U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Thermoelectric Clothes Dryer

Oak Ridge National Laboratory/Samsung Electronics America, Inc.
Kyle Gluesenkamp, PhD
gluesenkampk@ornl.gov

Project Summary

Timeline:

Start date: 10/1/2016

Planned end date: 09/30/2019

Key Milestones

1. Go/No-Go Milestone; Demonstrate at least 75% of the EF target and not more than 150% the dry time defined in product criteria. **Met** 09/30/2017
2. Go/No-Go Milestone 1; Projected retail premium <$565 at scale. **Met** 12/31/2017
3. Milestone; Establish power supply quality requirements to maintain TE performance. **Met** 03/31/18

Budget:

Total Project $ to Date:

- DOE: $800k

Total Project $:

- DOE: $1050k

Key Partners:

Samsung Electronics America, Inc.	CRADA Partner

Project Outcome:

The technical and commercial viability of solid state thermoelectric heat pump clothes dryer technology is evaluated to meet the MYPP goals of reducing conventional dryer energy consumption by 50% and having installed cost premium <$565. The project also addresses the BTO goal to develop advanced non-vapor compression heat pump solutions to facilitate phase-out of today's widespread refrigerants.

Team

ORNL

Kyle Gluesenkamp
R&D Staff, Project PI
- Project management
- System modeling and design
- Research plan development

Anthony Gehl
R&D Staff

Ahmad Abu-Heiba
R&D Staff
- Costing
- Data analysis

Philip Boudreaux
R&D Staff

Viral Patel
R&D Staff

- Experimental design and analysis
- Prototype fabrication and assembly
- Data acquisition and sensing
- Evaluation

Samsung Electronics America

A leading supplier of residential appliances in the US market

Guolian Wu
Senior Engineering Manager

Ravee Vaidhyanathan
Engineering Director

- Revision of product criteria and project goals based on consumer expectations
- Reporting of project progress to SEA management
- Biweekly review meetings

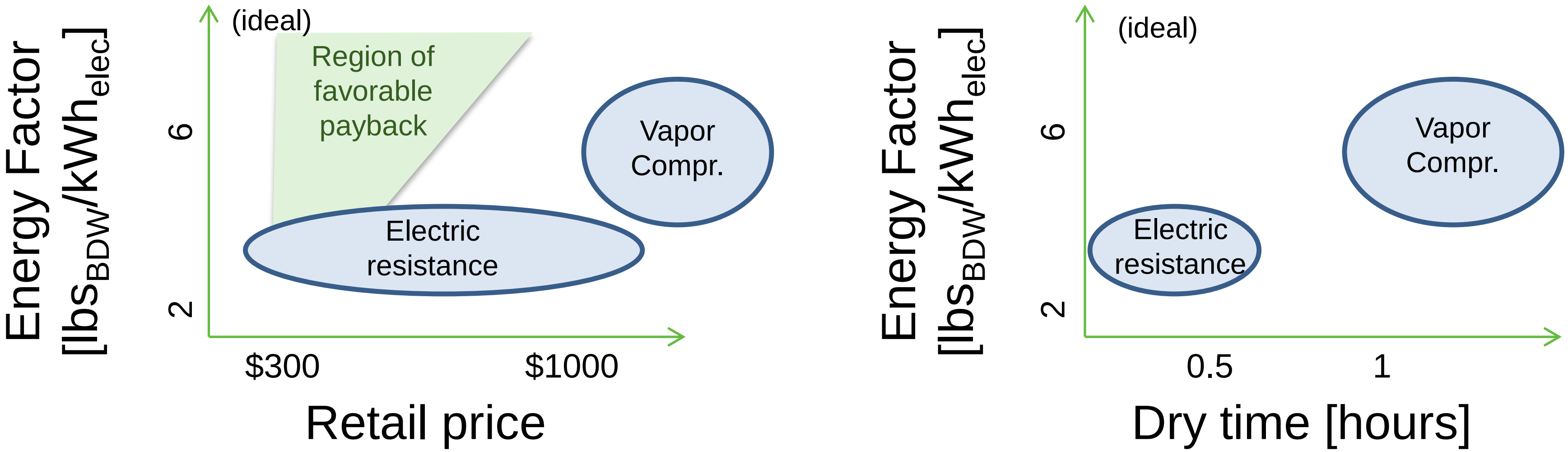
Challenge/Problem definition

The US clothes dryer market is huge in terms of energy consumption and cost of energy:

- 638 TBtu/yr: residential electric clothes dryers (primary energy market size, 2020)
- 5.6 million annual unit shipments (2008)
- 80% of US households have one

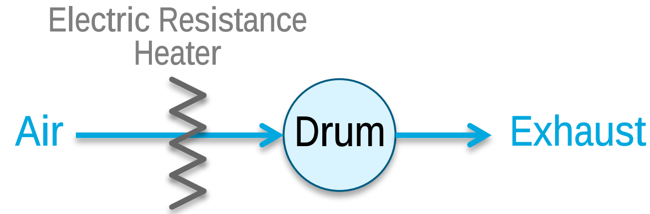
Vapor compression (VC) heat pump dryers can have up to 50% energy savings compared to base efficiency dryers. They recently entered the US retail market but have:

- Retail price premium of over $1100 compared with base models
- Long dry times
- Available options utilize refrigerants that may face regulatory restrictions

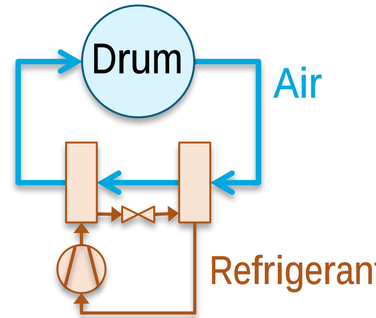


Approach – Background

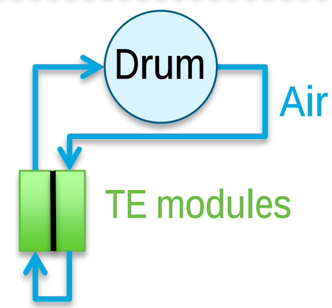
- *State of the art*: Conventional dryers
  - EF/Dry time: 3.73, 15-30 minutes
  - Retail: ~$350 - $1,100



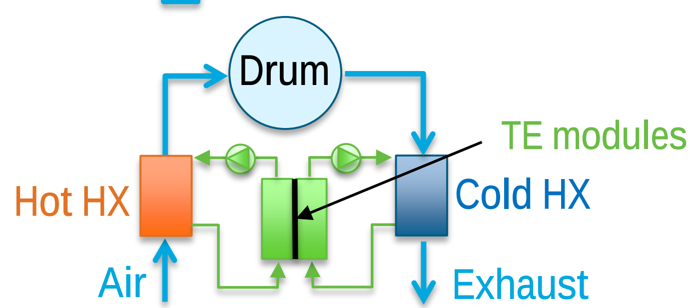
- *State of the art*: Vapor compression dryers
  - EF/dry time*: 4.3 – 6.4; 57 – 75 minutes
  - Products introduced to US market 2015
  - Retail: ~$1,600



- *This project, FY17*: Air-based thermoelectric (TE)
  - EF 6.03 obtained
  - Dry time longer than vapor compression



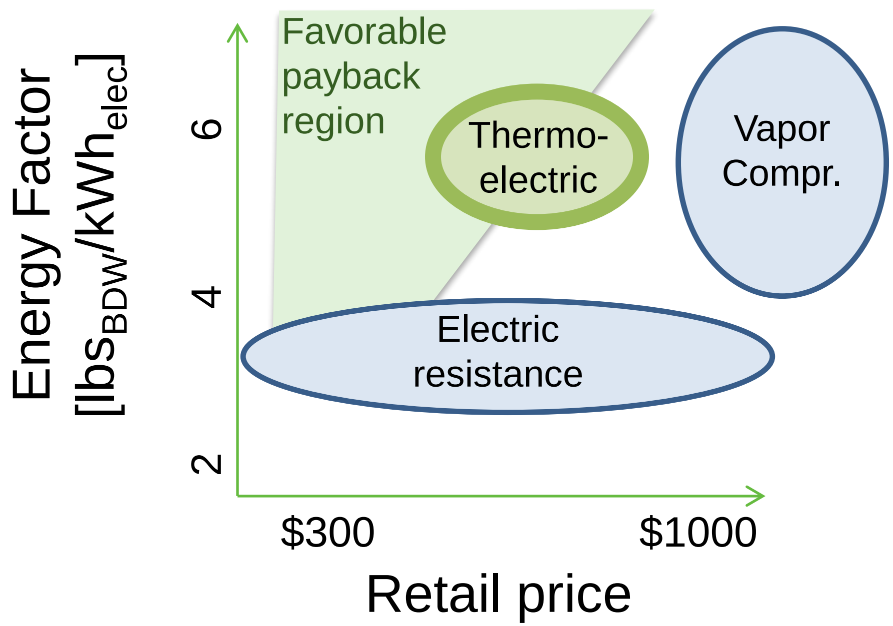
- *This project, FY18*: Pumped-loop (patent pending)
  - Target EF/dry time:
    - 6.1, 90 minutes (Eco mode)
    - 5.0, 70 minutes (Normal mode)
  - Achieved so far in FY18: **5.4, 80 minutes**



*based on ENERGY STAR qualified products list, April 2018

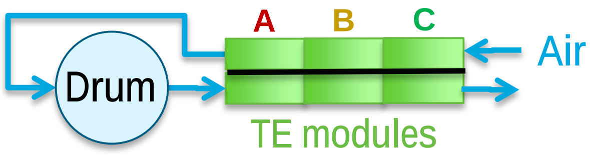
Approach

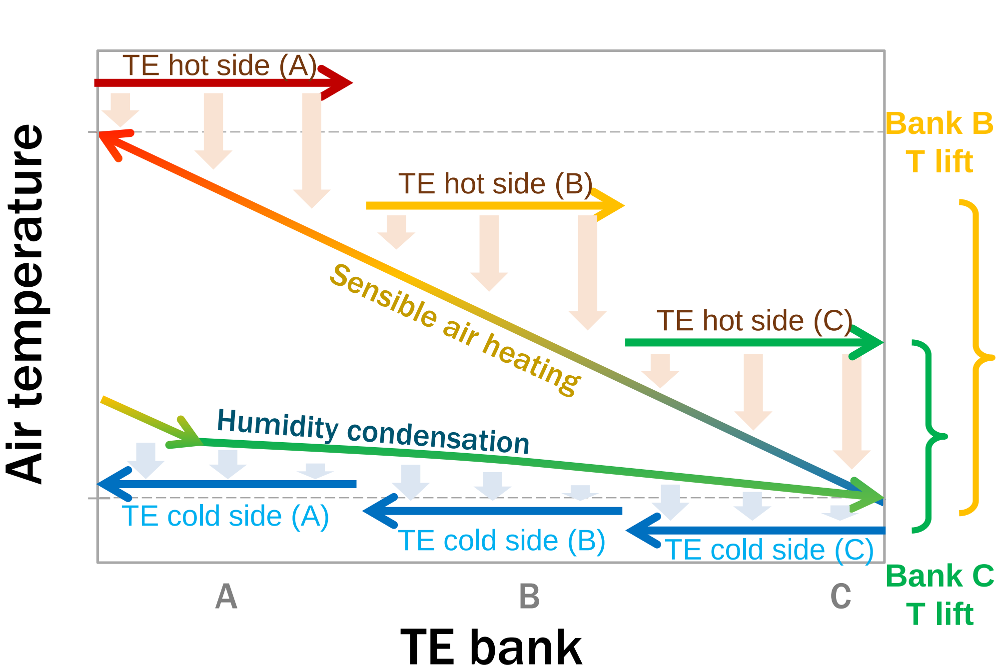
- Thermoelectric-based approach projected to have lower first cost than VC dryers by:
  - Replacing refrigerant lines, compressor and expansion device with low-cost TE modules, water-pumped loop and low-cost power supplies
- 40% energy savings compared to base efficiency dryers
- Faster dry times are possible (compared with VC dryers)
- Solid-state TE heat pump technology does not use any refrigerants

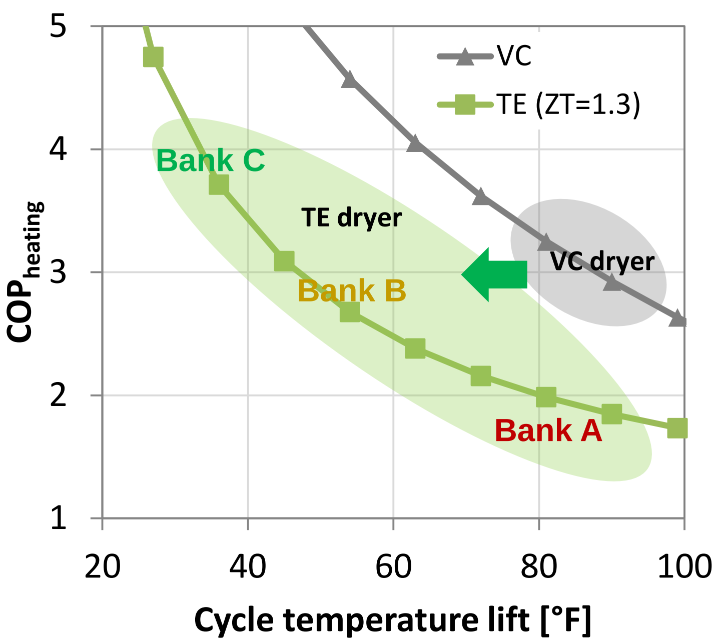


Approach

The traditionally inferior efficiency of thermoelectric heat pumps is overcome by taking advantage of inherent scalability/modularity of TEs







Approach

Approach:

- Thermodynamic system modeling
- Fabrication of TE dryer prototype with liquid-pumped-loop thermoelectric heat pump
- Accelerated experimental study of long-term effects of power quality and power cycling on thermoelectric module performance
    - Down-selection of low-cost power supply
- Prototype development, evaluation and comparison to baseline VC HPCD

Key Issues:

- Auxiliary power consumption

Distinctive Characteristics: High-performance design is achieved at low cost through unique utilization of:

- Commercially-available, high-volume production TE modules
- Low-cost power supplies for TE modules
- Compact hydronic mini-channel heat exchangers for liquid-pumped-loop
- Conventional fin-and-tube heat exchangers

Impact

- During project: Laboratory prototype will prove performance (EF and dry time), to save 40% primary energy (254 TBtu/yr) in electric clothes drying
- Intermediate term: Demonstrate a path to a low-cost approach, so that appliance OEM can initiate product commercialization.
- Long term: Position the US as leader in dryer industry, creating jobs and spurring further innovation, and saving 254 TBtu/yr.

BTO 2016-2020 Multi-year Program Plan Goal	Project Goal	Project Status
Increase electric dryer Energy Factor from 3.9 (2010 ENERGY STAR) to 6.1 lb/kWh	CEF = 6.1, 90 minute dry time (Eco mode) CEF = 5.0, 70 minute dry time (Normal mode)	**CEF = 5.4** **80 minutes**
Available for retail price premium of less than $565	Projected <$565 retail price premium at scale	**Met** **(FY18 Q1 Go/No-Go milestone)**

Progress and Accomplishments

Accomplishments:
In Year 1:
- Defined product criteria based on previous results and knowledge of consumer expectations and product insight from SEA
- Completed first prototype and achieved $\geq$75% target EF and $\leq$ 150% target dry time

In Year 2, Q1 and Q2:
- Completed cost projection: retail premium projected to be <$565
- Established power supply requirements based on unique long-term power cycling experimental data

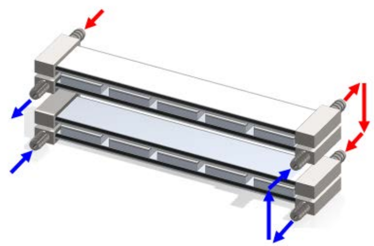
Market Impact: Samsung Electronics America evaluating commercialization potential. If successful, market entry will give consumers reasonably-priced, energy-efficient alternative

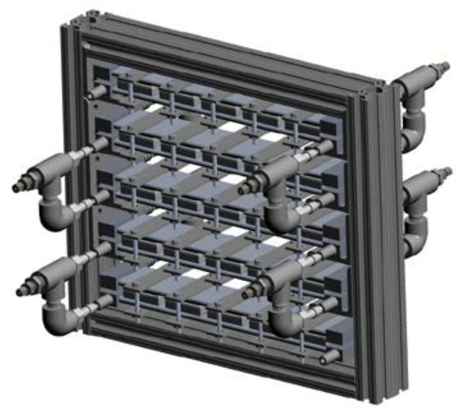
Awards/Recognition: None yet

Lessons Learned:
- Hydronic system design requires innovative engineering approach
- Cost of TE modules and power supplies are highest in incremental bill of materials relative to standard ER dryer
- Blower and drum motor power significant source of energy consumption
- Air leakage management is important for system performance

Progress and Accomplishments – Design

TE heat pump assembly consists of individual sub-assemblies



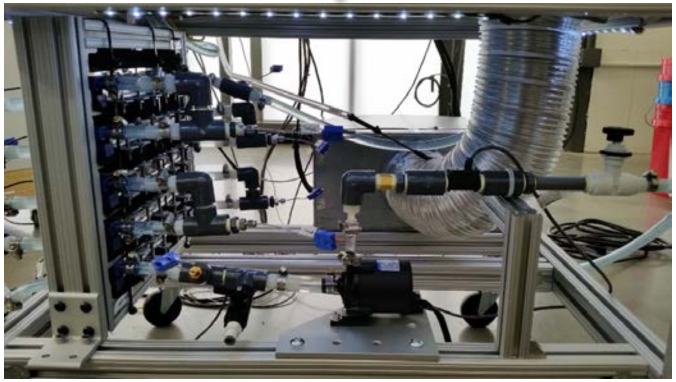


Completed prototype

Early dryer prototype design

Patent pending

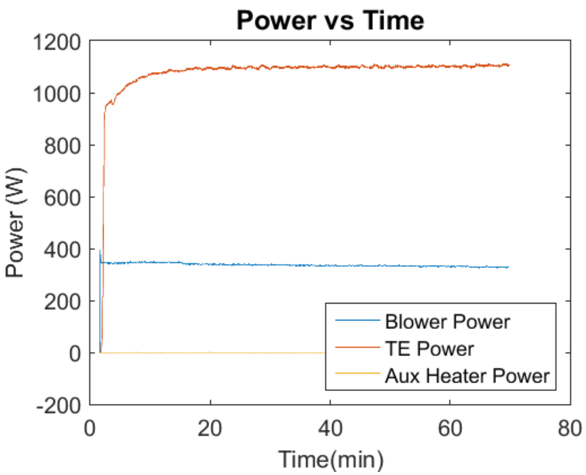
Progress and Accomplishments – Fabrication

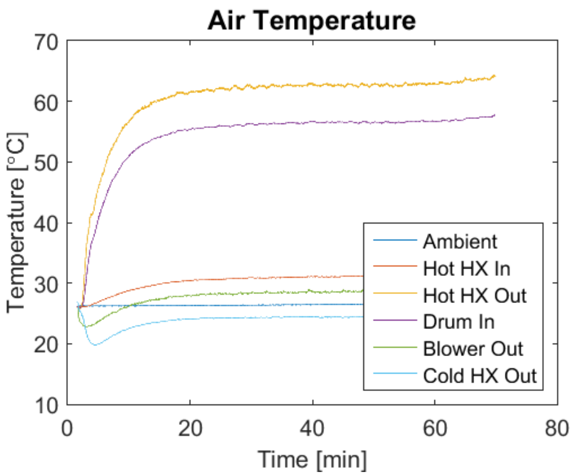


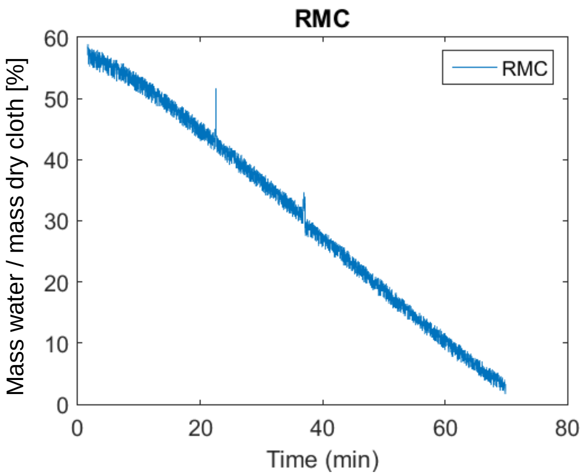
Patent pending

Progress and Accomplishments – Evaluation

- Drum inlet temperature achieved (~50-60°C) comparable to VC HPCD but lower than electric resistance dryer
- Blower/drum motor power is approximately 35% of TE power
- Real-time remaining moisture content (RMC) of clothes load is measured by a high-accuracy whole-dryer scale

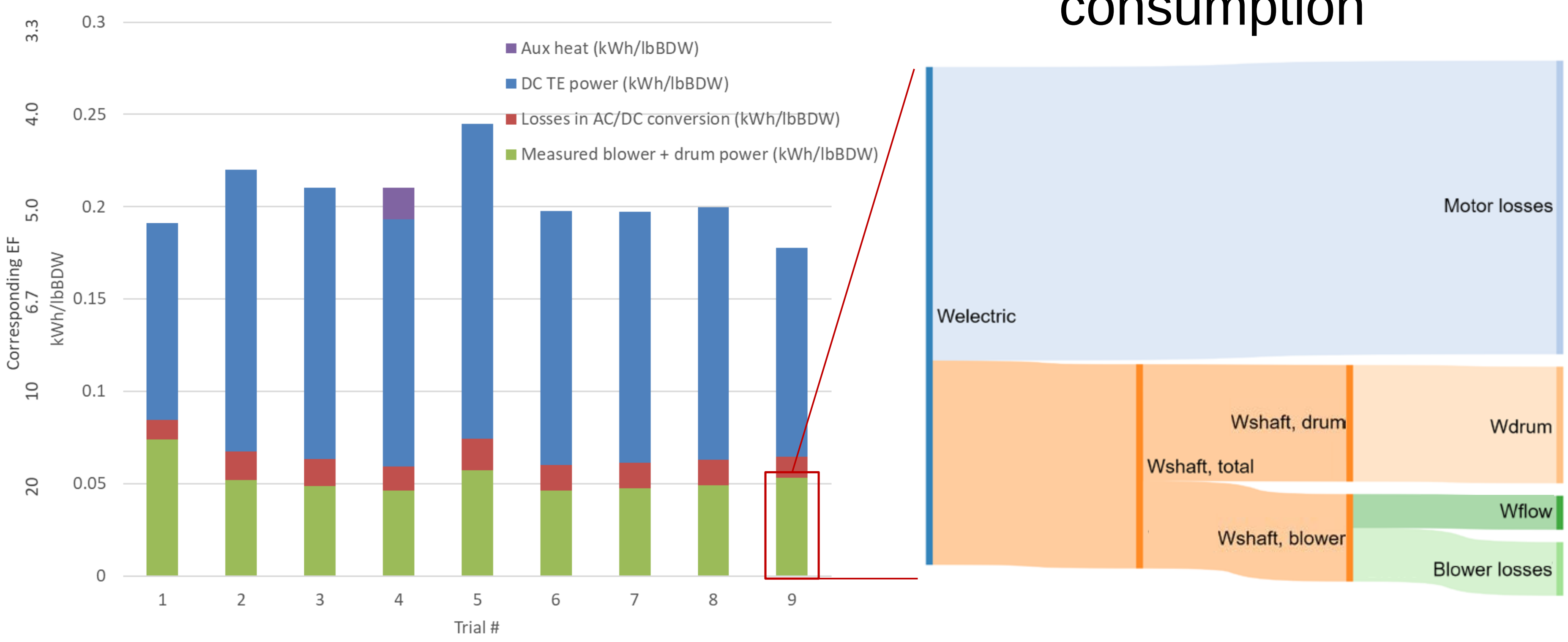






Progress and Accomplishments – Results

Auxiliary power consumption



Stakeholder Engagement

Partners, Subcontractors, and Collaborators: Industry partner, Samsung Electronics America

- Biweekly status meetings
- SEA fully engaged in engineering and technical discussions

Communications:

- Abstract accepted at *17th International Refrigeration and Air Conditioning Conference* at Purdue University, July 2018: "Thermoelectric Heat Pump Clothes Dryer using Secondary Loop Heat Exchangers: Experimental Evaluation and System Modeling"
- Guolian Wu, Kyle Gluesenkamp, Viral Patel, Ravee Vaidhyanathan. Patent application 62/654,239, filed April 6, 2018 "Apparatus and Method for a Thermoelectric Heat Pump Appliance with Secondary Fluid Loops".
- Patel, V. K., Wang, H., Gluesenkamp, K. R., Gehl, A., Ormston, G., Kirkman, E., "Long-term effects of power quality and power cycling on thermoelectric module performance," *ASME InterPACK*, San Francisco, CA, August 2018.
- Patel, V. K., Gluesenkamp, K. R., Goodman, D., Gehl, A., "Experimental evaluation and thermodynamic system modeling of thermoelectric heat pump clothes dryer," *Applied Energy*, Volume 217, 1 May 2018, Pages 221–232.
  DOI: 10.1016/j.apenergy.2018.02.055

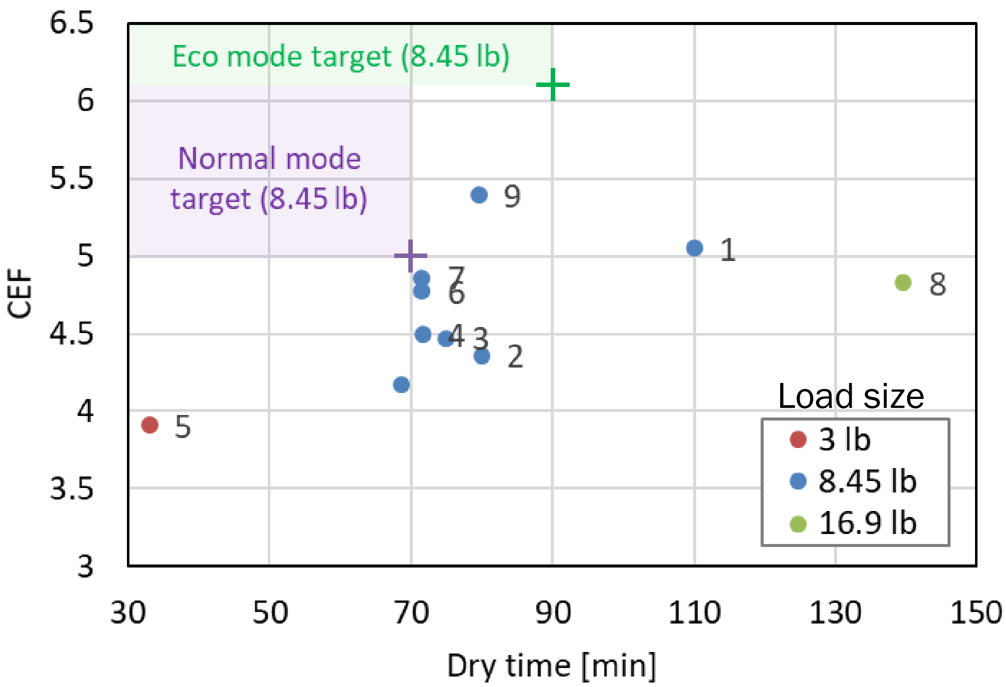
Remaining Project Work

Nearing project targets

- CEF = 6.1, 90 minute dry time (Eco mode)
- CEF = 5.0, 70 minute dry time (Normal mode)

To meet project targets, next steps are:

- Continue testing with variation in control strategy, air flow rate
- Identify design and component changes to improve performance



Thank You

Oak Ridge National Laboratory/Samsung Electronics America, Inc.
Kyle Gluesenkamp, R&D Staff Member, Building Equipment Research Group
gluesenkampk@ornl.gov

REFERENCE SLIDES

Project Budget

Project Budget: $1050k
Variances: None
Cost to Date: $497k
Additional Funding: Cost share from CRADA partner

Budget History					
FY 2017 (past)		FY 2018 (current)		FY 2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
350k	*	450k	*	250	*

* In-kind contribution from CRADA partner – exact total is confidential information

Project Plan and Schedule

- October 1, 2016 – September 30, 2019
- Go/No-Go met: December 31, 2017: Projected retail premium <$565 at scale

Project Schedule												
Project Start: Oct 1, 2016		Completed Work										
Projected End: Sep 30, 2019		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned)										
		Milestone/Deliverable (Actual)										
	FY2017				FY2018				FY2019			
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												
Q2: Product criteria defined												
Q4: First prototype fabricated												
Q4: ≥75% target EF and ≤150% target dry time												
Q1 Go/No-Go: Projected retail premium <$565												
Q2: Establish power supply requirements												
Current/Future Work												
Q3: Fabricate heat sinks <0.4 inWC, <5 K AT												
Q4: Prototype evaluation EF>6 in <70 min												