DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Clean Combustion Technology with Efficient and Autonomous Wood Heater Operation over the Full Cycle

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Systems Development and Integration Session A

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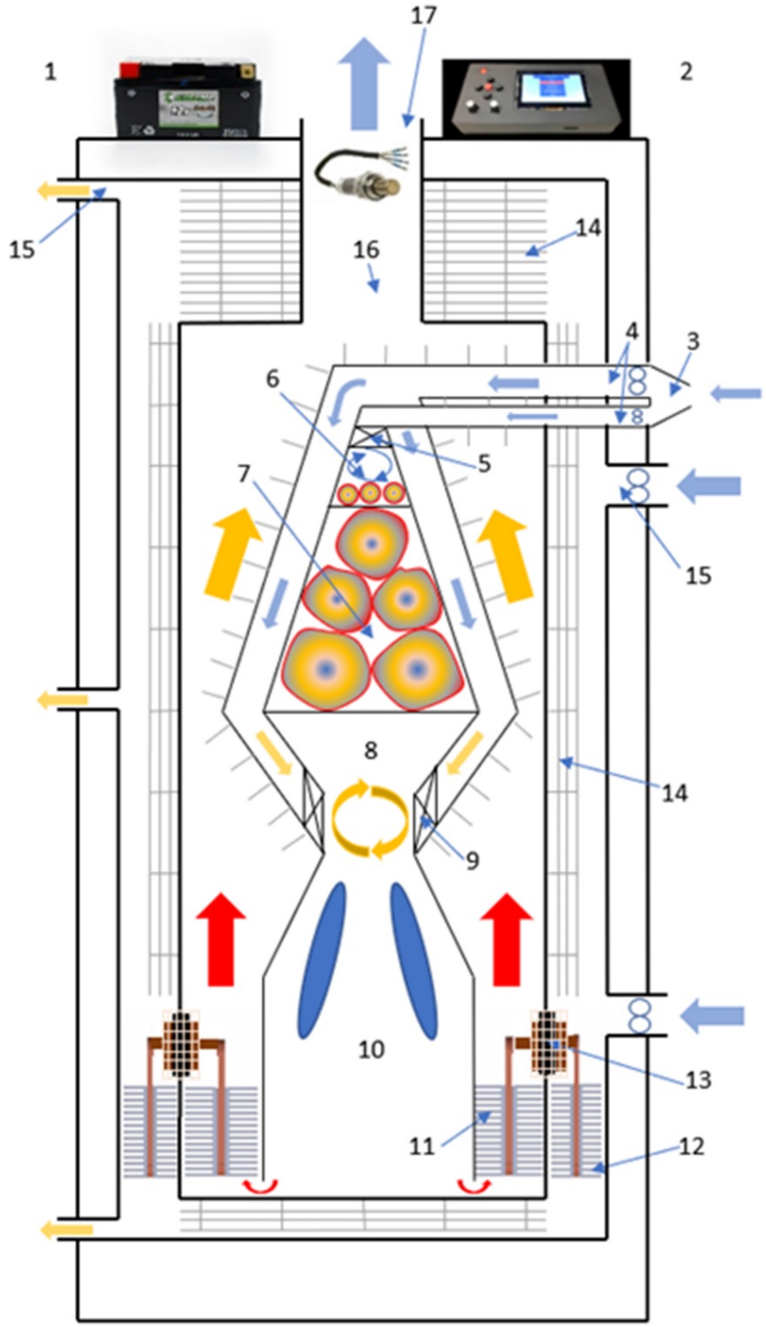
Project Overview

- *Advance the wood heater technology in four areas:*
  - ❑ *Two-stage combustion with forced air-flow to reduce emissions*
  - ❑ *Fan-assisted heat extraction to increase thermal efficiency*
  - ❑ *Thermoelectric generators to produce and manage power*
  - ❑ *Automation to optimize the operation for all phases of burning*
- *Present wood heater designs rely upon natural convection which can be difficult to control and catalytic aftertreatment systems with high maintenance costs*
- *Comply with stringent emissions and efficiency mandates*
- *Primary risks are the operational flexibility and reliability*

1 – Approach

Conceptual design developed at the University of Alabama

1. Battery;
2. Controller;
3. Intake;
4. Combustion Air Fans;
5. Axial Swirler;
6. Starter Logs;
7. Primary Zone;
8. Yellow Flame;
9. Radial Swirler;
10. Secondary Zone;
11. Heat-pipe Assisted Heating Surfaces;
12. Heat-pipe Assisted Cooling Surfaces;
13. TEG;
14. Extended Surfaces;
15. Convection Fans or Vents,
16. Thermocouple,
17. O2 Sensor



1 – Approach

- Combustion occurs in segmented primary and secondary zones to independently control the fuel-air mixture stoichiometry in each zone. A separate section for reliable ignition is introduced in the primary zone
- Combustion airflow rate in each zone is controlled in real-time using variable speed fans to match the heating load of the residence.

- Strategically located fins and baffles on the exterior surfaces, and vents are used for efficient heat transfer.
- Variable speed fans are used to automate the heat removal by convection.

- The wood heater is integrated with TEGs using heat pipes to maximize the heat flux and hence, the TEG conversion efficiency. Presently, TEGs are added mainly as an afterthought.
- A maximum power point tracking (MPPT) converter with a battery is used to store and manage power supply during start-up, shut-down, and steady operation.

- We will use robust oxygen concentration and temperature sensors to control not only the HRR in the combustor but also the heat extraction by convection.
- All functions of the wood heater will be controlled by a smart controller capable of WiFi communication

- The wood heater developed in this project will be a direct vent system, which is the first in the industry to the best of our knowledge.

1 – Approach

- The University of Alabama (UA) is collaborating with Unforgettable Fire, LLC (UFF, a privately-owned small U.S. business) and Virginia Tech (VT) to develop a residential wood heater that will exceed EPA 2020 emissions requirements and improve the weighted average thermal efficiency.
- UA team: wood heater development, integration, and testing.
- VT team: wood burning models and CFD analyses of combustor and heat transfer designs.
- UFF team: Industrial/field guidance and manufacturing support

- Technical risks include sensor reliability, fan life span, battery drainage, and variability in control algorithms. A risk register will be maintained to manage the risks.
- The team members participate in regular teleconferences, including with DOE project manager as required, to review tasks, milestones, and to make Go/No Go decisions.
- Team will work with university entities that promote diversity, equity, and inclusion.

Fig. 1 Project partners

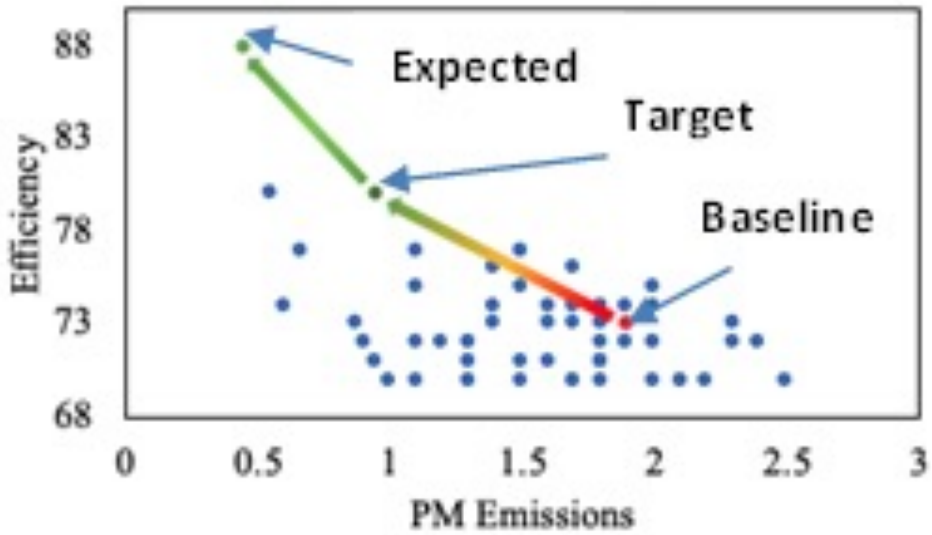


Fig. 11 Performance matrix of EPA approved non-catalytic wood heaters

1 – Approach

Task 1.0: Initial Verification (M1-M3) - Completed

- **Task Summary**: The certification test report and test data will be provided to DOE

Task 2.0: Combustor Development (M4-M33)

- **Task Summary**: A wood burning model for CFD analysis will be developed and validated using experimental data. The final combustor design will demonstrate reduction in PM emissions by 25-50% relative to the EPA 2020 emissions limits.

Task 3.0: Standalone Power (M4-M15)

- **Task Summary:** A battery power control subsystem and a thermal subsystem will be developed independently and combined for use with the wood heater in an opportunistic manner.

Task 4.0: Efficient Heat Extraction (M4-M33)

- **Task Summary:** Heat transfer system designs will be developed utilizing experimental studies and CFD analysis

Task 5.0: Automation (M4-M21)

- **Task Summary:** Wood heater automation capabilities will be developed including selection of robust sensors, controller development, and the control algorithm.

Task 6.0: Prototype Development and Testing (M22-M36)

- **Task Summary:** All electrical and mechanical systems will be combined to build the wood heater prototype. The final prototype will be integrated with Smart Apps.

1 – Approach

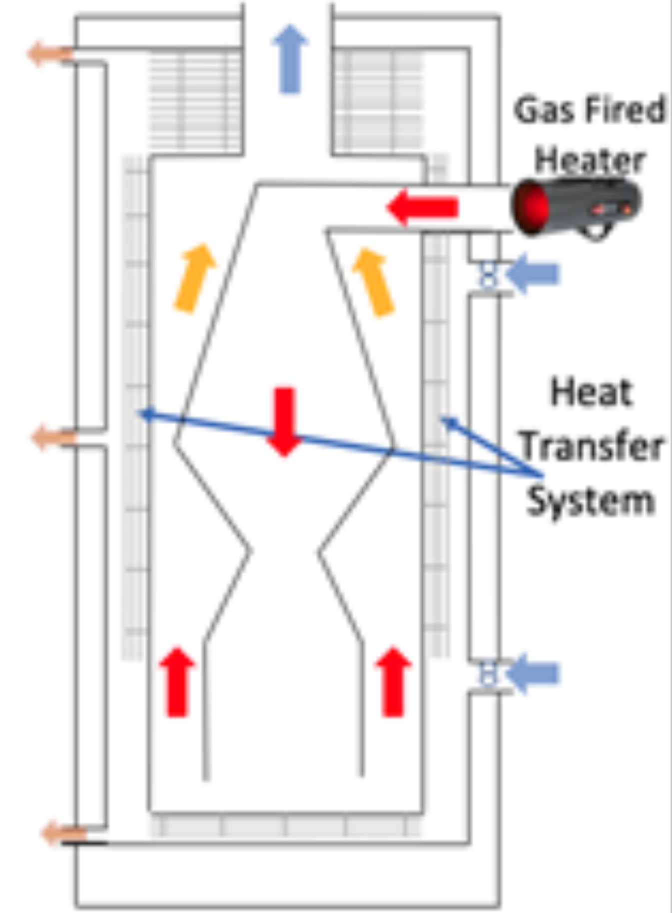


Fig. 7 Experimental setup for heat transfer surface studies.

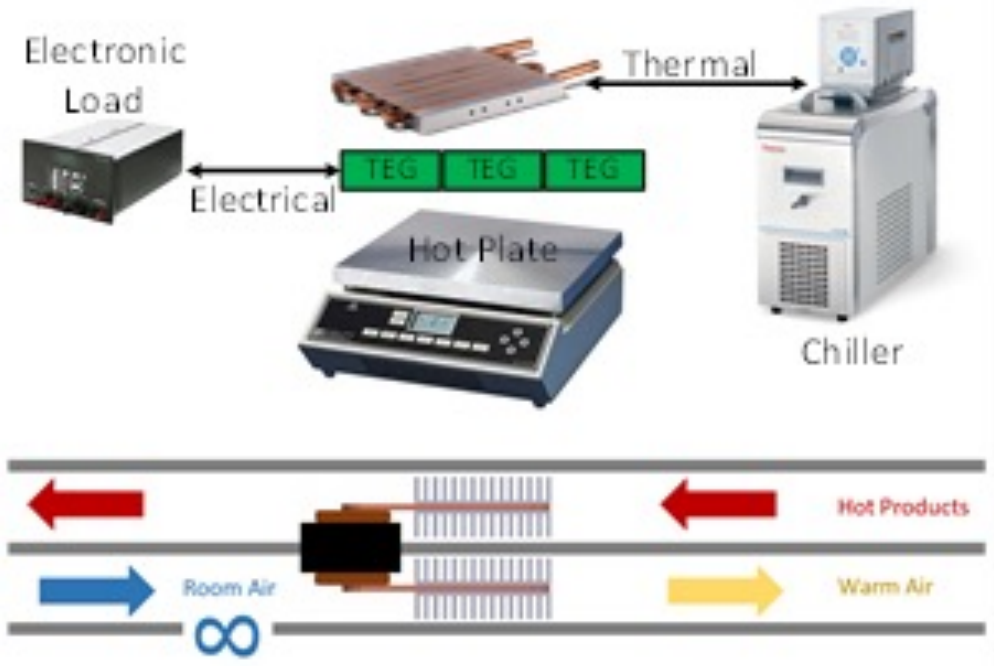


Fig. 5 Test apparatus to develop (top) power control sub system, (bottom) thermal subsystem

Fig. 8 UAC-106 general purpose controller platform

1 – Approach

- **Tasks 2.0 to 5.0 pertain to component level development.**
- **Component level tasks will be performed independently with each achieving specific performance goals**
- **Component level systems will be integrated to build the prototype for testing and demonstration.**
- **The proposed approach will mitigate technical risks as they arise by addressing them at the component level designs.**

2 – Progress and Outcomes

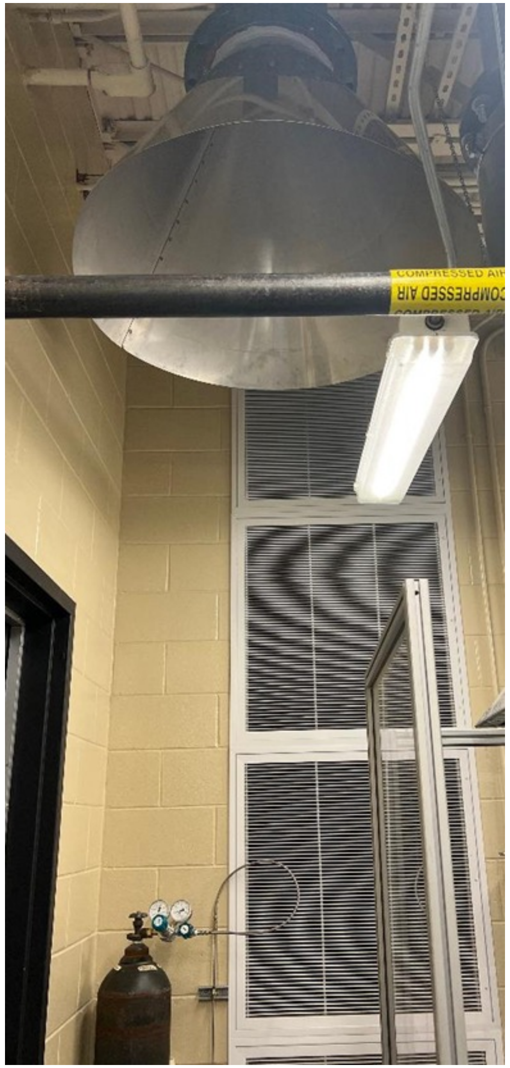
The project was initiated in December 2022. We have completed BP1: Initial verification phase.

- Designed, built, and installed a dilution tunnel
- Installed and operated baseline Katydid wood heater at Engine and Combustion Lab at UA

In preparation for BP2, we have performed preliminary component level experimental and computational studies.

- A wood heater incorporating the proposed concepts was designed and built to verify the workability of the approach, i.e., forced convection and two-stage design for combustion, in a viable system
- Initial development/validation of wood combustion models has been performed
- A thermoelectric generator incorporating heat pipe designs has been developed to verify its workability
- Preliminary experimental heat transfer studies have been performed to identify key design features
- Oxygen sensors were evaluated to identify a product for potential applications

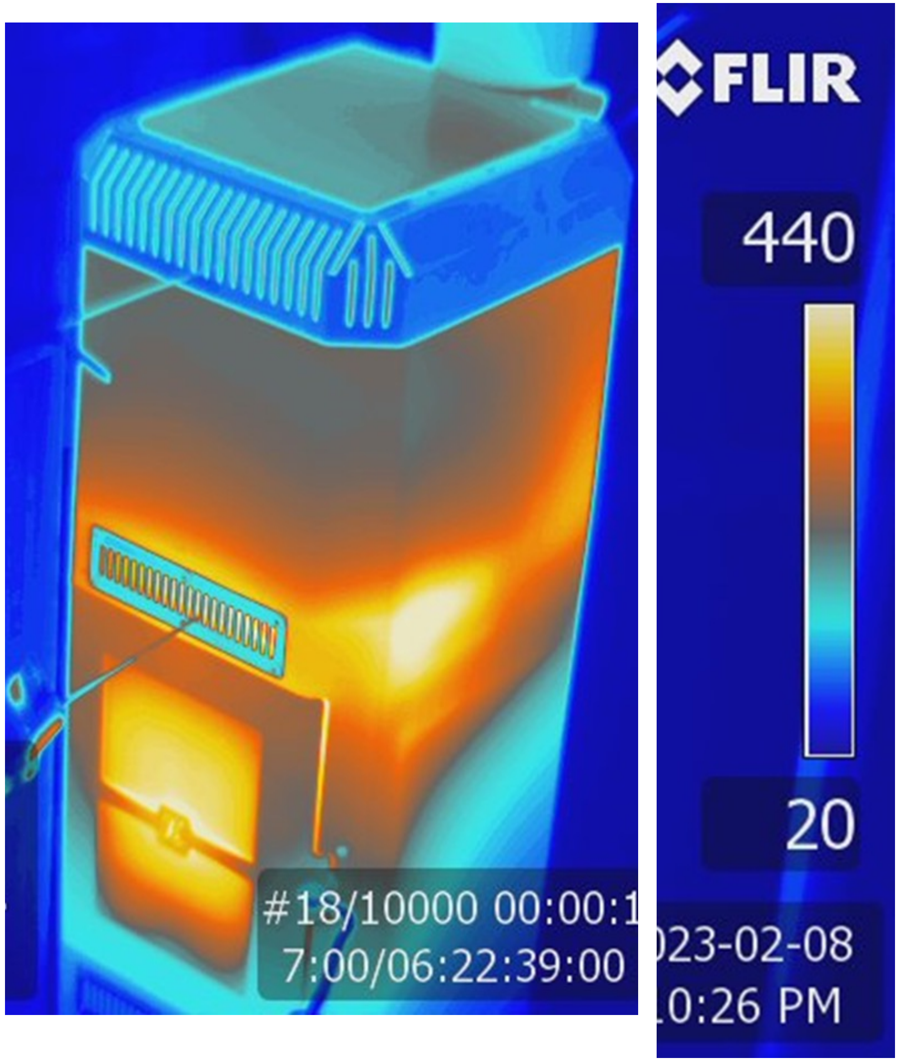
2 – Progress and Outcomes



Dilution tunnel intake

Dilution tunnel designed and installed at UA

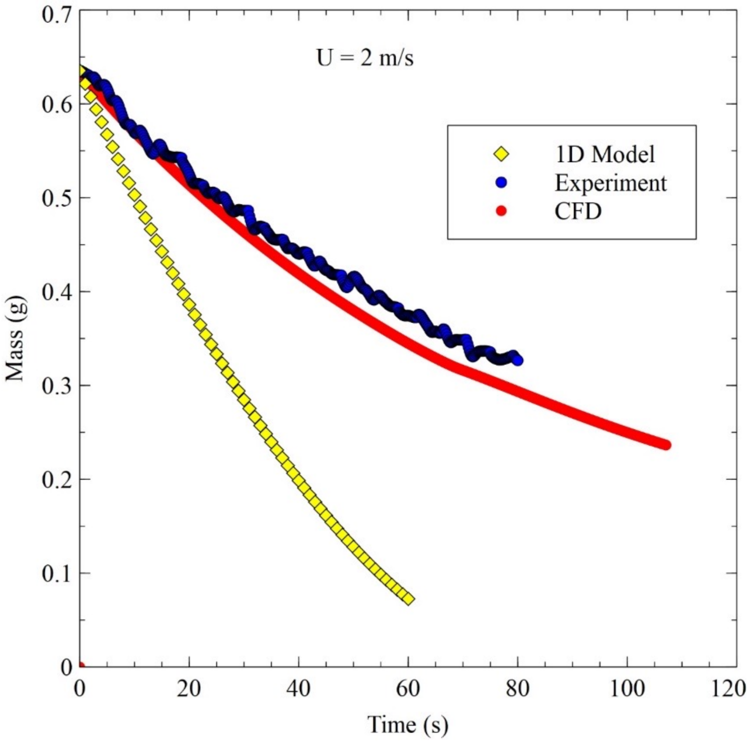
2 – Progress and Outcomes

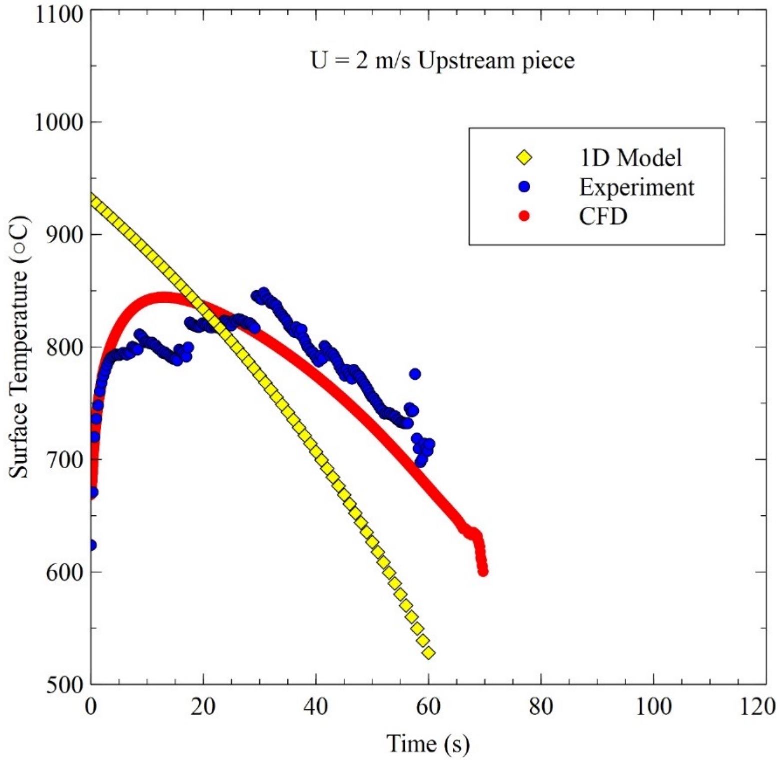


Baseline wood heater (Katykid) operated at UA

Sierra particle sampling system

2 – Progress and Outcomes



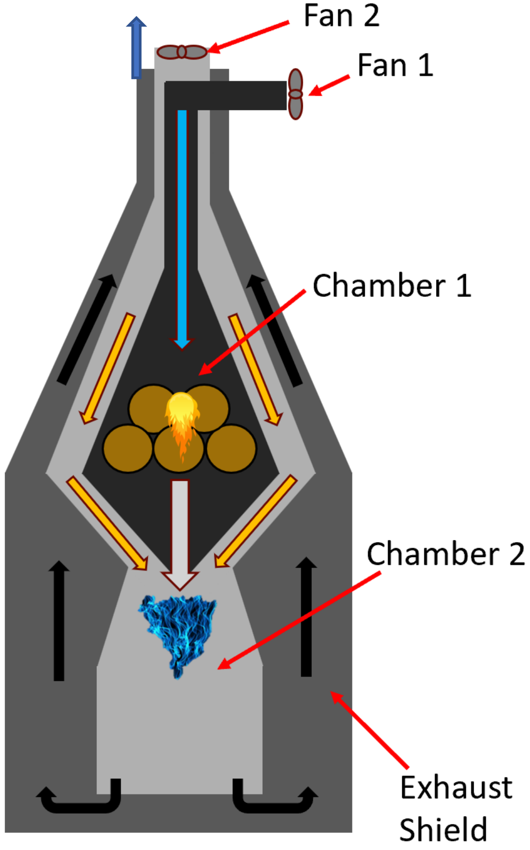


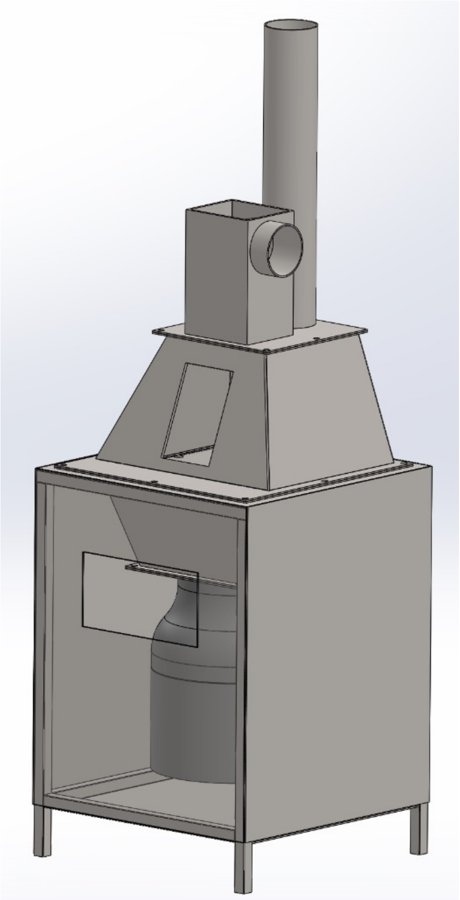
Char oxidation model successfully implemented and performs well against experiments and 1-D model for single firebrand

2 – Progress and Outcomes

Developed a prototype wood heater to demonstrate the basic concepts

2-D Concept → 3-D Model → Finished Prototype





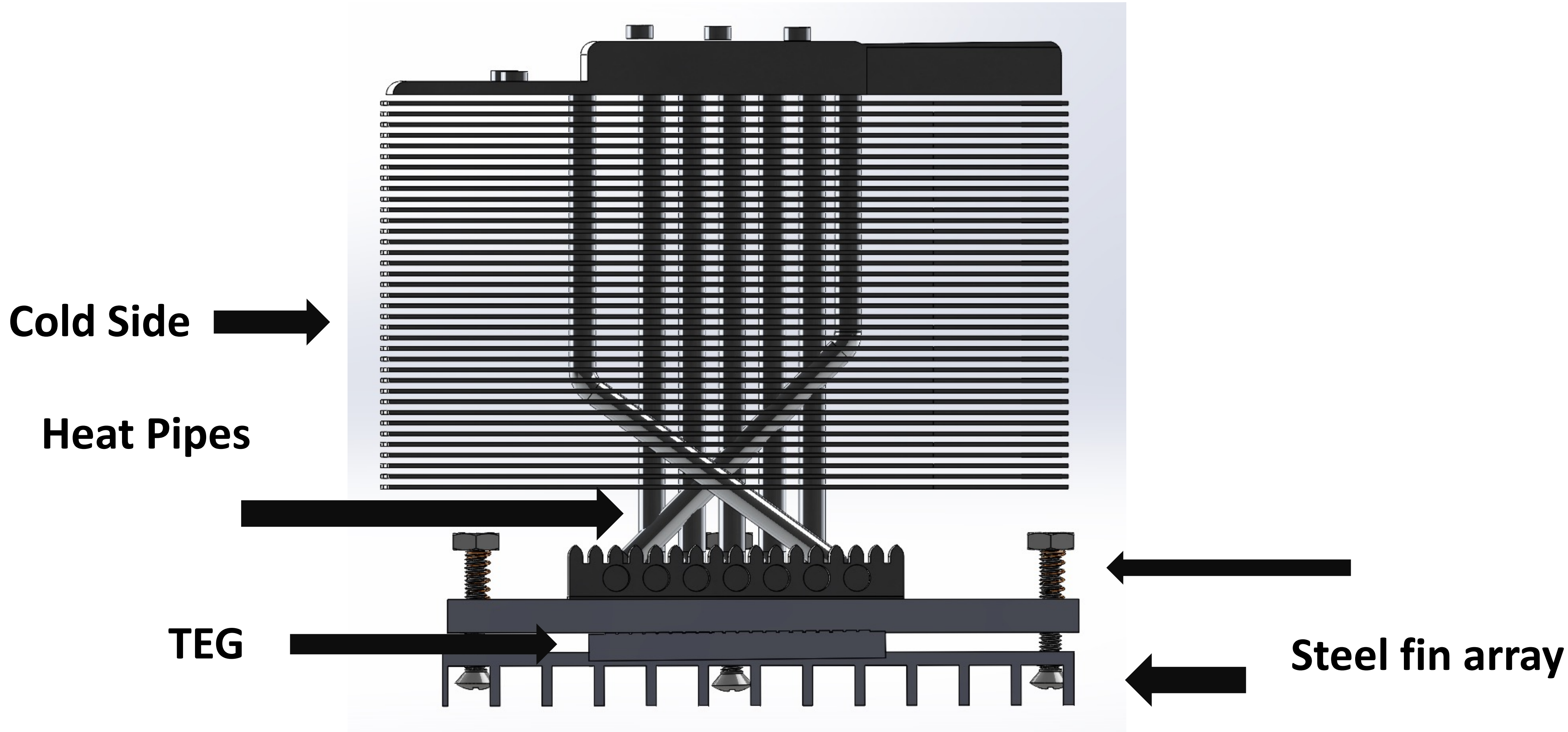
2 – Progress and Outcomes

Preliminary Test Results

1. Natural convection was eliminated by using fans
2. All concepts can be packaged in the developed prototype design
3. Achieved sustained burn in the primary combustion zone
4. Identified flow issues with secondary zone that will require flow optimization

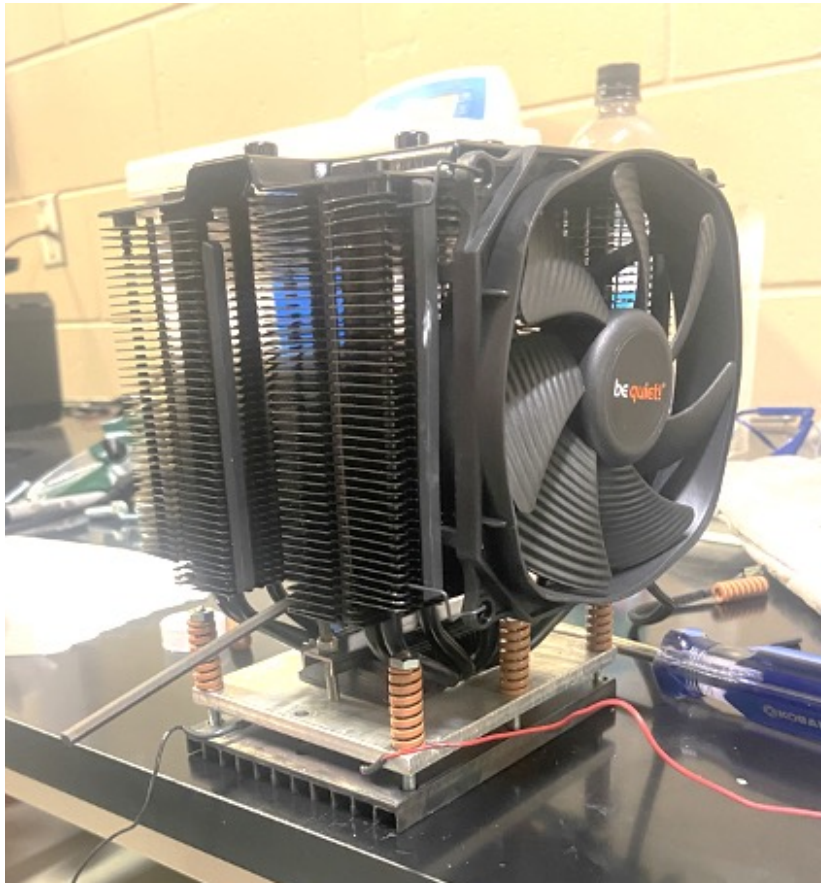
2 – Progress and Outcomes

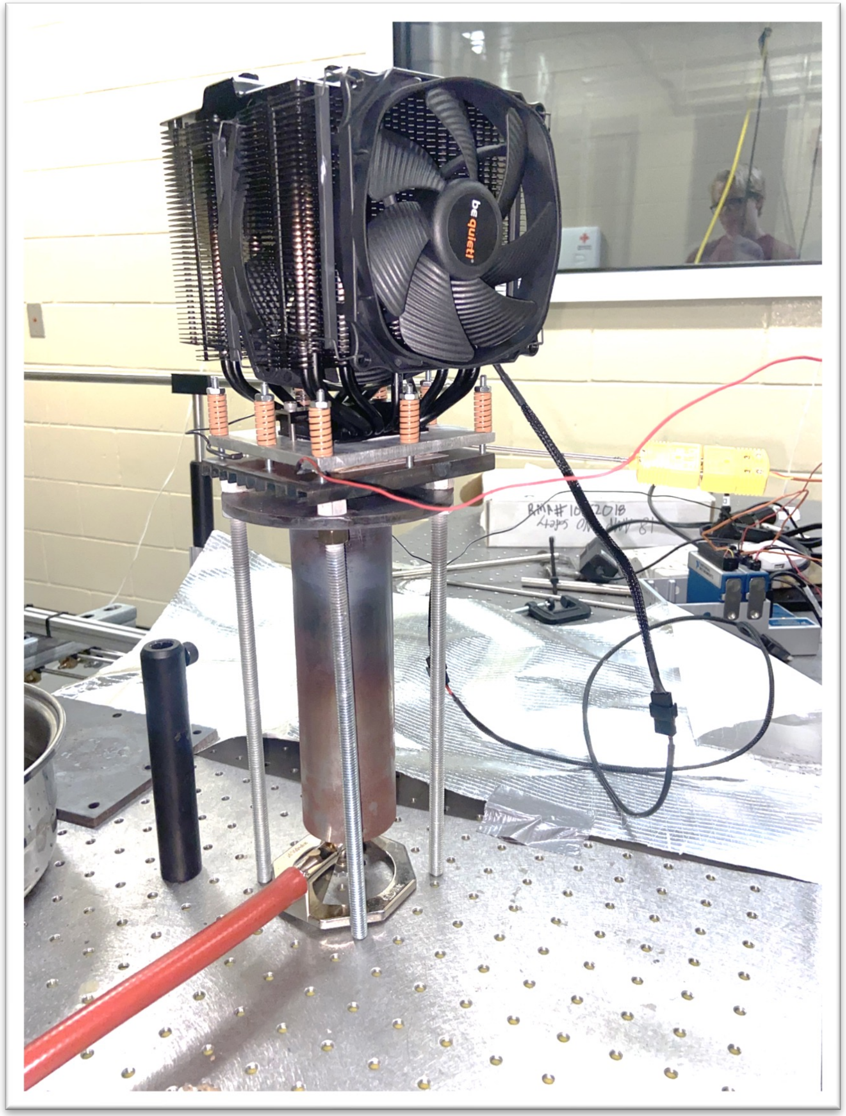
Design of the thermoelectric (TEG) module with heat pipe and heat exchangers



2 – Progress and Outcomes

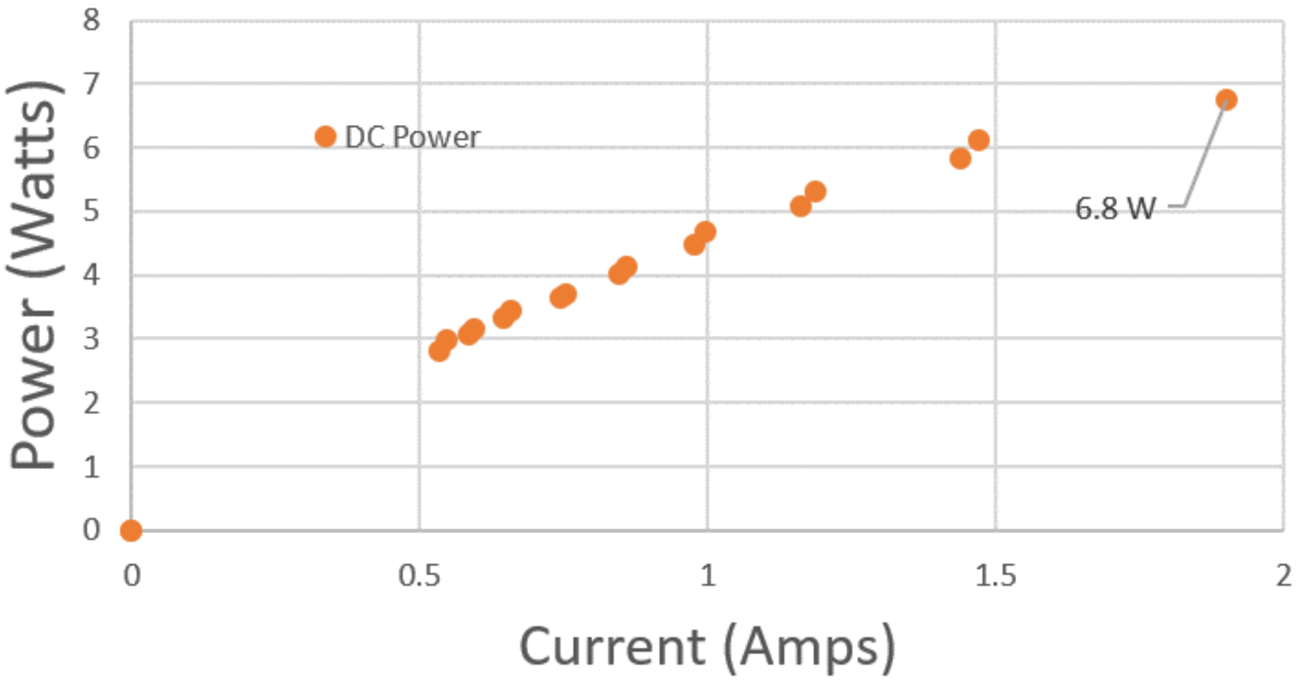
TEG design and testing



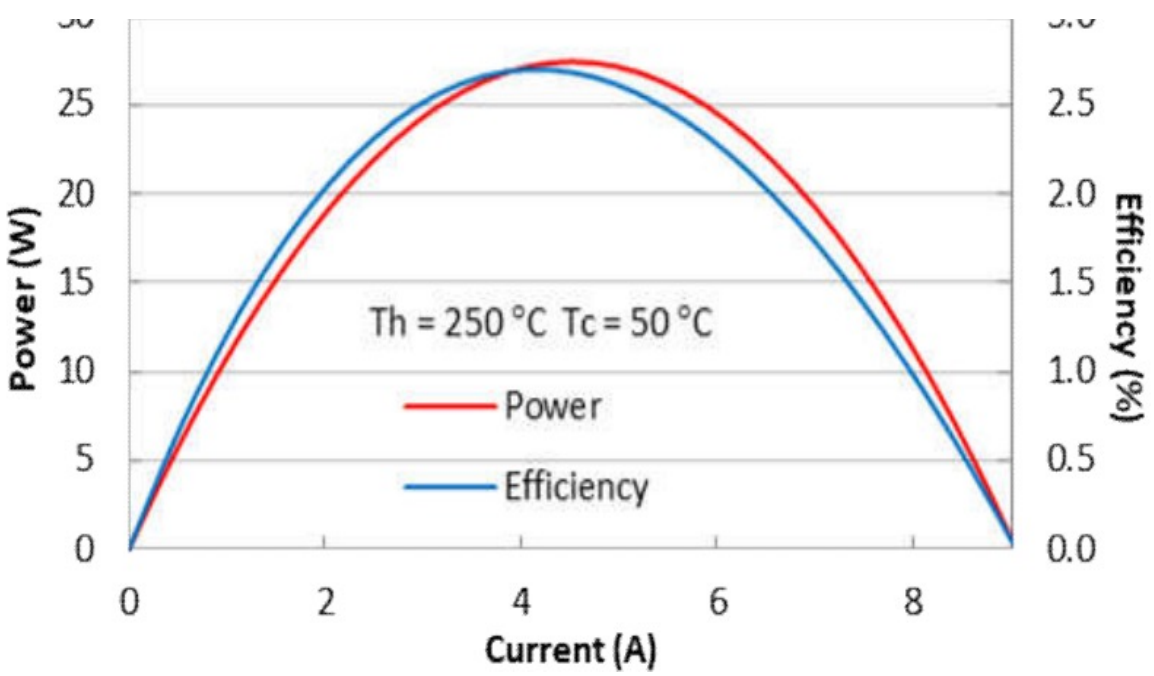


2 – Progress and Outcomes

Preliminary test results

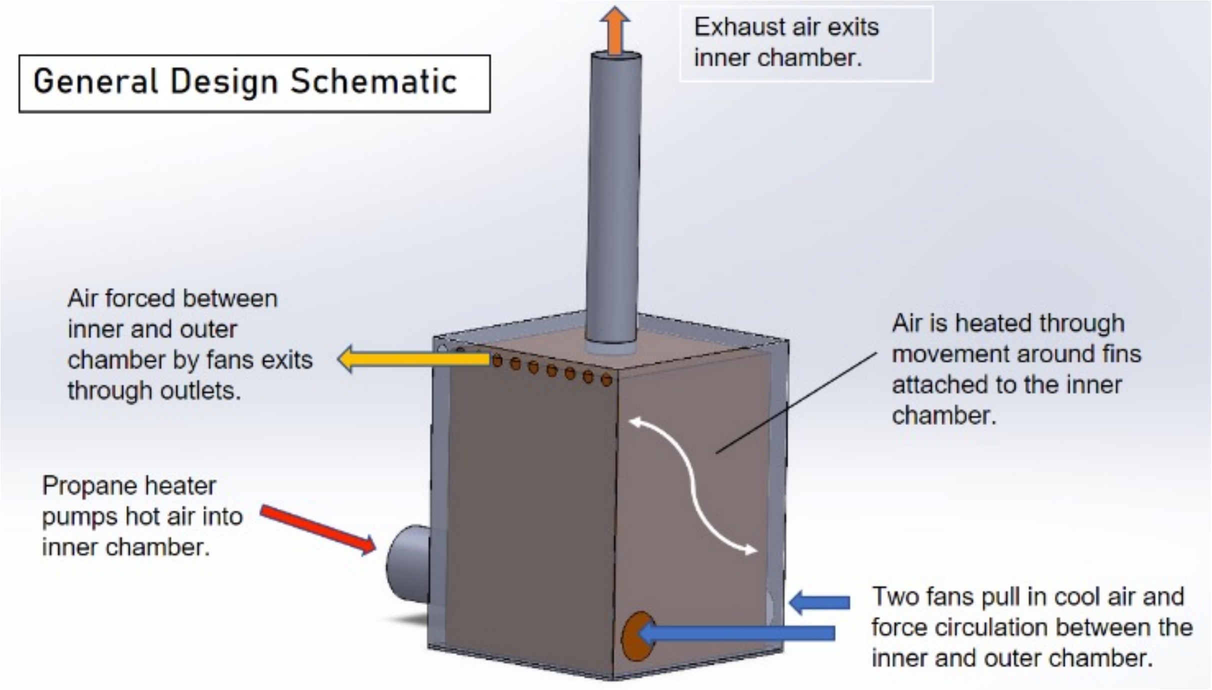


Target performance



2 – Progress and Outcomes

- Detailed thermal analysis of current wood stove shows that radiation and natural convection are equally important for heat transfer.
- Preliminary fan selection has been completed based on CFM required to achieve the desired flow.
- Review of available O_2 sensors has been completed based on cost, range, history of past use. Preliminarily, OZA685-WW1 O_2 Sensor has been selected.



Set-up is being built to determine the impact of forced convection & potential use of fins to increase heat transfer

3 – Impact

- The project will result in a greatly improved wood heater prototype ready for commercialization in collaboration with our small-business industry partner. It will be a ventless system (no chimney required), first of its kind in the industry.
- This project will generate scientific knowledge and advanced modeling and simulation tools to accelerate wood heater research and development.
- The combustion, heat transfer, TEG power and battery management, and automation concepts and related data generated in this research will be disseminated through research publications to benefit the industry and community as whole.

Quad Chart Overview

Timeline
- *December 1, 2022*
- *November 30, 2025*

	FY22 Costed	Total Award
DOE Funding	*$74,668*	*$1,642,815*
Project Cost Share *	$20,138	$437,868

TRL at Project Start: TRL 2
TRL at Project End: TRL 4

Project Goal
Reduce emissions at least by 25-50% relative to the EPA 2020 emissions limits and increase weighted average thermal efficiency at least by 5-15% over the baseline design of Kaydid wood heater sold by our industry partner

End of Project Milestone
Prototype hardware of the wood heater will be built by combining all mechanical components (combustion, heat transfer, TEG) and integrating them with the master controlled developed in previous subtasks.

The prototype will undergo extensive lab testing to optimize functionality and performance, and finally, it will be interfaced with Smart Apps to secure remote access, fault diagnostics, alerts, safety alarms, real-time performance monitoring, and data driven autonomous control. The final wood heater prototype will be ready for field testing, e.g., at a DOE lab, certification testing, and commercialization.

Funding Mechanism
DE-FOA-0002396; CFDA Number 81.087

Project Partners*
- Virginia Tech
- Unforgettable Fire, LLC

*Only fill out if applicable.

Backup Slides

Baseline Wood Heater Technology Performance Data

Baseline Wood Heater Technology	Katydid Wood heater by Unforgettable Fire, LLC
Residential Wood Heater Type	Room Heater
Catalyst	Non-Catalytic
Power Generation (if applicable)	None
Integrated Sensors	None
Other Technology	Wood heater utilizes a patented gasification technology with two-stage combustion. Efficient heat removal from the surfaces provides high thermal efficiency
Wood used for Testing	Douglas-Fir Species, Untreated, Air-dried, standard grade or better, dimensional lumber
Applicable Test Methods	U.S. EPA 40 CFR Part 60, Subpart AAA – Standard of Performance for Residential Wood Heaters (Appendix A, Method 28 and 5G)
Particulate Emissions Concentration	8.191 mg/m^3
Emissions Rate	1.9 g/hr
Emissions factor	1.66 g/kg and 0.262 lb/MMBTU
Weighted Delivery Efficiency	73 %
Max heat output	55,000 BTU/hr
Average Stack Gas CO	% (not documented in the certification report)
Average Stack Gas CO_2	% (not documented in the certification report)