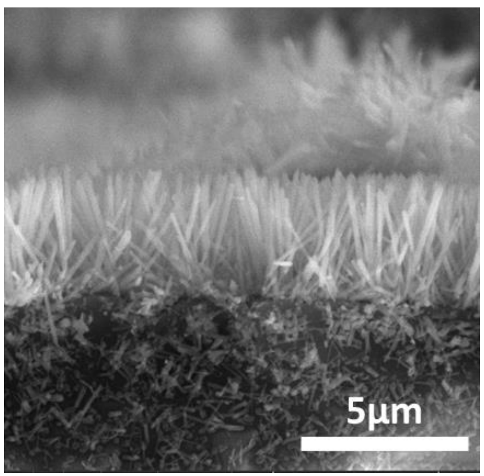
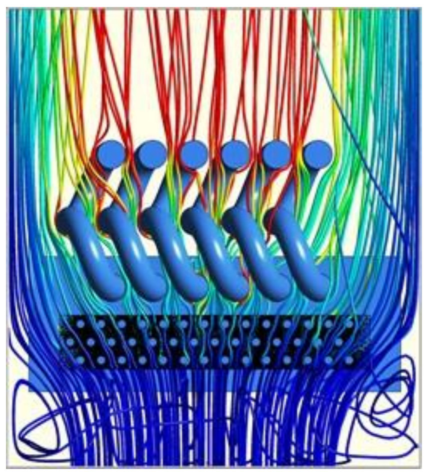
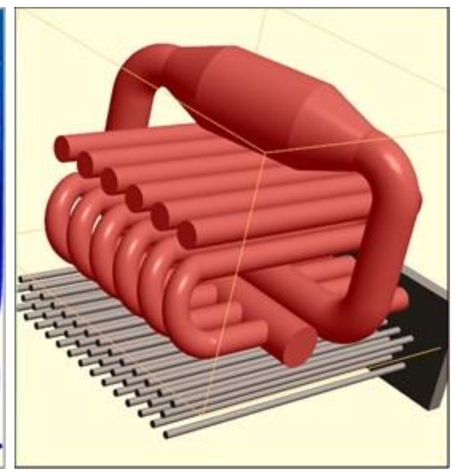
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advanced Adsorption Technology for New High-Efficiency Natural-Gas Furnace at Low Cost

(This is a new project launched in FY2019)







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Project Summary

Timeline:

Start date: 10/01/2018

Planned end date: 09/30/2020

Key Milestones

1. Demonstration of ZnO/BaO-based nano-array samples, 12/31/2018
2. Delivery of 1.0 L acidic gas trapping (AGT) component with nano-array monolith substrates, 9/30/2019
3. Integration of the AGT component into the retrofitted furnace, 1/31/2020

Budget:

Total Project $ to Date:

- DOE: $480K
- Cost Share: $

Total Project $:

- DOE: $960K
- Cost Share: $

Key Partners:

University of Connecticut	Synthesis of nano-array based monoliths
Rheem Manufacturing	Residential natural gas furnace
Corning Inc.	Monolith substrates

Project Outcome:

This project proposes an advanced adsorption technology based on nano-array monolithic AGT adsorbers for SOx/NOx acidic gas removal to enable a natural gas furnace with 98+% annual fuel utilization efficiency (AFUE) at a cost comparable with existing noncondensing furnaces. The new furnace with AGT technology will extend the market penetration of high-efficiency natural gas furnaces, and the AGT technology can be widely applied to both residential and commercial natural gas furnaces.

Team

- **Oak Ridge National Laboratory**
  Zhiming Gao,[1,2] Ayyoub Momen,[1]
  Mingkan Zhang,[1] Xiaobing Liu,[1]
  Kyle Gluesenkamp,[1] Tim LaClair[2], Josh Pihl,[2]
  Raynella Connatser,[2] Jim Parks,[2] Shen Bo[1]

  [1]Building Equipment Research Group
    - 40+ years of experience in building equipment research
    - Substantial experience and state-of-the-art facilities for natural gas furnace R&D

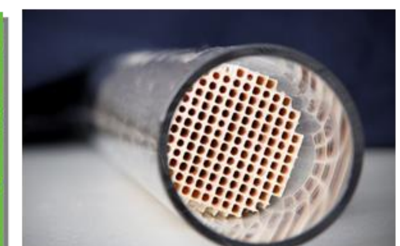
  [2]Applied Catalysis and Emissions Res. Group
    - 20+ years of cutting-edge solutions for catalysis and emissions control
    - Extensive collaboration with OEMs on catalysts for NOx and sulfation issues

- **University of Connecticut**
  Puxian Gao
- **Rheem Manufacturing** (furnace provider)
- **Corning Inc.** (ceramic substrate provider)





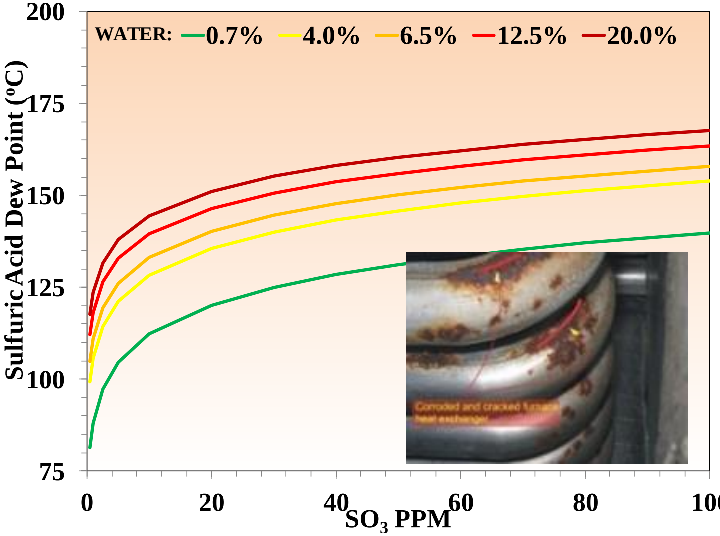



Challenge

- **47 million homes across the nation use natural gas furnaces**
  - 75% of current home furnaces are noncondensing units with an AFUE of 80% or less
  - Only 25% of homes use 90+% AFUE condensing furnaces
    - High cost and long payback time
- **Condensate freezes in condensing furnaces**
  - Occurrence at extreme cold weather
- **Flue gas comprises acidic gases**
  - ~4 ppm SO_2/SO_3, ~22 ppm NO/NO_2
  - If $T_{flue\ gas}$< dew points, acidic gases combine with water vapor to produce acidic solutions
  - Two strategies: (1) maintaining the exhaust above the dew point and (2) using corrosion-resistant stainless-steel alloy HXs

The proposed advanced adsorption technology enables furnaces to achieve enhanced efficiency and cost effectiveness simultaneously

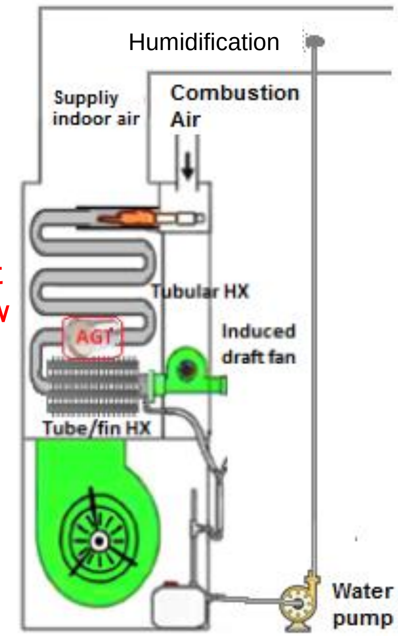


Sulfuric acid dew point: ~120°C @ 4 ppm sulfur

Approach: General

- Nano-array–based monolithic AGT adsorber enables new natural gas furnaces with higher AFUE at low cost while eliminating frozen condensate issues
  – Acidic gas removal
  – A low-cost, large second HX for ultrahigh efficiency
  – Neutral condensate, potential water source for humidification

Goal: New high-efficient furnace at low cost



Innovative material R&D

Component design

System optimization

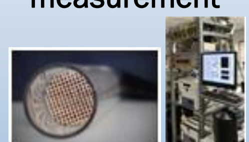
- Nanoparticles
- Nano-arrays
- Large-size monolith

- Design
- Fabrication
- Assembly

Synthesis of nano-array monoliths

- Quantification
- Characterization
- Evaluation

Catalyst property measurement



AGT component and accessories

- AGT installation
- System retrofit
- Low-cost HXs

Furnace retrofit and AGT implementation

AGT regeneration control

- Control
- Optimization
- Update

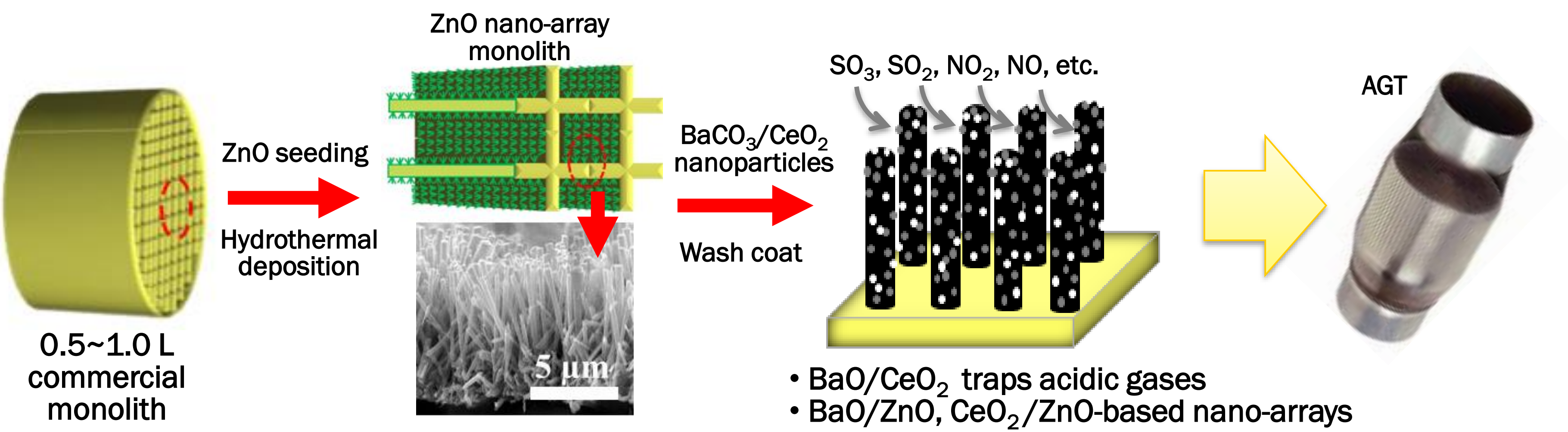
- Prototype
- Refinement
- Tests

New prototype

Approach: Nano-Array Monolith and AGT

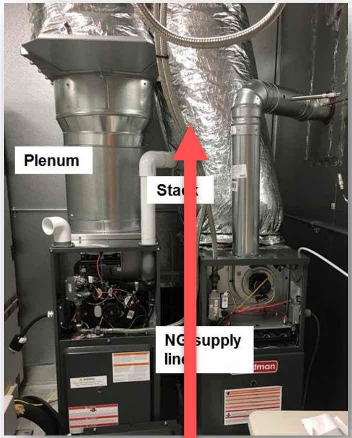
- A flow-through device with a "forest growth" nanostructure on the channel surfaces of a monolith substrate
  - Material: low-cost alkali or alkaline earth metal oxides (e.g., Ba, Sr, Ca, Li, K, or Na)
- AGT mechanism (@ heating regions I, II, III, IV, V):
  - Continuous SOx/NOx adsorption
  - 1.0 L AGT: periodic regen via furnace control
    - 2–3 regen events maximum per heating season
    - 5 minutes per regen; 500~600°C exhaust T
  - 2~3 L AGT: alternative design without regen, an annual replacement

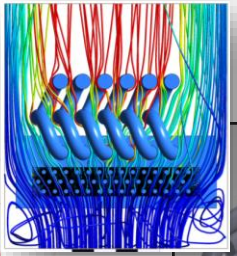
Acidic gas adsorption
$BaO + SO_2 \rightarrow BaSO_3$
$BaO + SO_3 \rightarrow BaSO_4$
$BaO + 2NO + 0.5O_2 \rightarrow Ba(NO_2)_2$
$BaO + 2NO_2 + 0.5O_2 \rightarrow Ba(NO_3)_2$



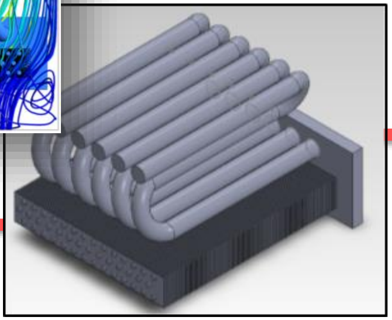
Approach: Furnace Retrofit and AGT Integration

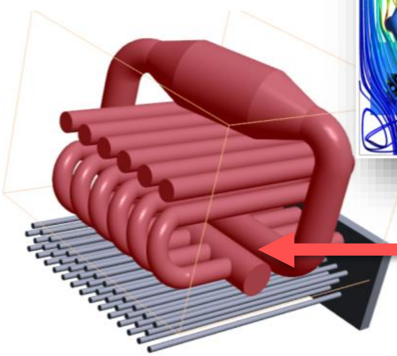
- **ORNL comprehensive facilities for furnace R&D**
  - Rheem 84,000 BTU condensing gas furnace, etc.
  - Large environmental chambers
  - Various furnace venting systems
- **Furnace retrofit and AGT integration**
  - CFD simulations: SolidWorks/Ansys/Fluent analyses using Rheem HXs' geometry data
  - 3D high-fidelity geometric and mathematic model for HXs and AGT integration optimization
  - Experimental furnace data used for model validation and refinement





CFD simulation





Impact

- EIA 2015 residential energy consumption survey
  - 2.45 quadrillion Btu of natural gas for space heating
  - 130.1 million tons of CO_2 (Scout's Baseline Energy Calculator)

25% of home furnaces @ 90+% AFUE
vs.
75% of home furnaces @ 80% or less AFUE

- AGT adsorber technology enables new furnaces to achieve 98% AFUE and maintain low cost
  - Potential savings: 0.33 QBtu of natural gas annually*
  - Reduce CO_2 emissions by 17.6 million tons*
  - Target: 1–2 year payback time

Furnace Type	Furnace Only	Furnace installed
80% AFUE, Rheem non-condensing furnace	$825	$2,300
92-95% AFUE, Rheem condensing furnace	$1190	$2990
96% AFUE, Rheem condensing furnace	$1500+	$3,400+
98+% AFUE, Our new furnace w/ AGT	$950	$2,425

Comparison of 80,000 Btu/h natural gas furnaces with various technologies

(*75% of home furnaces @ 80% AFUE converted to the new 98% AFUE furnaces)

MYPP BTO Emerging Technology's goal: develop cost-effective technologies capable of reducing a building's energy use per square foot by 45% by 2030
(https://www.energy.gov/sites/prod/files/2016/02/f29/BTO%20Multi-Year%20Program%20Plan%20-%20Final.pdf)

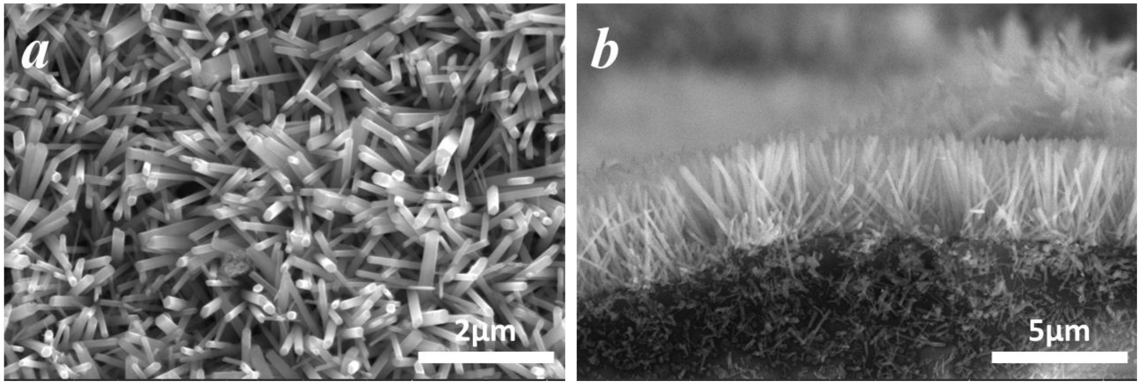
FY 2019 Milestones

Date	Milestones	Status
Dec 2018	Demonstration of ZnO/BaO-based nano-array samples	Complete
March 2019	Delivery of 1.0 L ZnO/BaO-based nano-array monolith substrates	Complete
June 2019	Completion of characterization and identification of the adsorber performance	On track
Sept 2019	Adsorption/desorption demonstration and quantification of the adsorber in bench reactors	On track
Sept 2019	Completion of AGT component assembly and accessory parts fabrication	On track

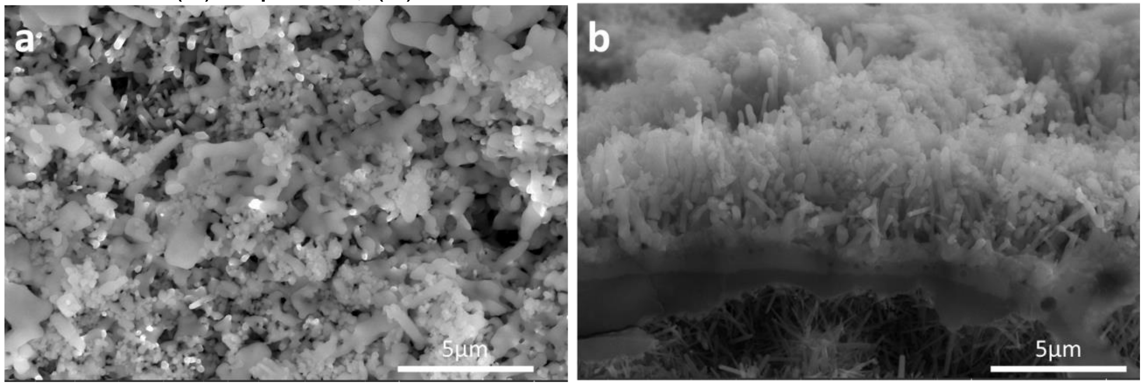
Go/No-Go: Successful delivery of 1.0 L AGT component with a nano-array monolith substrate, 09/30/2019

Progress: Synthesis of Nano-array (Early-Stage)

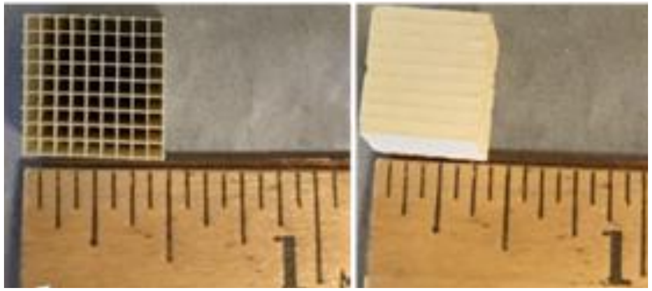
Successfully demonstrated the deposition of $BaCO_3/ZnO$ nano-arrays onto commercial cordierite substrates



Scanning electron micrograph (SEM) images of ZnO nanoarray on the cordierite: (a) Top view, (b) cross-section view



SEM image of $BaCO_3$ nanoparticle-wash coated ZnO nano-array: (a) Top view, (b) cross-section view

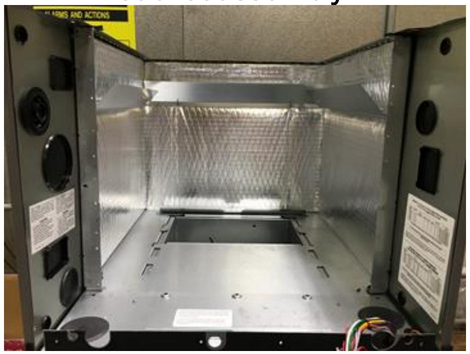


Sample size: 0.5 × 0.5 × 1.0 cm

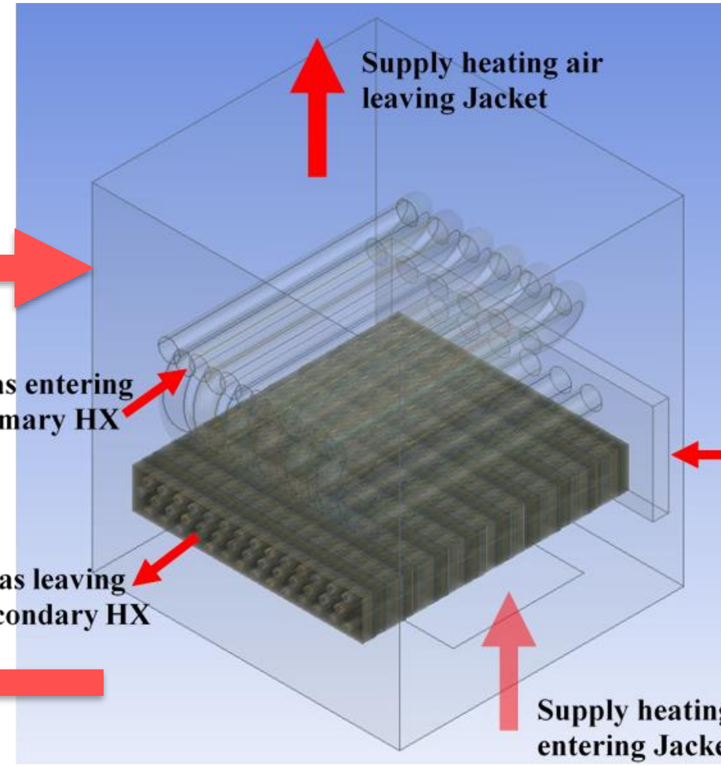
- Two nano-array samples: $BaCO_3/ZnO$ and CeO_2/ZnO
- SOx/NOx adsorption /desorption tests for the $BaCO_3/ZnO$ and CeO_2/ZnO nano-array samples are being performed
- Established the reactor setup and protocol for sample testing

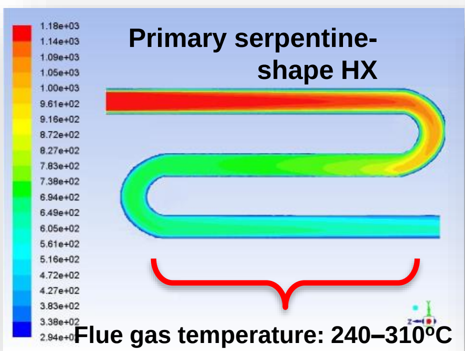
Progress: Preliminary Design (Early-Stage)

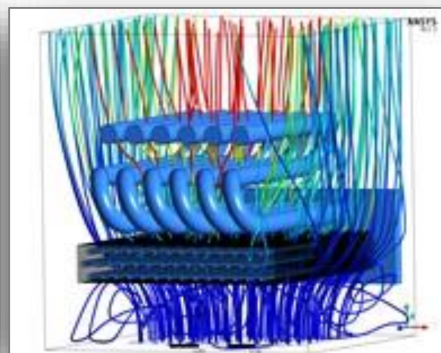
Jacket assembly



Primary and secondary HXs







Preliminary design for AGT integration

Furnace: Rheem 84000Btu/h condensing furnace

Simulation tool: ANSYS/FLUENT

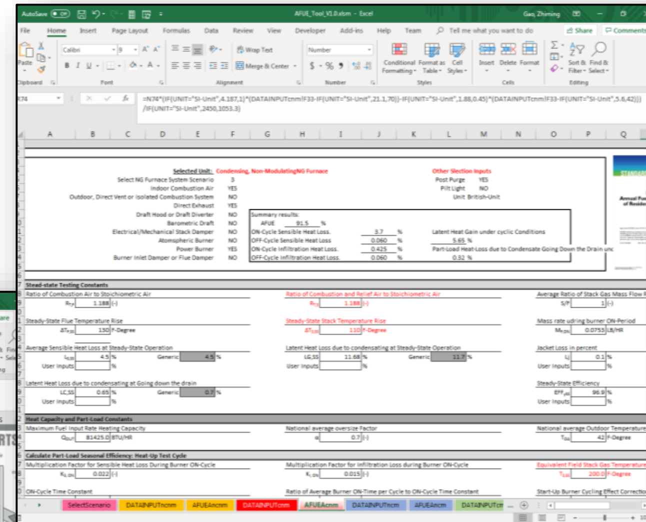
Simulation conditions:

- Flue gas inlet temperature = 900°C
- Flue gas flow rate = 14.72 g/s (air vs. NG = 2.2:1 mole%)
- Supply heating air entering jacket = ~21°C
- Supply heating air flow = 1313–1983 L/s

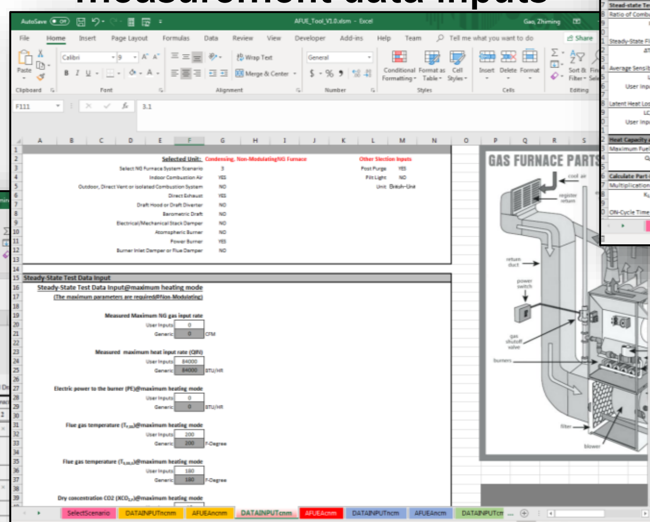
Progress: AFUE Analysis Tool (Mid-Stage)

- Developed Excel-based AFUE tool using Visual Basic for Applications (VBA)
  - Residential and light commercial furnaces
  - Configurations: both condensing and noncondensing furnaces with single-stage, two-stage, and step-modulating control

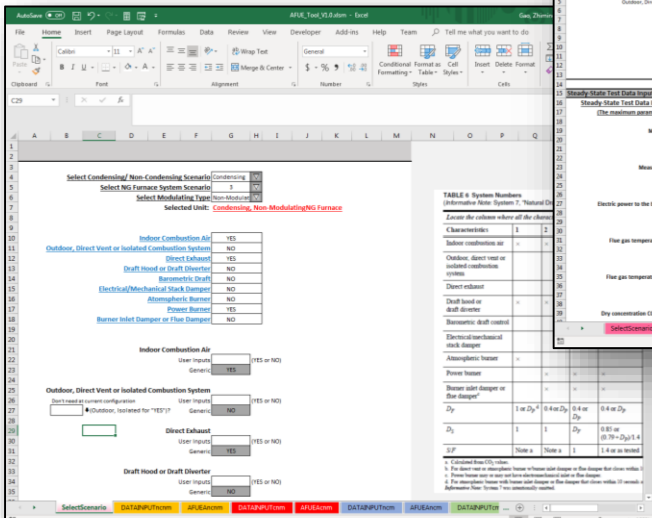
Results: AFUE and other key data



Geometry and measurement data inputs



Unit and configuration selection

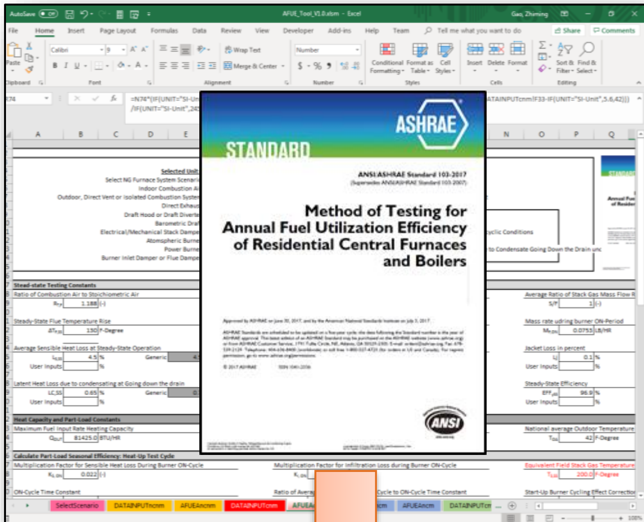


Key features:
- User-friendly interface
- Easy to use
- Comprehensive coverage
- Detailed results

Reference: ANSI/ASHRAE Standard 103-2017 (i.e., Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers).

Progress: Furnace Test Preparation (Early-Stage)

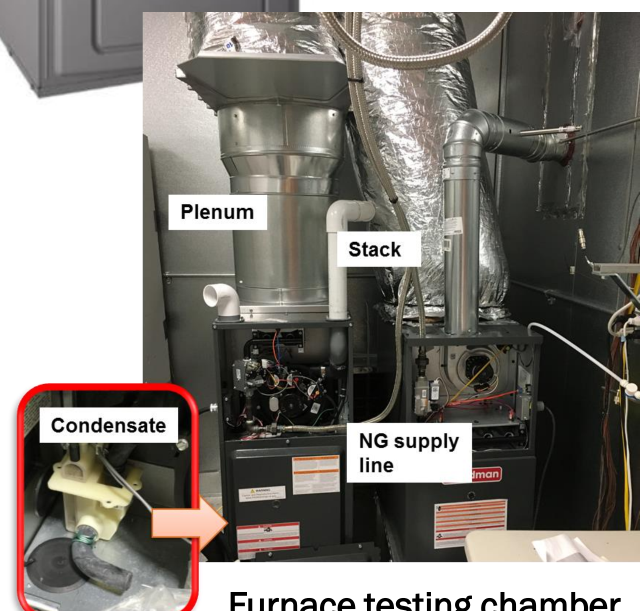
AFUE analysis tool



Rheem 84,000 Btu/h condensing furnace with single-stage control

Condensing NG Furnace with [illegible]e-Stage Control Data Input		
Instruments	**Resolution**	**others**
Thermometers	+/- 1F	
Gas pressure meter	+/- 0.2 in of water	
Gas flow meter	+/- 0.5%	
CO2 % meter	+/- 0.1%	
Timer	+/- 0.5/hr	
Steady-state Data measurement	Location	others
Heat input rate	Adjusting NG flow rate (+/-2%)	Maximum heat input rate (or nameplate
Flue gas temperature 1	Flue gas before enter stack	Measured at maximum heat input rate
Flue gas temperature 2	Flue gas after stack	Measured at maximum heat input rate
Room Temperature	Nearby NG furnace unit	Measured at maximum heat input rate
Jacket surface temperature	Each surface	Measured at maximum heat input rate
XCO2 dry concentration 1	Flue gas before enter stack	Measured at maximum heat input rate
XCO2 dry concentration 2	Flue gas after stack	Measured at maximum heat input rate
Cumulated 30min NG Flow	NG supply line	Measured at maximum heat input rate
NG temperature	At NG flow meter	Measured at maximum heat input rate
NG pressure	At NG flow meter	Measured at maximum heat input rate
Cumulated 30min Condensate mass	-	Measured at maximum heat input rate
Energy input rate to the pilot light	-	if enabled
Heat-Up, Cool-down and Cyclic Tests		
Flue gas temperature at heat-up test	at 0.5min, 2.5min	Measured at maximum heating mode
Flue gas temperature at cool-down test	at 1.5min, 9min (+tp if post purge enabled), and time at shutof	Measured at maximum heating mode
Flue gas temperature & post purge time at post purg	at time=tp/2, tp	if enabled
Cumulated 3or6 cycle NG Flow at cyclic testing	NG supply line	Measured at maximum heating mode
Cumulated 3or6 cycle Condensate mass at cyclic te	-	Measured at maximum heating mode

Measurement instrument and data list



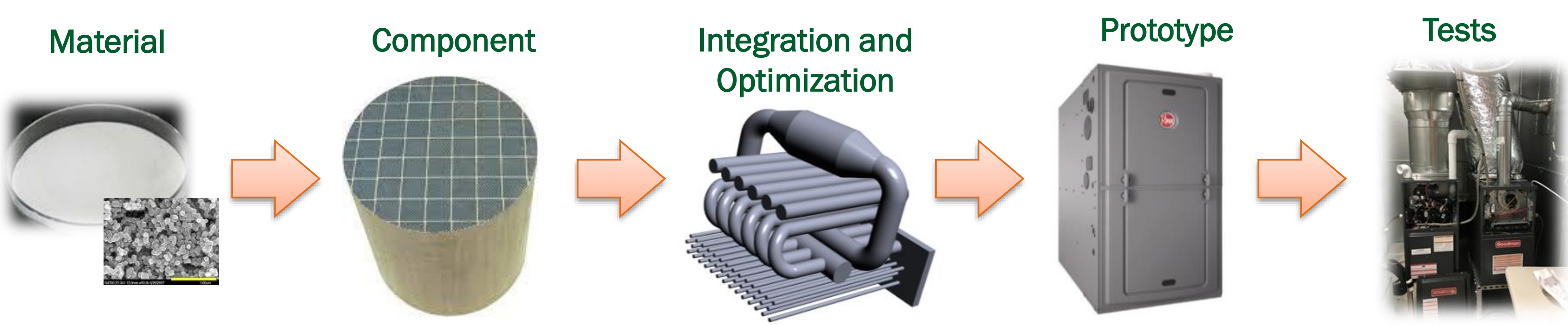
Furnace testing chamber

Stakeholder Engagement

- **The project is at early stage with successful samples developed, preliminary simulations and tool development completed**
- **Working with industrial partners, utility companies, UT-Battelle Office of Technology Transfer**
  - Rheem Manufacturing
  - Corning Inc.
  - R-Squared Puckett Inc.
  - Knoxville Utilities Board
  - Invention Disclosure 201804153, DOE S-138, 820, 2018
- **Cross-cutting team engagement to maximize technical innovation and market success**
  - Building Equipment Research Group, ORNL
  - Applied Catalysis and Emissions Research Group, ORNL
  - University of Connecticut
- **Related ORNL furnace activities**
  - Drop-in, Retrofit Furnace with Maximum Efficiency – Self Powered System (BTO-03.02.02.26.1926)
  - Novel Furnace Based on Membrane Technologies (BTO-03.02.02.26.1923)

Remaining Project Work

- FY 2019
  - Quantify SOx and NOx adsorption capacity of the adsorbers
  - Identify detailed conditions required to perform adsorber regeneration
  - AGT component design, fabrication, and assembly
  - Baseline furnace tests
- FY 2020
  - Retrofit existing furnace to create prototype gas furnace with AGT
  - Develop and demonstrate AGT regeneration control strategy
  - Evaluation of the new furnace under standard test procedures



Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: DOE total $960K, new project beginning in FY2019
Variances: No variances
Cost to Date: $103K of FY2019 budget (through March 2019)
Additional Funding: No additional direct funding

Budget History					
FY 2018 (past)		FY 2019 (current)		FY 2020 – (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$480K		$480K	

Project Plan and Schedule

- <u>Go/No-Go: Successful delivery of 1.0 L AGT component with the nano-array monolith substrate, 09/30/2019</u>

Project Schedule												
Project Start: October 1, 2018		**Completed Work**										
Projected End: September 30, 2020		**Active Task (in progress work)**										
		Milestone/Deliverable (Originally Planned)										
		Milestone/Deliverable (Actual)										
	FY2019				**FY2020**				**FY2021**			
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												
Q1: ZnO/BaO-based nano-array sample												
Q2: 1.0-liter nano-array monolith substrate												
Q3: Adsorber characterization												
Current/Future Work												
Q4: Adsorber tests in bench reactors												
Q4: AGT component assembly and accessory												
Q5: Preliminary furance retrofit												
Q6: AGT integration to the retrofitted furnace												
Q6: AGT regeneration control in the furnace												
Q7: Testing new furnace with AGT												
Q8: Comparing new furnace with baselines												