DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Development of Forced-Air Combustion Systems with Automated Controls to Reduce Emissions from Cordwood Room Heaters in Everyday Use

April 5, 2023
Wood Heaters

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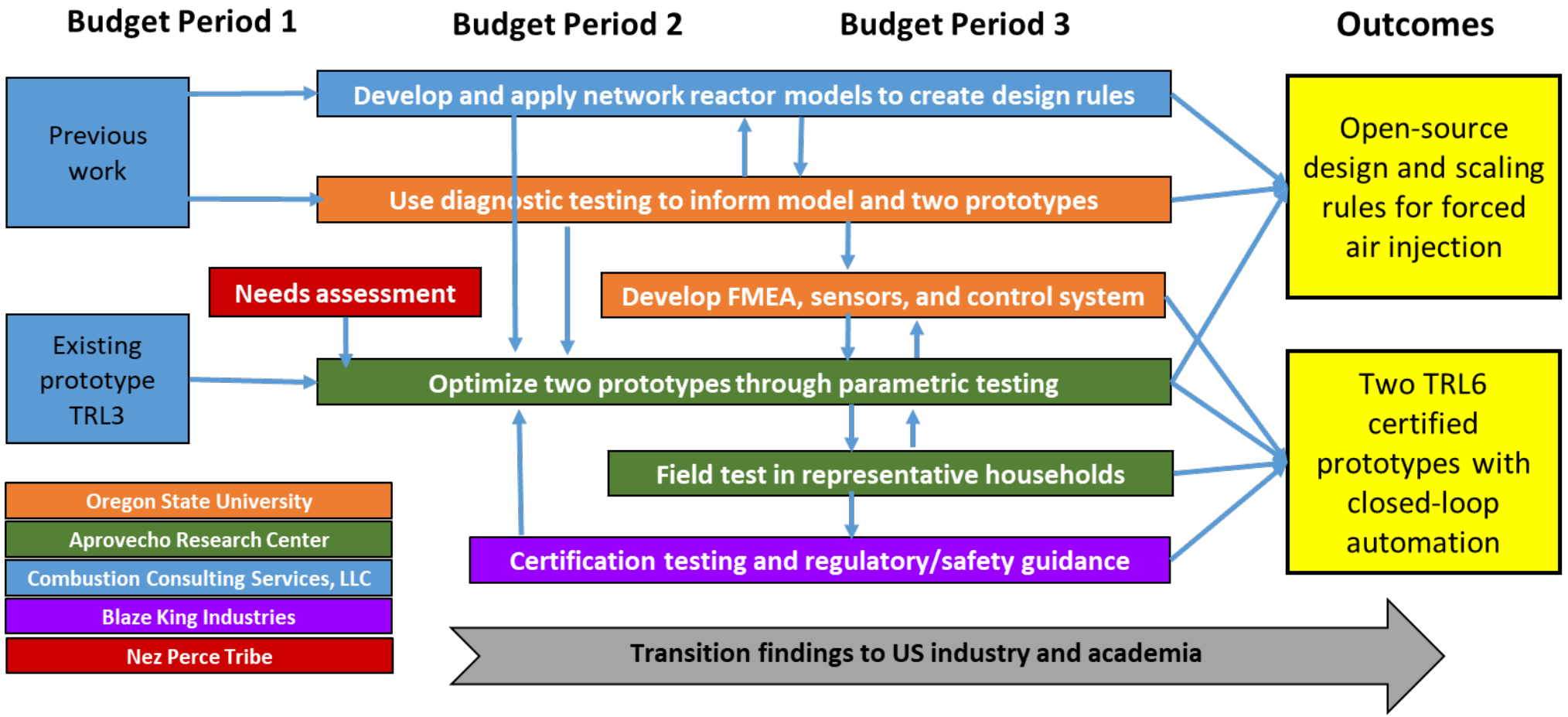
Project Overview

- *Incorporate jets of forced air into the combustion chamber of cordwood room heaters to reduce PM emissions throughout the real-world burn cycle*
  - *Preliminary data show a 90% reduction in PM relative to baseline*
  - *Objectives:*
    - *Retrofit two existing wood stoves to bring legacy stoves to EPA 2020 compliance*
    - *Publish open-source design rules to enable application to future designs*
  - *Design based on:*
    - *Detailed combustion diagnostics and chemical reactor network modeling*
    - *Extensive needs assessment with users from target/underserved populations*
    - *Guidance from industry, regulatory, and tribal advisory groups*

1 - Approach



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Challenges and Risk Mitigation

- Technical Risks
  - Not feasible to develop a universal retrofit
    - Customize for two common designs that are the most likely to be highly polluting
    - Develop design rules that can be applied to new stove designs
  - Customer needs for performance, safety, noise, space, and aesthetics must be met
    - Conduct detailed user needs assessment
    - Ensure heater still functions effectively when the power is out by using FMEA and fail-safe control positioning.
- Compliance/Regulatory Risks
  - Safety and performance expectations
    - Ensure design can meet the full range of performance and safety tests
    - Consult with regulatory advisory group throughout project

Metrics and Decision Points

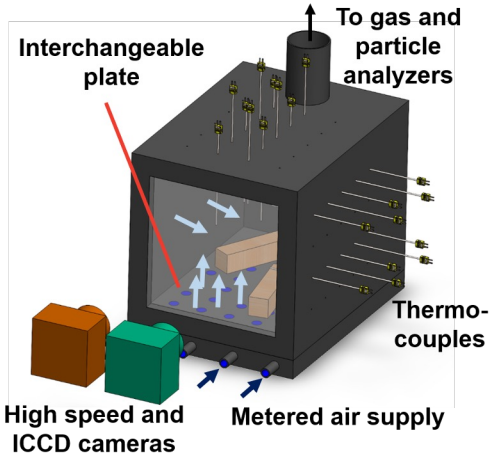
- Go/No-Go Decision point 2 (Month 12):
  - Testing protocol defined, Heater models identified, Needs assessment complete
- Go/No-Go Decision point 3 (Month 30):
  - At least one prototype developed that meet performance criteria with manual control
    - 2.5 g/hr or less PM2.5
    - 5% or greater efficiency improvement relative to baseline
- Go/No-Go Decision Point 4 (Month 46)
  - Prototypes *certified* to meet performance criteria with automated control

Diversity, Equity, and Inclusion

- Focus user research and design outcomes to address specific needs of underserved populations who rely on wood heat and are disproportionately affected by health impacts of smoke exposure
- Collaboration with/advising by three tribal communities in the Pacific Northwest
  - Nez Perce
  - Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Tribes
  - Confederated Tribes of Umatilla
- Intentional recruiting of underrepresented groups on the project team

Task 1 - Fundamental Combustion Diagnostics

- Develop sub-scale canonical experiment of forced air burning of wood
- Measure baseline emissions, temperature and species distributions, and performance
- Modify full-scale firebox, collect temperatures, velocity and species data
- Assess performance of heater 1 for varying forced air conditions
- Map the performance at the most polluting stages such as start-up, refueling and burning of wet wood



Task 2 - Chemical reactor network models

- Literature and software review, review of emissions models (including PM)
- Compilation of gas phase and solid phase kinetic models
- Design of network reactors
- Refinement of reactor model relative to experiments
- Initial recommendations and iterations of heater design, based on experimental results

Task 3 - Baseline, Prototyping, and User Testing R&D

- Needs assessment and user testing in rural and tribal communities
- Catalog and select two most common existing legacy room heater designs based on developed criteria
- Baseline field studies of performance and user behavior
- Lab testing of two baseline heater models for efficiency and emissions through all operational stages
- Develop prototypes and conduct systematic statistical parametric testing of design space
- Detailed design of prototypes up to TRL 6 for two heater models
- Safety testing against UL 1428, EPA performance testing, durability testing, field testing

Task 4 - Control System Development

- Create dynamic model based on literature
- Use linearized model to test sensitivities to different sensing point options, cost of sensors and required bandwidth
- Create Model Predictive Controller (MPC) around dynamic model
- Run preliminary failure mode and run away scenarios
- Use experimental data to train a digital twin for real world compensation and degradation
- Use FMEA to inform a fail-safe control system, including lower lever contingency controls and limp home mode
- Finalize sensors, control algorithms, interface

Task 5 - Market Transformation and Open Source Design

- Recruit student researchers and ARC staff from target underserved populations
- Convene Industry Advisory Group
- Secure Institutional Review Board (IRB) approval for user testing, put IP agreements in place
- Engage with tribal and low-resource community leadership to drive planning and buy-in
- Research regulatory and safety requirements with fire, insurance, and certification officials
- Develop design rules and scaling/control parameters based on tasks 1-4
- Webinars and Outreach for academia and manufacturers, publications
- Complete preliminary business plan, estimated cost of production, and market analysis

2 – Progress and Outcomes

- Verification
- Details on Tasks 1-5

BP & Go/No-Go #1 - Verification

Residential Wood Heater Type	Baseline US Stove Model 2469E During Verification	Prototype Forced air in US stove Model 2469E During Verification	Percent Change During Verification	Percent Change During Application
Emissions Rate		1.63 g/hr PM2.5	-82.5	
Overall HHV Efficiency				

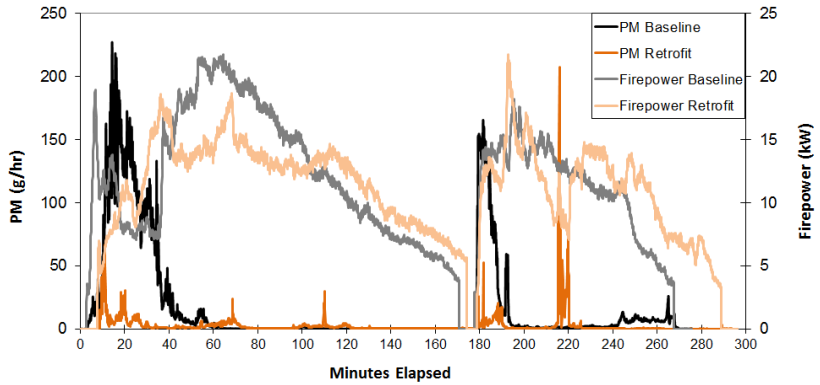


Figure 3 Real-time Firepower and PM emissions of the Baseline and Retrofit cases

Table 1
Forced-Air Wood Heaters
Overview of Verification Test Data

Objective	Key Performance Parameter	Red Flags	Anything Lacking?	Readiness to Proceed	Path Forward
Retrofit Stove Improved Performance versus Baseline Stove	Particulate emissions	none	nothing noted	yes	Proceed to BP2.
	Particulate emission rate	none	nothing noted	yes	
	Measured stove efficiency	yes	Missed verification target	yes	Proceed to BP2 with caution

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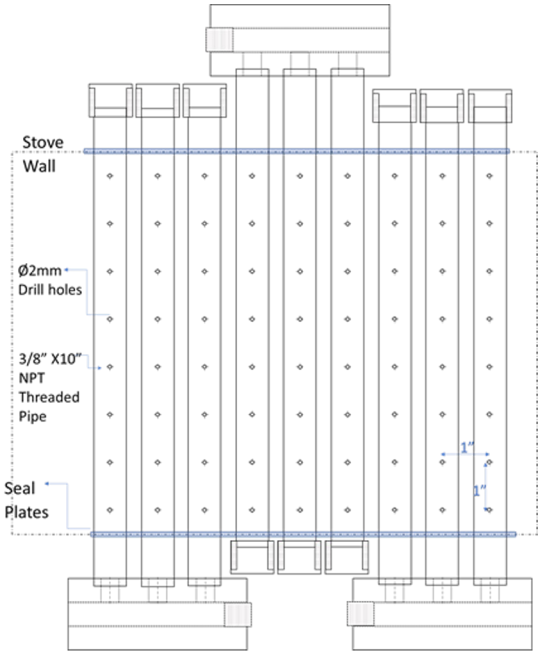
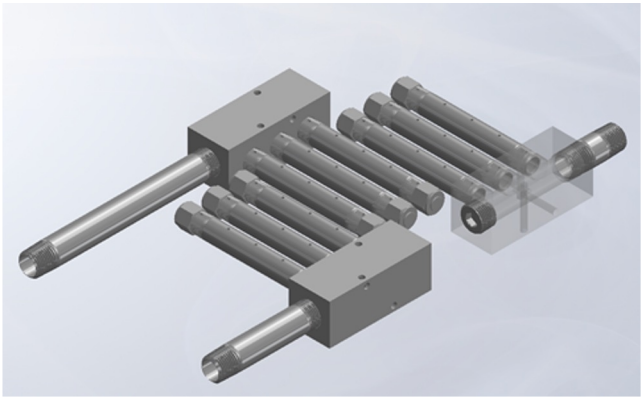
Task 1 - Fundamental Combustion Diagnostics

- Training on operation and testing of the stoves and the sensor box calibration
- Forced air system design for the parametric test rig





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Task 1 - Fundamental Combustion Diagnostics

- Laboratory equipment purchased, installation complete by April 2023
  - Laboratory Emissions Measurement System (LEMS)
  - Filter climatization and weighting system
  - TSI Nanoscan
  - Thermo-Fischer TEOM
  - High-speed camera
- NEXT MILESTONE: 1.1 Instrument setup and operation complete (Month 17)

Task 2 - Chemical Reactor Network Models

- Literature review somewhat underway
- PhD Student/post-doc hiring stalled
  - Visa issue for initial student
  - Actively recruiting
- Considering modeling needs during experimental planning
- NEXT MILESTONE 2.1: Network Reactor Model complete (Month 13)

Task 3 - Baseline, Prototyping, and User Testing R&D

- Surveys created and distribution begun
- Interviews with users, stove salespeople, chimney sweeps, etc.
- Baseline heater models cataloged and selection plans based on:
  - Stove operational category
  - Units in service
  - Manufacturer collaboration
  - Ease of retrofitting

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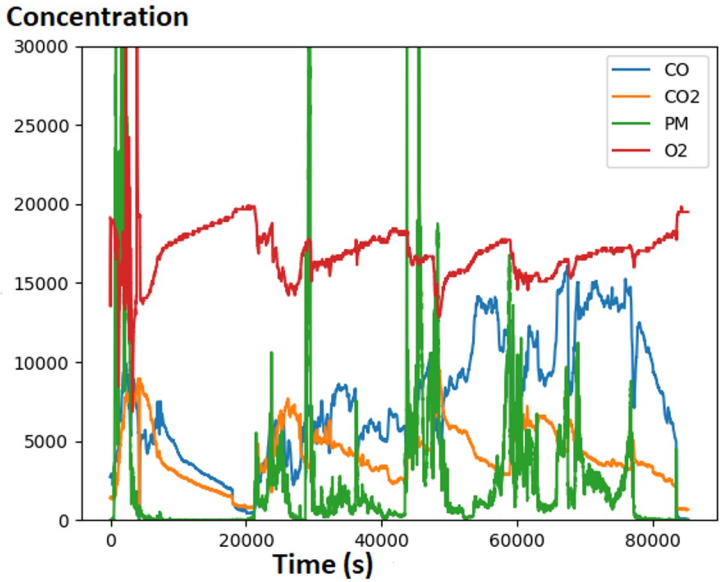
Task 3 - Baseline, Prototyping, and User Testing R&D

- Lab and field equipment gathered, software under development
  - Consultation with advisers regarding equipment & methodology
- Novel use of in-home FUEL, temperature, and air quality sensors



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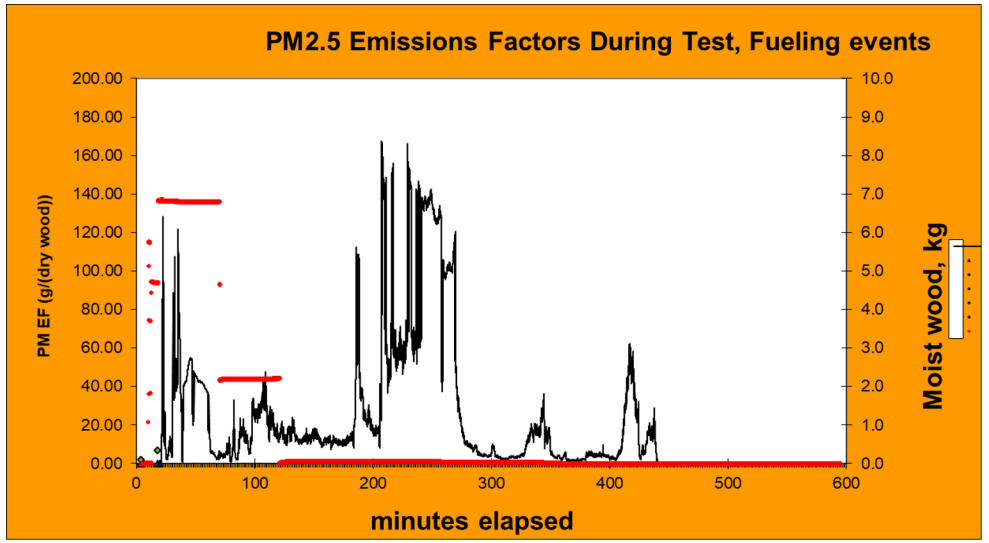
Task 3 - Baseline, Prototyping, and User Testing R&D

- Baseline field testing started
  - 22.0 g/hr PM2.5, 3.85 g/min CO in household test during evening into night burn
  - Results consistent with verification baseline (24.6 g/hr PM2.5, 2.9 g/min CO)
- NEXT MILESTONE 3.1: Selection of 2 heater models in (Month 7)



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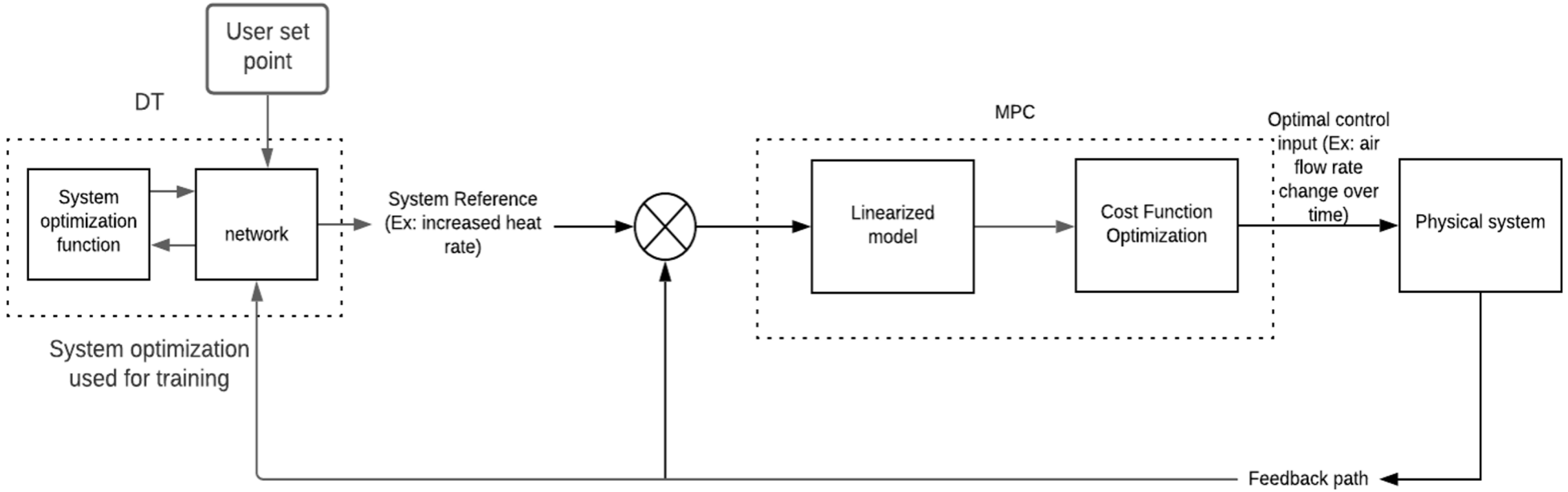
Task 4 - Control System Development

- Dynamic models from literature investigated.
- Model recreation and validation forthcoming.
- NEXT MILESTONE: 4.1 Functioning MPC created (Month 17)



Task 5 - Market Transformation and Open Source Design

- Team established following best recruiting practices from diverse populations (Milestone 5.1 - Complete)
- Advisory Groups convened at least once each: Industry, Regulatory, Tribal
- Institutional Review Board (IRB) approval for user testing secured
- Three tribal communities engaged, research permitting complete or in process
- NEXT MILESTONE: 5.2 Design rules and scaling parameters developed (Month 46)

Name	Organization
Industry	
Ashnil Reddy	Blaze King Industries
Chris Neufeld	Blaze King Industries
Aaron Saxton	Blaze King Industries
John Voorhees	US Stove
John Crouch	Hearth Patio and Barbecue Association
Lyrik Pitzman	pfs-teco
Regulatory	
Nick Czarnecki	Fairbanks North Star Bureau Air Quality Division
George Allen	NESCAUM
Lisa Rector	NESCAUM
Larry Brockman	US EPA BurnWise
Tori Heroux	Portland DEQ
Tribal	
Johna Boulafentis	Nez Perce
Ali Grove and others	CTCLUSI
Matthew Campbell and others	CTUIR (Umatilla)
Gillian Mittelstaedt	Tribal healthy homes network
Charles Anderson	Northwest Indian Housing Association,

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3 - Impact

- Currently 4% of US homes heat primarily with wood, yet wood heat is responsible for 22% of PM pollution
  - Many communities are considering curtailing wood heat to meet increasingly stringent air quality guidelines
- Certification performance does not translate to real-world performance
- If successful, forced air injection can bring existing legacy stoves into EPA 2020 compliance across the real-world burn cycle at a fraction of the changeout cost
- Our data show that climate impact of wood heat can be reduced 95% compared to baseline
- We are partnering with existing US manufacturers like USStove and Blaze King to bring this technology to market when development has progressed
  - Pellet stove design negotiations underway
- Fundamental insights and design rules will be published and shared open source to provide maximum health and climate impact

Summary

- Proposal and verification data both show 82% or greater reduction in PM emission rate, reaching 1.63 g/hr and exceeding performance target of 2.5 g/hr across the burn cycle
- Forced air controls can ameliorate known high-polluting events, like
  - startup
  - burning wet wood,
  - overfeeding, and
  - Overdraft/underdraft conditions
- Extensive user-centered design and testing will ensure the automated heater is successful in real-world conditions
- We’re grateful for the chance to explore this potentially transformative technology

Quad Chart Overview

Timeline

- *August 1, 2022*
- *August 31, 2025*

	FY22 Costed	Total Award
DOE Funding	*(08/01/2022 – 12/31//2022) $17,021*	*$2.5M*
Project Cost Share *	$3,968	$627,067

Project Goal

The goal of this project is do apply fan-driven jets of primary air to modulate the burn and dramatically reduce PM formed in the firebox while improving the user experience with cordwood heaters. We will develop design rules and forced-air retrofit kits with closed loop automated controls to bring legacy cordwood room heaters into compliance beyond current emissions limits.

End of Project Milestone

Two prototypes certified to meet performance criteria with automated control:

- *2.5 g/hr or less PM2.5*
- *5% or greater efficiency improvement relative to baseline*

Funding Mechanism

FY21 BETO Scale-up and Conversion FOA DE-FOA-0002396. Topic Area 4: Residential Wood Heaters.

TRL at Project Start: 3
TRL at Project End: 6

Project Partners*

- Aprovecho Research Center
- Blaze King Industries
- Combustion Consulting Services
- Nez Perce Tribe, CTCLUSI, CTUIR

*Only fill out if applicable.

Additional Slides

Responses to Previous Reviewers' Comments

- Verification (Go/No-Go #1)
  - achieved its retrofit stove PM 2.5 emission target,
  - missed it overall HHV efficiency improvement target
    - The moisture content of the wood used for verification (~9%) was significantly lower than that of the wood used in the application tests (~16%). This moisture variation may have skewed the test results.
  - Recommend that OSU develop a plan of specific development steps to improve HHV efficiency
  - Subsequent testing will be done with cord wood of the same species and having more uniform moisture content to allow more meaningful comparative analysis of developments

Publications, Patents, Presentations, Awards, and Commercialization

- For a related effort focused on pellet stoves, we are finalists in the US DOE 5th Wood Heater Design challenge
- Commercialization planned with USStove Manufacturer for the pellet stove
- Similar commercialization plans in the works with partners USStove and Blaze King as project progresses