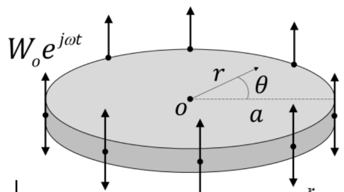
- **The project has made significant advancements in our fundamental understanding of ultrasonic drying and has been disseminated to the wider research community:**

1. Dupuis, E., Momen, A. M., Patel, V. K., and Shahab, S., 2019, "Electroelastic investigation of drying rate in the direct contact ultrasonic fabric dewatering process," *Applied Energy*, Vol. 235, pp. 451-462. DOI: https://doi.org/10.1016/j.apenergy.2018.10.100.
2. Patel, V. K., Reed, F. K., Kisner, R., Peng, C., Moghaddam, S., and Momen, A. M., 2019, "Novel Experimental Study of Fabric Drying Using Direct-Contact Ultrasonic Vibration," *ASME Journal of Thermal Science and Engineering Applications*, Vol. 11, pp. 021008-1:021008-10. DOI: 10.1115/1.4041596.
3. Dupuis, E., Momen, A. M., Patel, V. K., and Shahab, S., "Ultrasonic Piezoelectric Atomizers: Electromechanical Modeling and Performance Testing," *Proc. ASME 2018 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, San Antonio, TX, USA, September 2018.
4. Dupuis, E., Momen, A. M., Patel, V. K., and Shahab, S., "Multiphysics modeling of mesh piezoelectric atomizers," *Proc. SPIE Conf. Smart Structures + Nondestructive Evaluation*, Denver, CO, March 2018.

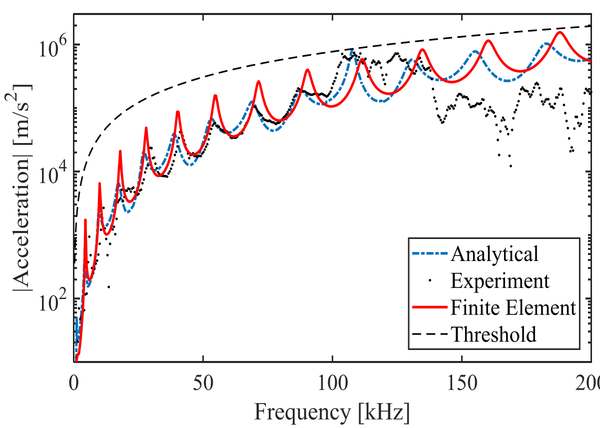
Progress — Ultrasonic Transducer Modeling

Plate deformation due to PZT actuation

- Free and forced vibration studies
- COMSOL finite element model (FEM) – circumference of plate given prescribed value for amplitude of displacement, W_0
- Laser doppler vibrometer (LDV) measurements of acceleration



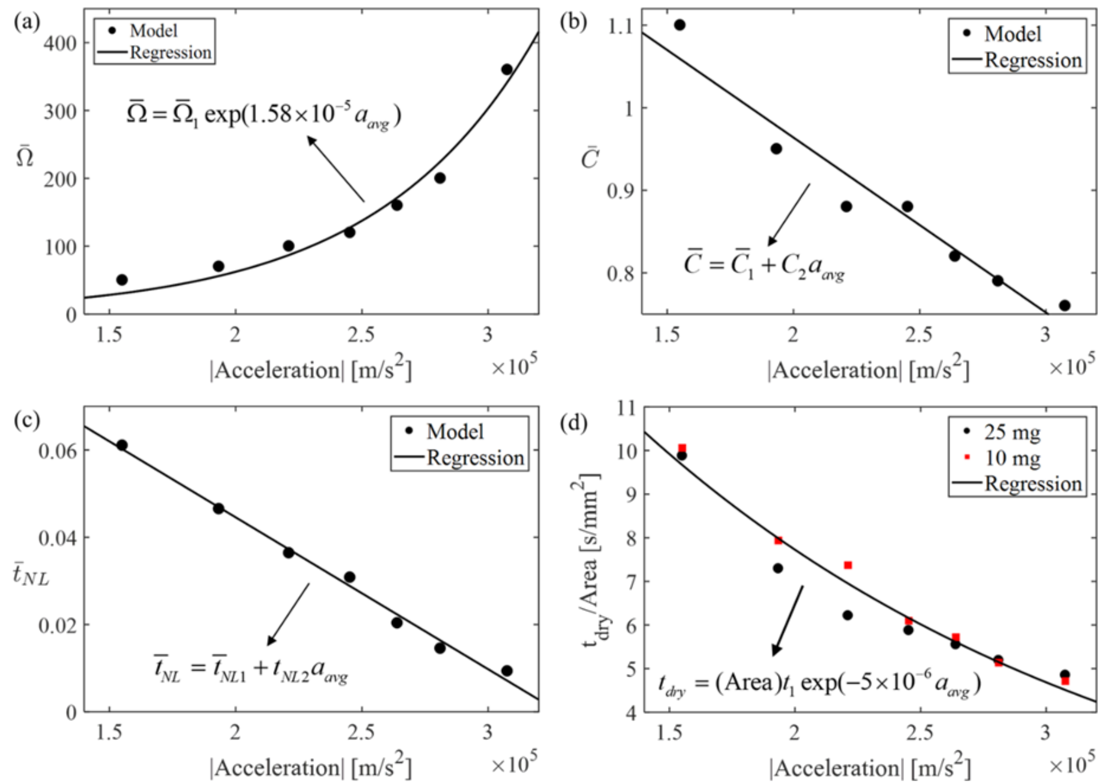
$$\left| a(r,t) \right| = \left| \sum_{n=1}^{\infty} -\phi_n(r) \frac{2\pi\rho_s h_s \omega^4 W_o \int_0^{r_s} r\phi_n(r)dr}{\omega_n^2 - \omega^2 + 2j\zeta_n\omega_n\omega} e^{j\omega t} \right|$$



Empirical ultrasonic fabric drying model

$$\bar{M}(t) = (1+\bar{C}) + (\bar{M}_{sat} - \bar{C})e^{-\bar{\Omega}\bar{t}}$$

$$\bar{k} = \frac{\bar{M}\big|_{t=t_{NL}} - 1}{1-\bar{t}_{NL}} \qquad \begin{cases} 0 < \bar{t} \le \bar{t}_{NL} \\ \bar{t}_{NL} < 1 \end{cases}$$



Curve-fit equations combined into single, holistic expression!

$$\bar{M}(a_{avg},t) = (1+\bar{C}_1 + C_2 a_{avg}) + (\bar{M}_{sat} - \bar{C}_1 - C_2 a_{avg}) \times \exp\left\{ -\bar{\Omega}_1 \, e^{(1.58\times10^{-5} a_{avg})} \, t \Big/ \left[(\text{Area}) t_1 e^{(-5\times10^{-6} a_{avg})} \right] \right\}$$

Progress — Ultrasonic Transducer Modeling

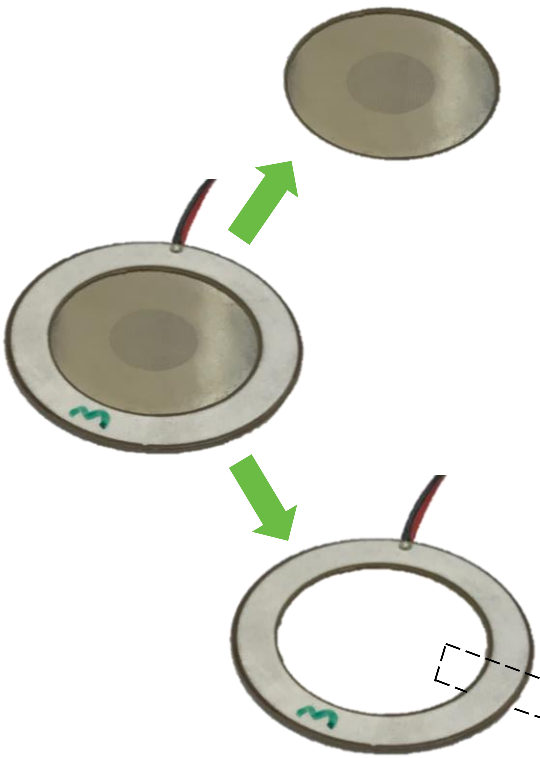
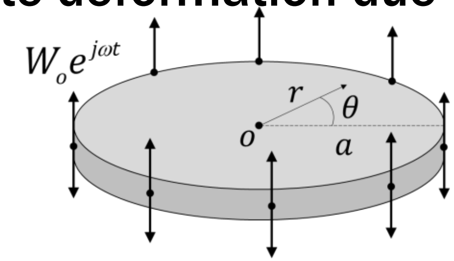
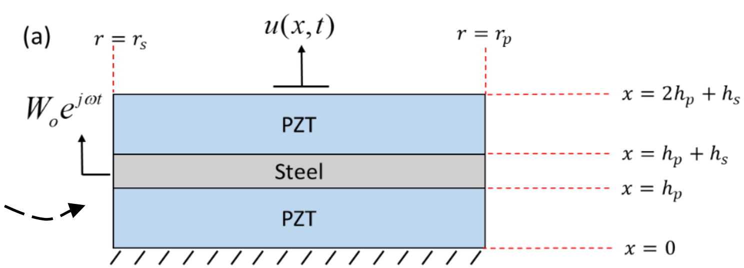


Plate deformation due to PZT actuation



$$a_{rel}(r,t)=\sum_{n=1}^{\infty}\phi_n(r)\frac{2\pi\rho h\omega^4 W_o\int_0^a r\phi_n(r)dr}{\omega_n^2-\omega^2+2j\zeta_n\omega_n\omega}e^{j\omega t}$$

Annular bimorph model using Hamilton's Principle

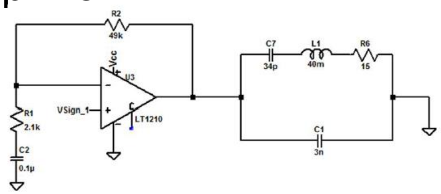


$$\int_{t_1}^{t_2}\left[\delta\int_V (T-U+W)\right]dt=0$$

$$u_i(x,t)=\sum_{n=1}^{\infty}\frac{\phi_{ni}(x)Y_p d_{33}A\frac{V}{L}\left[\phi_{n3}(h_p+h_s)-\phi_{n1}(h_p)-\phi_{n3}(2h_p+h_s)\right]}{\omega_n^2-\omega^2+2j\zeta_n\omega_n\omega}e^{j\omega t}$$

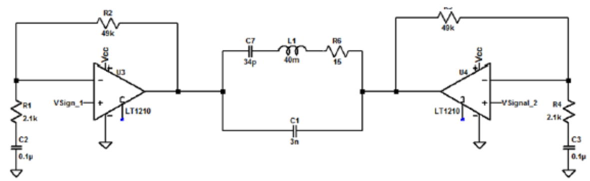
Progress — Amplifier Development

ORNL Gen 1: High-power single-ended output op-amp amplifier



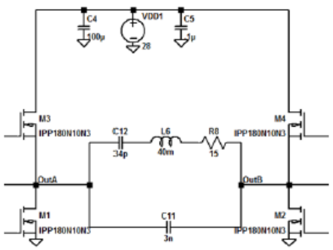
Commercial general-purpose amplifier 1

ORNL Gen 2: Differential output op-amp

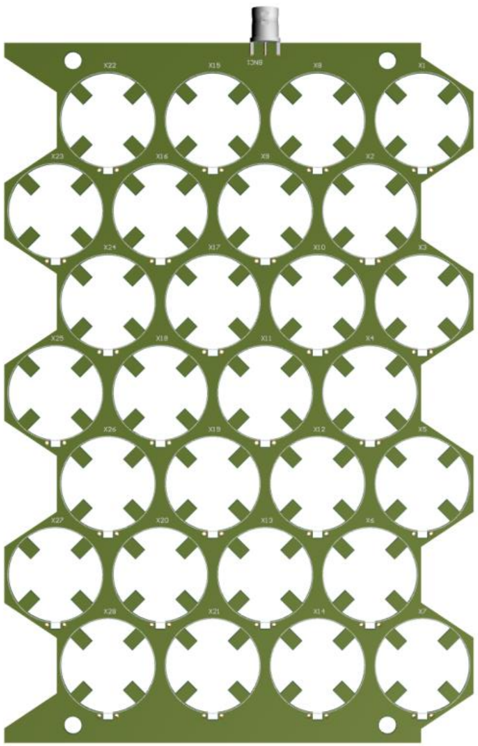


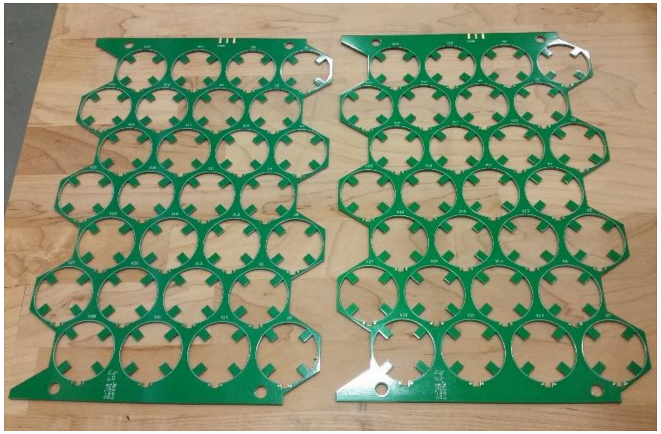
Commercial general-purpose amplifier 2

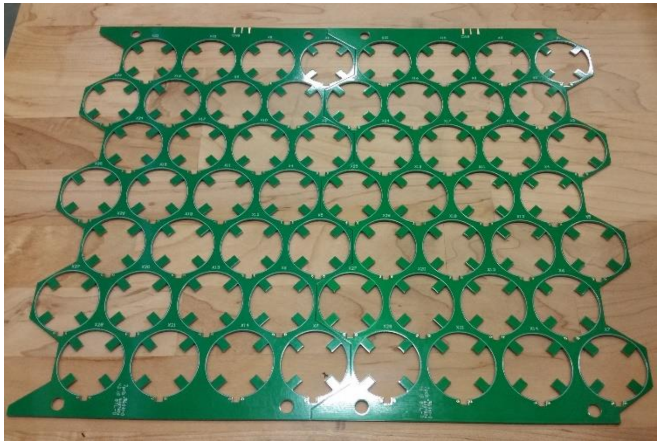
ORNL Gen 3: H-Bridge amplifier

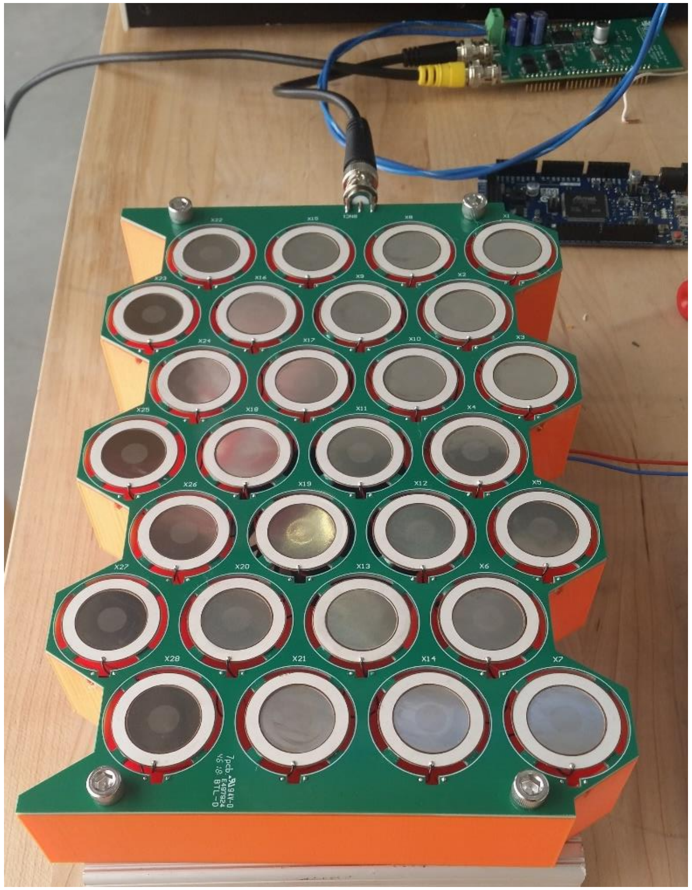


Progress — Experimental Setup



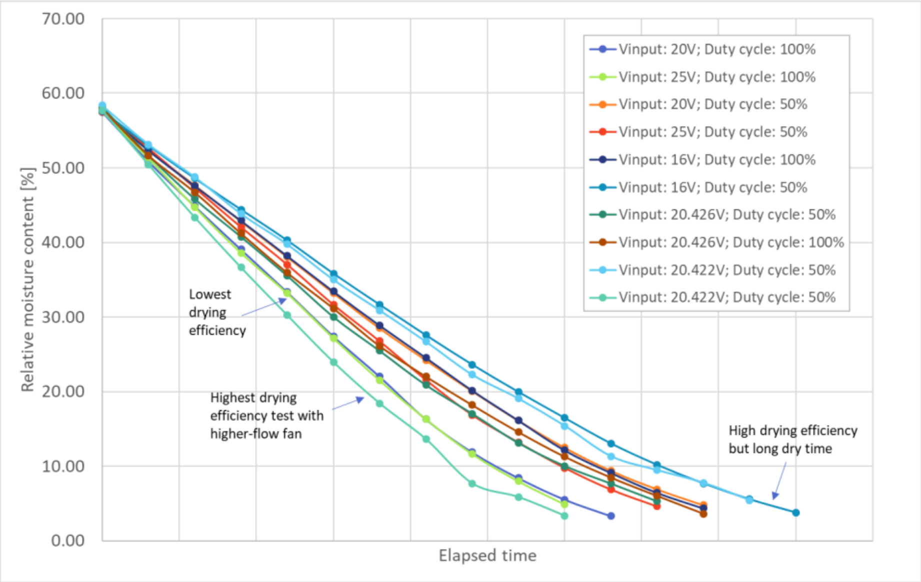


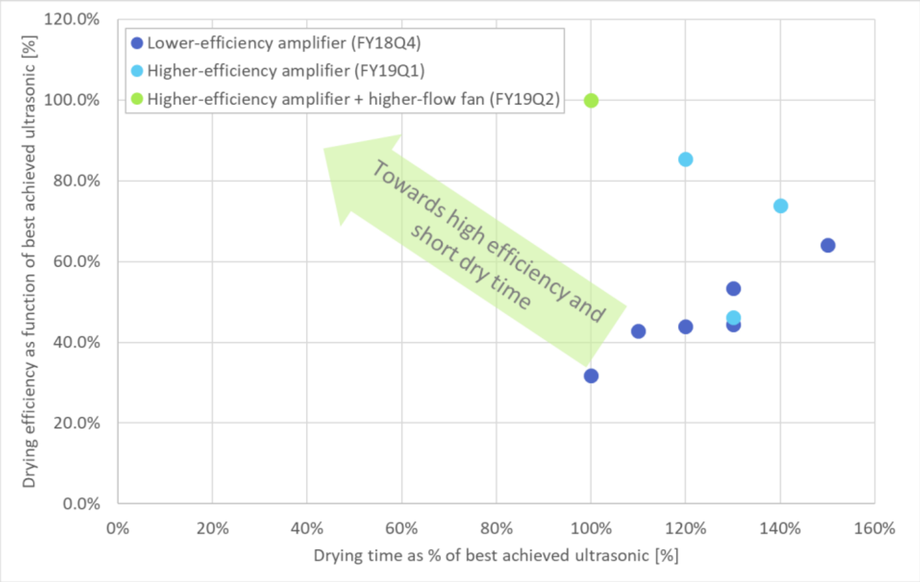




Progress — Experimental Results

Average input voltage [V]	Duty cycle	Dry time as % of best achieved ultrasonic [%]	Drying efficiency as % of best achieved ultrasonic [%]	Amplifier efficiency [%]	Notes
20.0	100%	110%	42.8%	0.70	
25.0	100%	100%	31.8%	0.76	Lowest drying efficiency but shortest dry time
20.0	50%	130%	53.4%	0.69	
25.0	50%	120%	43.9%	0.78	
16.0	100%	130%	44.5%	0.67	
16.0	50%	150%	64.1%	0.65	High drying efficiency but long dry time
20.4	50%	120%	85.4%	0.86	Started using higher-efficiency amplifier
20.4	100%	130%	46.1%	0.87	
20.4	50%	140%	73.9%	0.82	
20.4	50%	100%	100.0%	0.82	Highest ultrasonic drying efficiency and shortest dry time





Stakeholder Engagement

- **This CRADA involves close collaboration with our industrial partner, GE Appliances, who provides guidance on**
  - Target energy efficiency and drying time specifications
  - Fraction of drying to be carried out by ultrasonic elements
    - Whether this should be incorporated into main drying cycle or as an additional feature
  - Dryer prototype design and fabrication
  - Integration of ultrasonic subsystems into prototype
  - Testing and cycle parameters
- **In 2018, Ultrasonic Technology Solutions exclusively licensed the technology in the commercial and industrial field of use**

Remaining Project Work

- **FY 2019**
  - Full dryer design with parts ordered
- **FY 2020**
  - Functioning prototype ultrasonic dryer with the capability to measure drying performance as well as energy advantage
  - Testing and final report on dryer project to include performance, secondary factors, and ultrasonic drying model

Thank You

Oak Ridge National Laboratory
Viral K. Patel, R&D Associate Staff
patelvk@ornl.gov

REFERENCE SLIDES

Project Budget

Project Budget: DOE: $1900K, cost share: $1300K
Variances: No variances
Cost to Date: $741K
Additional Funding: None

Budget History					
07/12/2017– FY 2018 (past)		FY 2019 (current)		FY 2020 – 07/12/2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,000k	$400k	$400k	$400k	$500k	$500k

Project Plan and Schedule

Project Start: 07/12/2017	Completed Work
Projected End: 07/12/2020	Active Task (in progress work)
	Regular Milestone/Deliverable
	Go/No-Go Milestone/Deliverable

	FY2018				FY2019				FY2020			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past work												
Q3 - Ultrasonic actuator model												
Q5 - Piezoelectric transducer design improvement												
Q5 - Form factor evaluation												
Q6 - Full scale dryer scoping												
Current/Future Work												
Q8 - Full scale dryer design												
Q10 - Dryer prototype build												
Q12 - Testing of prototype dryer												