Project Team:

NTRE TECH LLC

Advancing the Next Generation of Innovative Technologies

BABCOCK & WILCOX

THE OHIO STATE UNIVERSITY

DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Advanced Low-Emission Residential Fluid-Bed Biomass Combustor

Date: 04-03-2023

Technology Area Session: Systems Development and Integration Session A

Project Sponsor:

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Independent Engineer:

ICF

Principal Investigator: Bartev B. Sakadjian

Organization: NTRE TECH LLC

Project Overview - Objectives

- *Design, construct and test a low-emission and efficient residential wood-fired central heater based on the novel application of bubbling fluidized-bed (BFB) technology.*
- *25% to 50% reduction in emissions relative to the 2020 residential wood heater emission EPA limits*
- *5% to 15% improvement in the weighted average delivered efficiency to current baseline heater designs.*

Fuel: *Biomass Pellets or Wood Chips*
Technology: *Bubbling Fluidized Bed*

Project Overview – Project Team

Expertise in designing and scaling up reactor systems process simulations, developing and testing products

NTRE TECH LLC
Advancing the Next Generation of Innovative Technologies

A premier supplier of industrial and utility boiler and environmental systems →large installed base of biomass-based boilers globally.

B&W BABCOCK & WILCOX

Renowned expertise in the fluidization. Capabilities: Laboratories, analytical tools and prototype and pilot-scale testing.

THE OHIO STATE UNIVERSITY

Development of advanced energy conversion and environmental control technologies

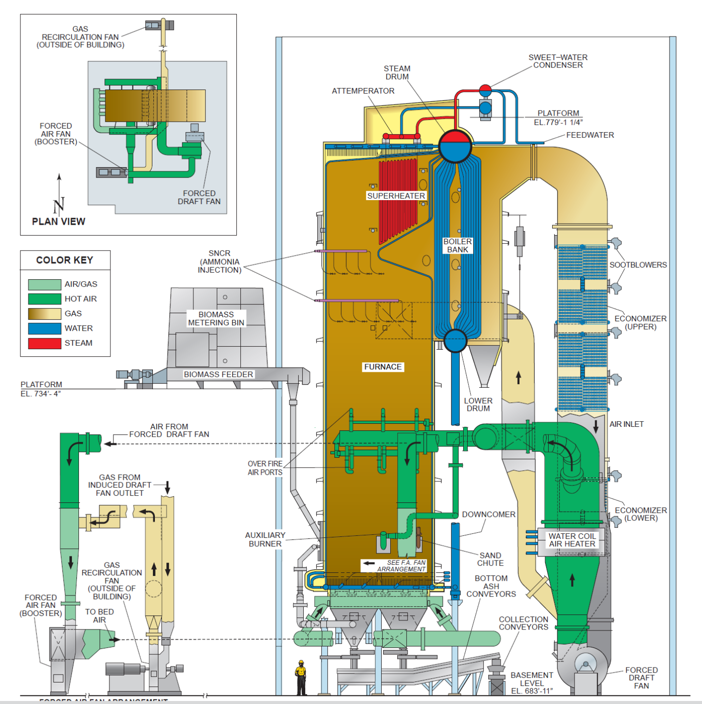
Project Overview - Project Alignment with BETO Goals

- BETO objective: to support the development and testing of low-emission, high efficiency residential wood heaters.
- Fluid-bed technology has the potential to meet the lower overall emission targets set in the FOA.
- The project would focus on innovations on Fluid Bed technology to enable its use at the residential-scale (in central heater applications) and allow its near-term commercialization in the residential market.
- Project promotes the clean use of biomass fuels making new heaters significantly cleaner and improving the air quality in communities where people burn wood for heat.
- The proposed research project objectives align well with the FOA's objectives and is responsive to the requirements.

1 – Approach - Technical Scope Summary

To achieve the stated objectives:

1. Develop, design, and engineer a novel system incorporating innovative features of a fluidized bed configuration that allows frequent changes in load, features that promote optimal operation under transient conditions and smart controls.
2. Perform simulations of the furnace hydrodynamics, characterize bed material performance, and assess individual component performance through lab testing.
3. Develop and implement an instrumentation scheme, smart sensors, and automated controls.
4. Construct and test a prototype and validate performance against a baseline.
5. Assess market potential and techno-economic feasibility of the new product.



Leveraging Industrial Experience In Fluid Bed Technology & Biomass Energy Conversion

1 – Approach - Tasks

Budget Period (BP) 1	BP 2 : Prototype Design, Installation, Initial Testing and Supporting R&D	Budget Period 3: Parametric Testing, Design Improvements, Final Validation
• Task 1.0: Initial Verification	• Task 2.0: Preliminary Design and Lab Testing • Task 3.0: Controls, Automation and Dynamic Operation • Task 4.0: Test Facility Detailed Design & Fabrication • Task 5.0: Prototype Fabrication, Installation and Initial Testing	• Task 6.0: Parametric Testing • Task 7.0: Prototype Final Testing • Task 8.0: Commercialization, Manufacturing Plan, & Final Reporting

1 – Approach – Key Challenges

- The residential market poses particular challenges vs. industrial or utility markets:
  - Frequency of load variation.
  - Unattended operation.
  - Reliability
  - Ease of startup and shutdown
  - Cost accessible
  - Ability to accept fuel variations
  - Easy to handle ash removal
  - Maintenance
  - Service program
- Top Challenges of implementing fluid-bed technology in wood-fired heaters:
  1. Scaling down the process
  2. Simplifying / automating its operation in order to adapt it for the residential market
  3. Frequent load variations

1 – Approach – Go/No Go Decision Points

- **Budget Period 1 Go/No Go Decision Point – Initial Verification**
- Verification to confirm benchmark data and assumptions provided in application, which will establish the project baseline against which future performance and cost improvements are evaluated.
- Verification team (including independent engineer) will work closely with project team to discuss project details, review application data, metrics, and procedures provided in original application.
- Verification of experimental procedures and data records.
- **Budget Period 2 Go/No-Go Decision Point. Intermediate Validation**
- Verification team to assess progress towards the targets established in the application. Demonstrate that a working prototype / evaluations methods are in place. Prototype has been constructed, installed, and ready to continue further testing.
- Verify experimental procedures and initial determination of efficiency/ emissions using EPA Methods.
- Design, simulation and initial results indicate that the prototype design has the potential to meet PM emissions of 0.08 lb/MMBTU or lower and efficiencies improvements of 5-15%.
- **Final Verification Test - END OF PROJECT GOAL**

1 – Approach – Risk Analysis

Description of Risk	Risk Level	Mitigation Strategies
Unable to fully characterize the fluid-bed operation	Low	Leverage experience from similar/larger scale testing. B&W has identified fluid bed controlling variables to control larger industrial boilers.
Uncontrolled emissions are higher than anticipated	Medium	Multiple emission control strategies could be implemented to reduce emissions. • Emissions could be further reduced by changes in the design of the PM collecting device, recirculation, staging, cat converter. • Assess options available for Industrial /Utility Markets • Novel approaches e.g. catalytic bed material
Projected cost of the retail unit is higher than target value	High	Develop strategies to reduce costs: material of construction, integrating sensors and removal of non-essential systems. Leverage technologies from the automotive/consumer industry. FOAK to Nth unit Cost Reduction.
Complex and labor-intensive operation	Medium	Use modern proven sensor technology and automation protocols to reduce operational complexities

2 – Progress and Outcomes

Tasks Completed: Task 1, 2 and 3

BP3 Tasks Not Displayed

ACTIVITY

Budget Period 1 Initial Verification

Task 1.0 Verification

Subtask 1.1: Initial Application Verification

Budget Period 2 Prototype Design, Installation, Initial Testing and Supporting R&D

Task 2.0: Preliminary Design and Lab Testing

Subtask 2.1: Design Basis & Initial Market Assessment

Subtask 2.2: Simulations & Cold Flow Model Study

Subtask 2.3: Fluidized Bed Furnace Mechanical Design

Subtask 2.4: Bubbling Bed Material Lab Testing and Analysis

Task 3.0: Controls, Automation and Dynamic Operation

Subtask 3.1: Electrical, Instrumentation and Controls Philosophy and Requirements

Subtask 3.2: Dynamic Operation, System Analysis & Data Handling

Task 4.0: Test Facility Detailed Design & Fabrication

Subtask 4.1: Mechanical & Electrical Specifications Documents & P&IDs

Subtask 4.2: HAZOP and Risk Analysis

Subtask 4.3: Detailed Mechanical, Control and Instrumentation & Fabrication Drawings

Subtask 4.4: Prototype Cost for Fabrication & Installation

Subtask 4.5: Prototype Fabrication, Installation and Testing Schedule

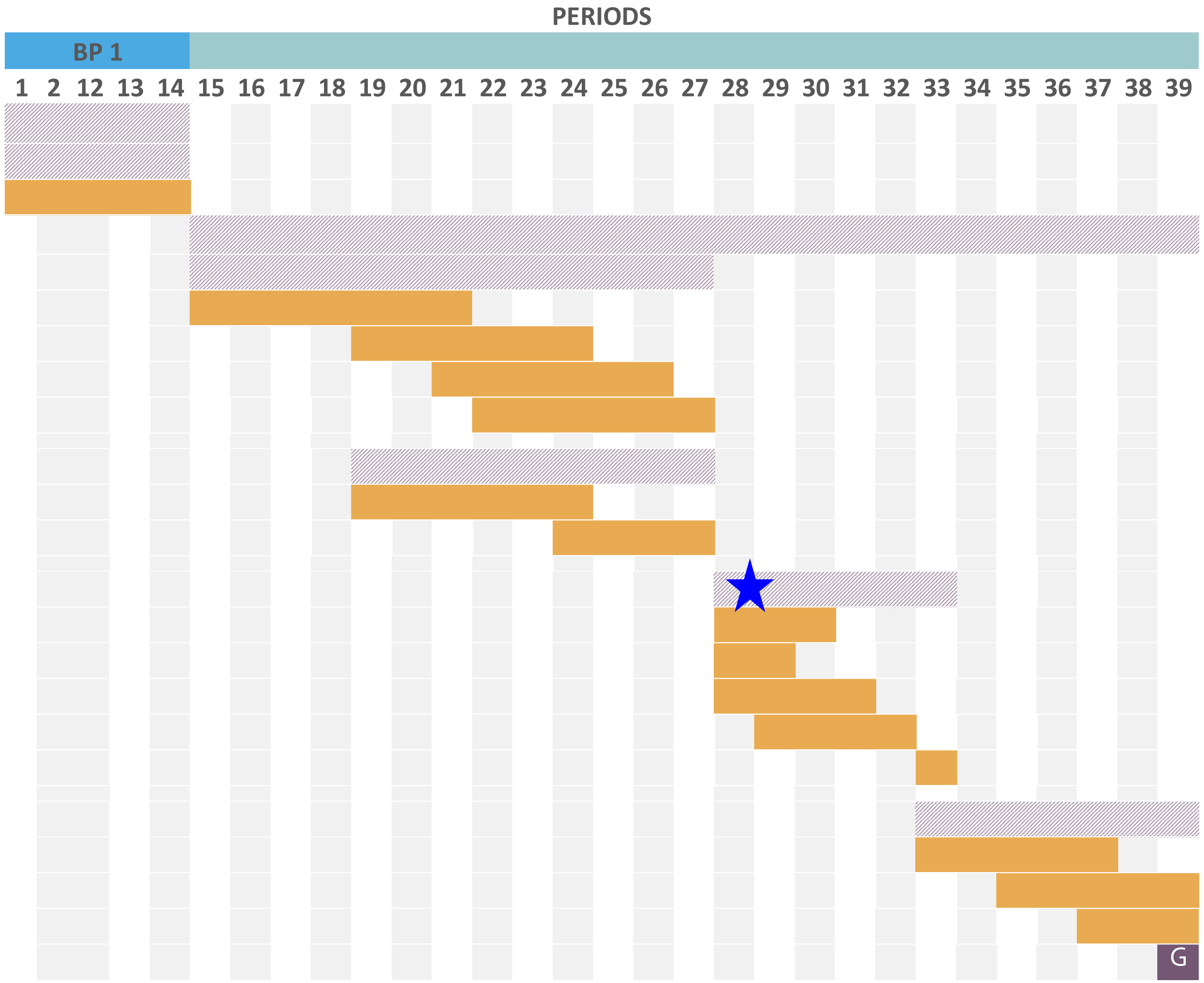
Task 5.0: Prototype Fabrication, Installation and Initial Testing

Subtask 5.1: Prototype Fabrication and Installation

Subtask 5.2: Startup / Shakedown Testing

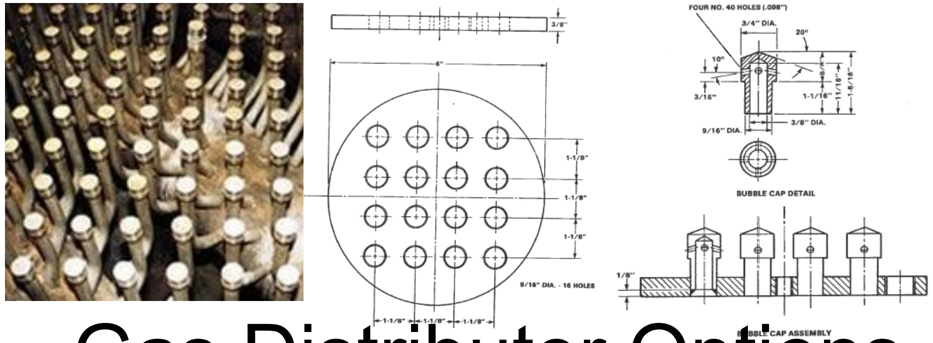
Subtask 5.3: Intermediate Validation

Budget Period 2 Go/No-Go Decision Point



2 – Progress and Outcomes
- Preliminary Design of System & Mechanical Components

- Preliminary design: Evaluating alternate approaches and designs for the different sections
  - Fluidization Calculations and Hydrodynamics
    - Design Bed Material and alternate materials at hot and cold conditions
  - Sizing of the Combustor
  - Gas Distributor Design Options
  - Air Staging: Overfire Air Design Options
  - Air Control and Flue Gas Recycle
  - Turndown
  - Emissions Control: Particulate
  - Heat exchange: Fluid-Bed / Walls / Convection Pass



Gas Distributor Options

Size: 12 - 48 in	Type: AEL Vertical		Connected in: 1 parallel 2 series		
Surf/unit(eff.) 54.2 ft²	Shells/unit 2		Surf/shell(eff.) 27.1 ft²		
PERFORMANCE OF ONE UNIT					
Fluid allocation		Shell Side		Tube Side	
Fluid name					
Fluid quantity, Total	lb/h	2462		292.2	
Vapor (In/Out)	lb/h	0	0	292.2	292.2
Liquid	lb/h	2462	2462	0	0
Noncondensable	lb/h	0	0	0	0
Temperature (In/Out)	°F	100	152.83	1832	150
Bubble / Dew point	°F	174.26 / 174.26	173.64 / 173.64	/	/
Density Vapor/Liquid	lb/ft³	/ 61.282	/ 59.445	0.001 /	0.004 /
Viscosity	cp	/ 0.7005	/ 0.4359	0.0502 /	0.019 /
Molecular wt, Vap				29.13	29.13
Molecular wt, NC					
Specific heat	BTU/(lb-F)	/ 1.0804	/ 1.0863	0.3154 /	0.2548 /
Thermal conductivity	BTU/(ft-h-F)	/ 0.36	/ 0.377	0.05 /	0.015 /
Latent heat	BTU/lb				
Pressure (abs)	psi	6	5.91	1.08	0.9
Velocity (Mean/Max)	ft/s	0.05 / 0.07		111.16 / 228.86	
Pressure drop, allow./calc.	psi	1.2	0.09	0.22	0.18
Fouling resistance (min)	ft²-h-F/BTU	0.001		0.0102	0.0107 Ao based
Heat exchanged 140891 BTU/h			MTD (corrected) 492.72 °F		
Transfer rate, Service 5.27		Dirty 7.8		Clean 8.59	BTU/(h-ft²-F)

Heat Exchanger Sizing

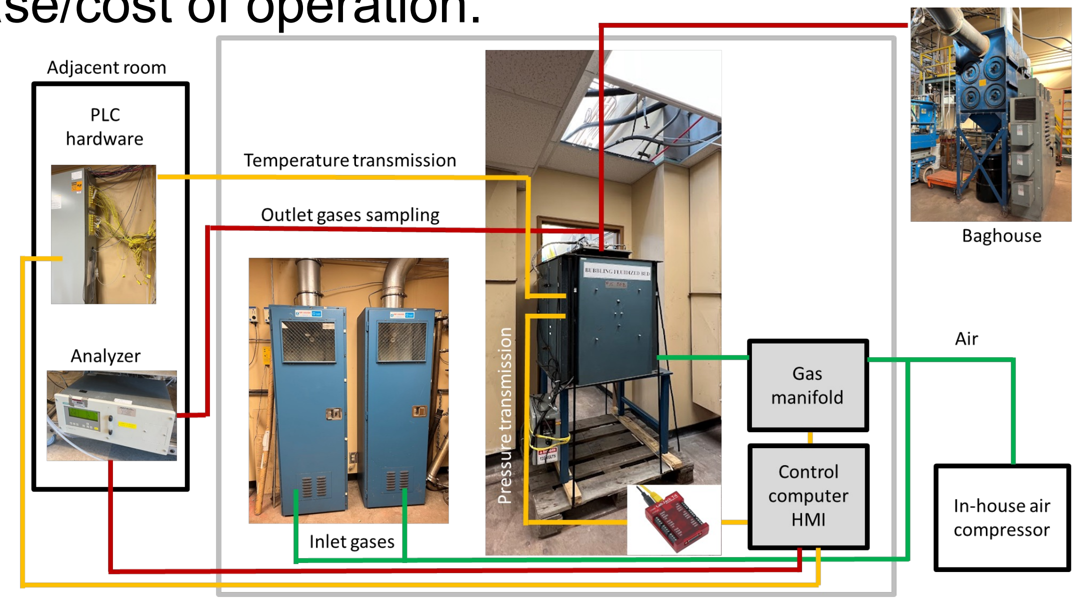
COMBUSTION SYSTEM CAN MEET DESIRED DIMENSIONS FOR A RESIDENTIAL SYSTEM.

COMPACT AND MODULAR APPROACH.

SCALING OF SYSTEM IS FEASIBLE.

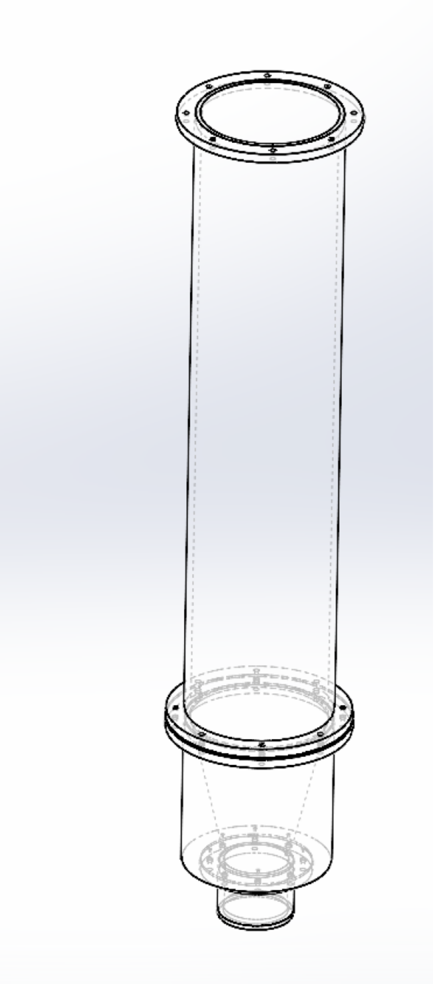
2 – Progress and Outcomes - Installation of Laboratory Hot Bench Scale Test Unit

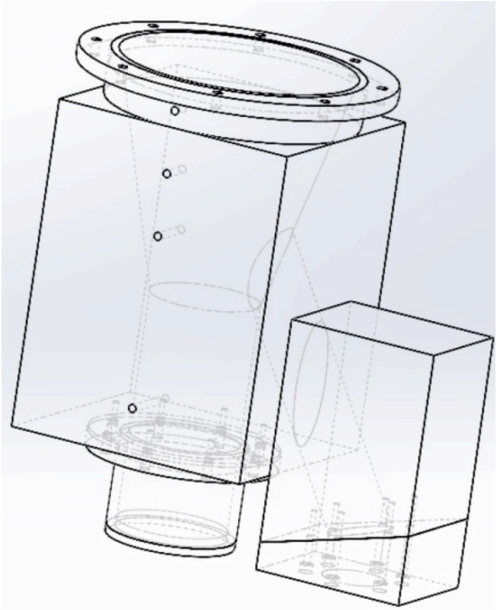
- To perform screening and characterization testing
- Bed material in the fluidized bed.
  - Low-cost readily available bed materials
  - Engineered formulations that show potential of enhancing the combustion process (lowering emissions), reliability, and ease/cost of operation.
- System Modifications Design -Completed;
- Auxiliary System Built and connected;
  - Control System;
  - Gas Outlet to Baghouse;
  - Gas supply and Analysis;
  - Biomass Feeding System.
- Includes 2” Fluid Bed Reactor;



2 – Progress and Outcomes
Fluid Bed Cold Flow Model

Assembly of Cold Flow Model Test Systems





Turndown testing

- Testing to get design information on how we would operate the bed for desired turndown

Distributor Design

- Low cost, lower DP, reliable operation with required turndown, ash /material removal

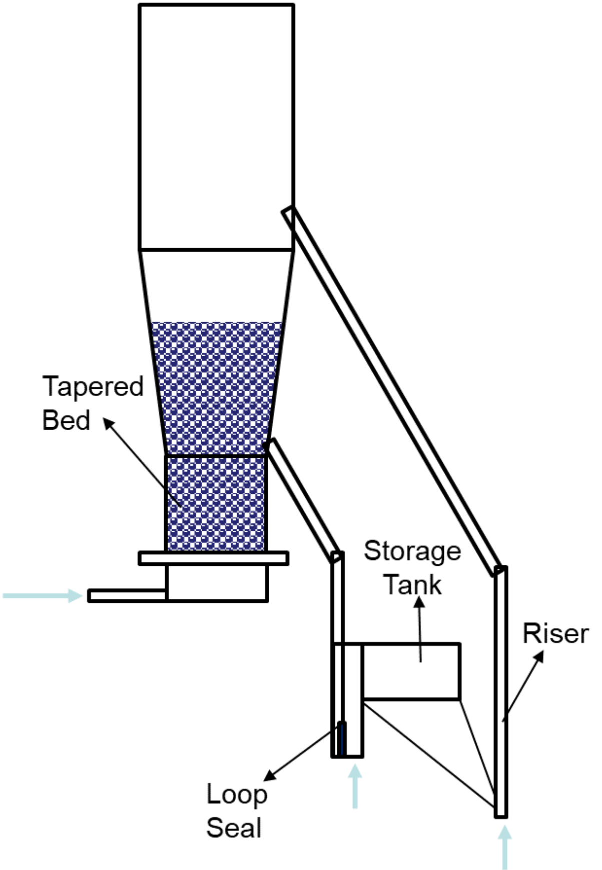
ID Fan vs. FD Fan test

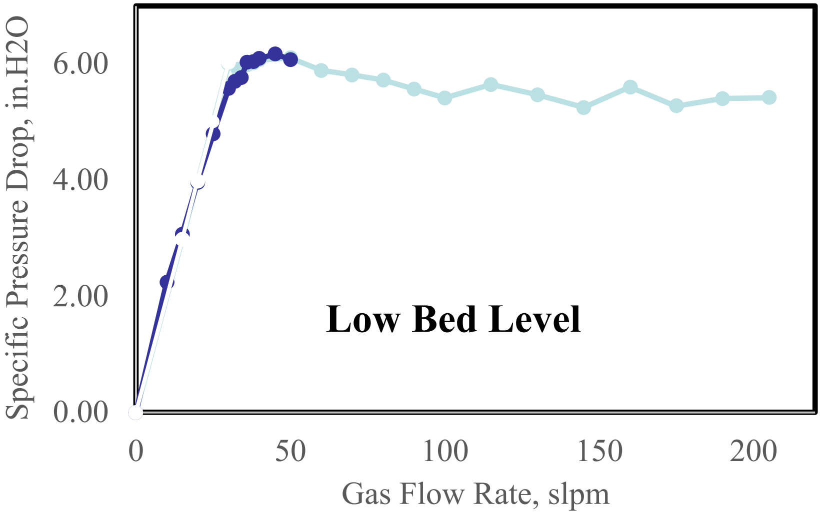
- Pressure Balance impact on fluidized bed medium and fuel.
- Implications on number of fans, infiltration, safety systems, operation

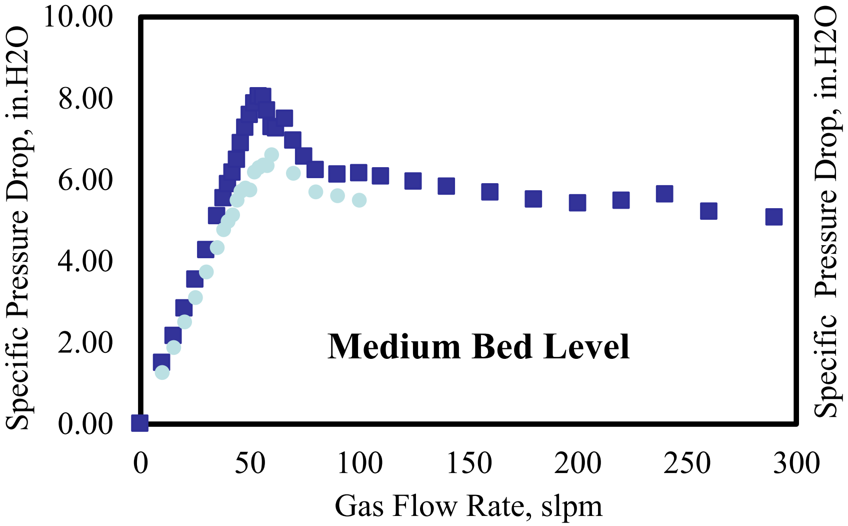
Demonstrated through analysis and cold flow model testing, the ability to control the combustions zone under transient conditions. Low-load operation to allow us to meet efficiency and emissions targets.

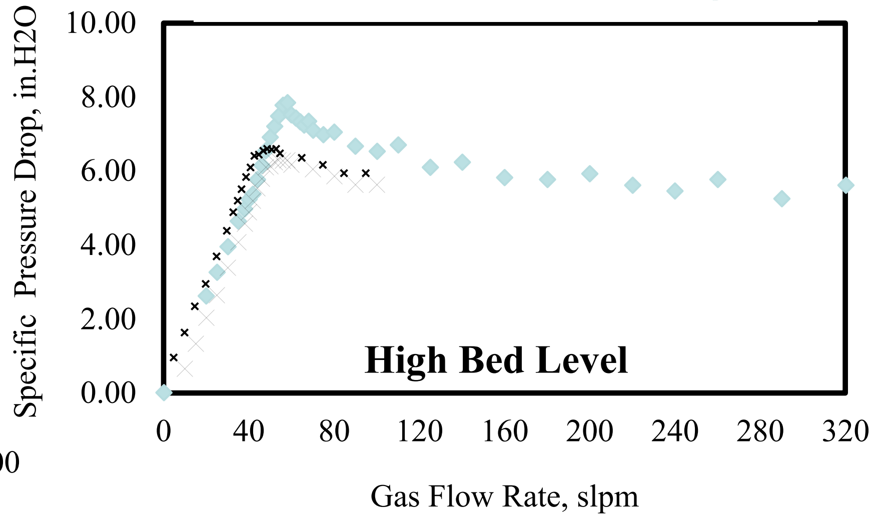
2 – Progress and Outcomes -Fluidized Bed Hydrodynamics

- Operational range of the fluidized bed reactor tested;
  - Bed Levels vs bed section adjustment
  - Different particles (sizes, densities);
  - Various gas flow rates;
- Suitable operational conditions obtained for two feasible design options;
- Pressure drop, bed volume fraction and pressure fluctuation measured.









2 – Progress and Outcomes - Process Design and Simulations

STEADY STATE MODELING

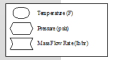
- Developing and Detailing Process
- Aspen Plus Simulation – Heat and Mass Balance
- B&W - commercial proprietary tools

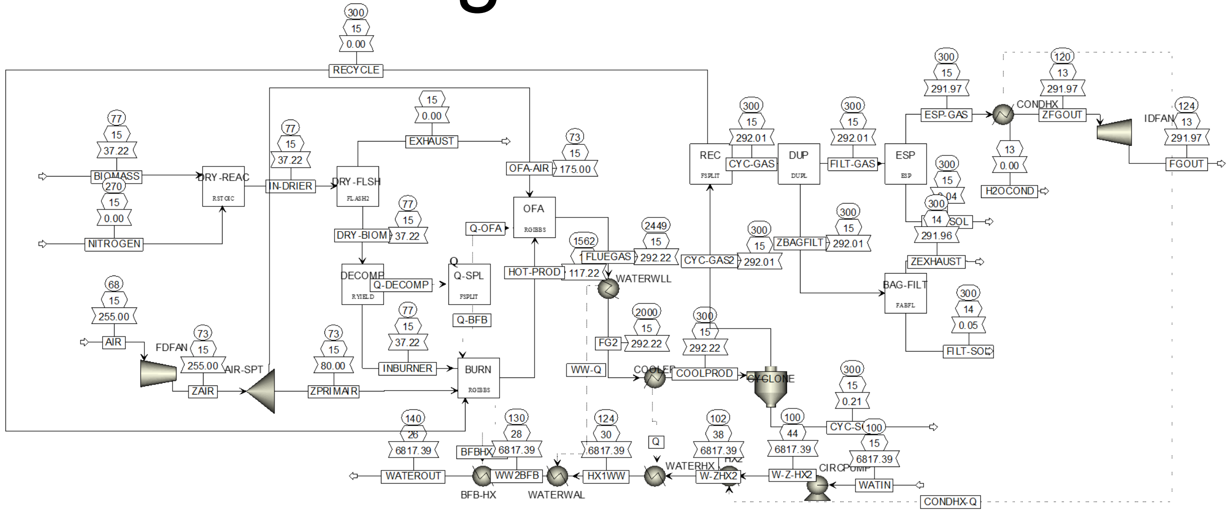
TRANSIENT OPERATION

- Initial development of start-up, minimum-load, full-load operation, turndown, shutdown, and emergency process
- Milestone – Dynamic Operation, Systems Analysis & Data Handling Report

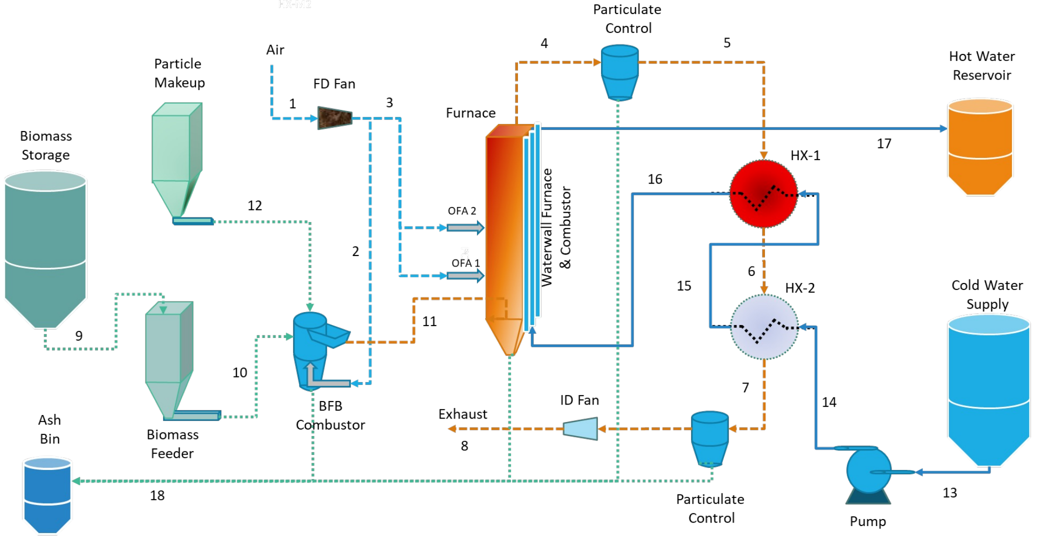
PROCESS CAN BE DESIGNED TO MEET HIGH EFFICIENCIES >90%.

ANALYSIS USED TO SET DESIGN TO ACHIEVE HIGH TURNDOWN WHILE MEETING LOW EMISSIONS





Aspen Process Simulation Flowsheet



Process Flow Diagram

Baseline Performance Comparison and Target Emissions

Metric	Units	EPA Target	Stoker	BFB	Features to meet Target	Target Improvement
NOx	lb/MMBtu	Not regulated	0.18 - 0.28	0.15 - 0.24	Efficient combustion, O_2 control, Air staging	14% to 16% Reduction
CO	lb/MMBtu	Not regulated	0.10 - 0.30	0.05 - 0.15	Efficient combustion, O_2 control	50% Reduction
PM	lb/MMBtu	0.10 to 0.15	0.10	NA	U-Beam / high-efficiency multiclone, efficient combustion	40% Reduction (0.06 lb/MMBtu)
Efficiency	% fuel basis	-	65 - 70	70 – 75	Operation, flue gas temp / O_2 control, heat exchanger design	5% to 15%

Design, Modeling Outcome

Prototype Rating and Range of Operation

MASS BALANCE	Max	Nominal	Mid	Min
Thermal Input, Btu/hr	300000	250000	150000	75000
Thermal Input, kWth	87.92	73.27	43.96	21.98
Biomass Pellet heating Value (dry), BTU/lb	8730.00	8730.00	8730.00	8730.00
Pellet % Moisture	7.75	7.75	7.75	7.75
Biomass Pellet heating Value (as received), BTU/lb	8053.43	8053.43	8053.43	8053.43
Biomass Pellet Heating Value, kJ/kg	18732.27	18732.27	18732.27	18732.27
Biomass Input, g/s	4.69	3.91	2.35	1.17
Biomass Input, lb/hr	37.22	31.01	18.61	9.30
Ash Content, (wt%)	0.77	0.77	0.77	0.77
Atomic Carbon, (wt%)	51.26	51.26	51.26	51.26
Atomic Hydrogen, (wt%)	6.18	6.18	6.18	6.18
Atomic Nitrogen (wt%)	0.06	0.06	0.06	0.06
Atomic Sulfur (wt%)	0.01	0.01	0.01	0.01
Atomic Oxygen, (wt%)	41.72	41.72	41.72	41.72

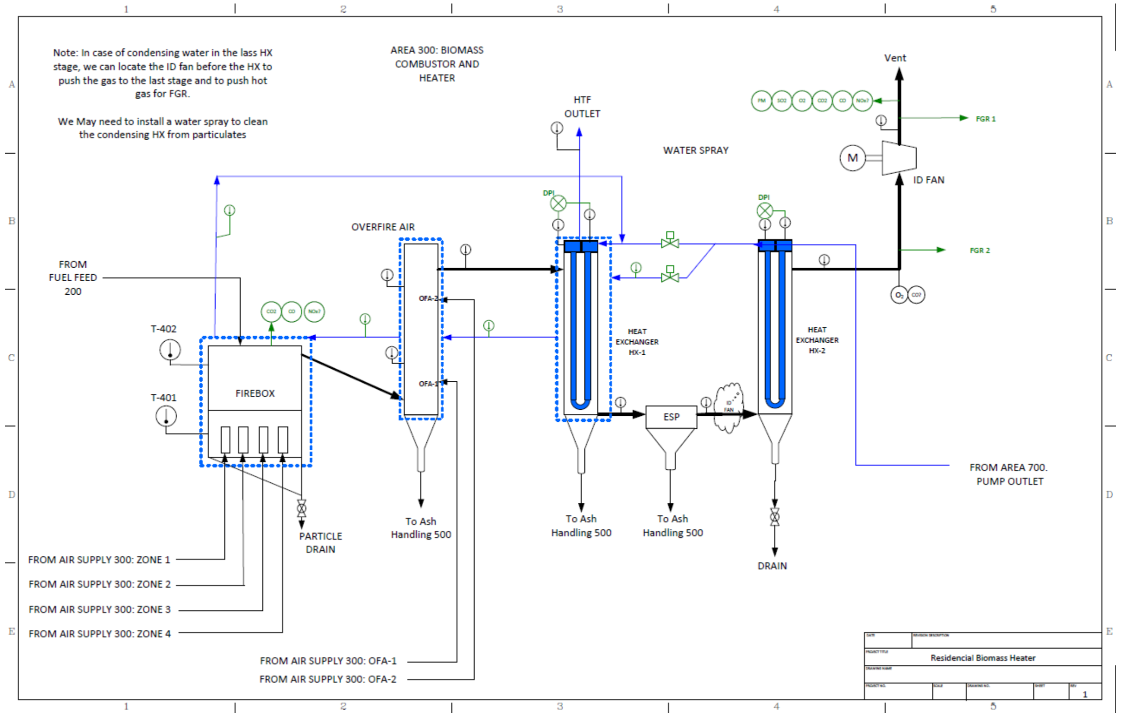
Thermal Efficiency vs. Flue Gas Outlet Temperature

Scenario	Flue Gas Exit Temperature		Heat Output		Efficiency	Notes
	oF	oC	Btu/hr	kW	%	
A	140	60.0	271207	79.5	90.4	No Condensation
B	120	48.9	275832	80.8	91.9	Condensing Mode
C	110	43.3	282279	82.7	94.1	Condensing Mode
D	100	37.8	287285	84.2	95.8	Condensing Mode
E	90	32.2	291228	85.4	97.1	Condensing Mode

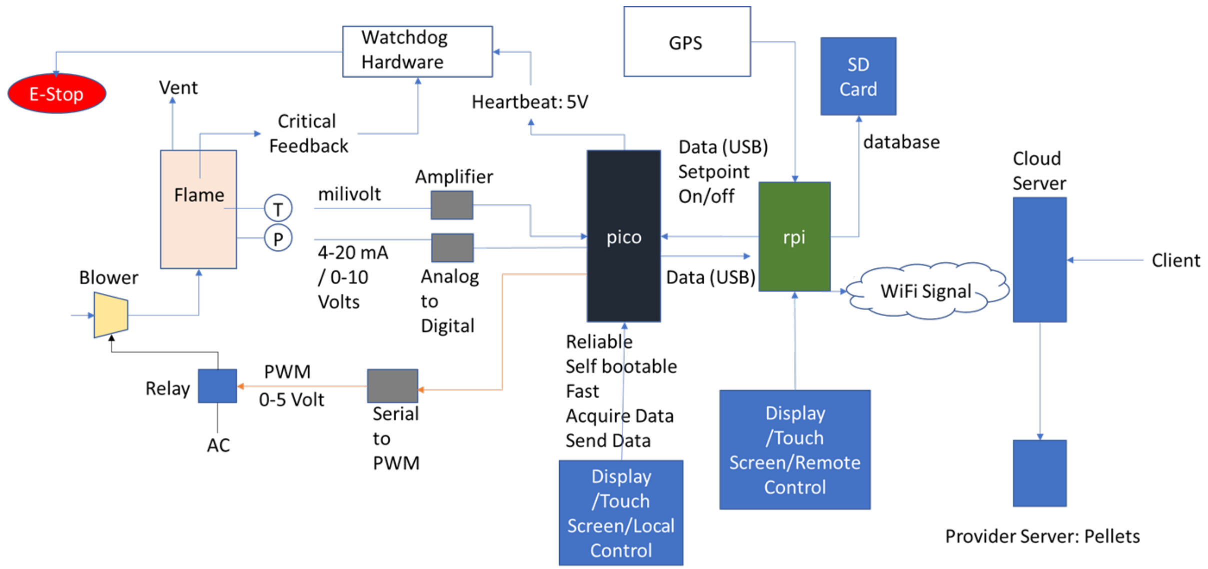
- Prototype Thermal Rating 300,000 Btu/hr
- Able to support transient operation
- Process Models Demonstrate Ability to achieve >90% Efficiency
- PM Capture of 95%
- Able to meet Project Targets – Low Emissions and High Efficiency

Electricals Instrumentation and Controls

Process & Instrumentation Diagrams



Controls System Architecture



BUILT IN SENSORS, INSTRUMENTATION & CONTROLS WILL ALLOW NEEDED AUTOMATION NEEDED TO BRING FLUIDIZED BED INTO THE RESIDENTIAL MARKET.

2 – Progress and Outcomes - Milestones

Number of Task, Milestone, Go No/Go Decision Points	Title - Tasks, Subtasks, Milestones, Deliverables, Go No/Go Decision Pts	
1	BP1 Verification Milestone	☑
Go/No-Go	Go/No-Go Decision Point	☑
2	Design & Market Basis Milestone	☑
2	Preliminary Design and Lab Testing Milestone	☑
3	Electrical and Controls Philosophy and Requirements Milestone	☑
3	Dynamic Operation & System Analysis Milestone	☑
4	Mechanical and Electrical Specifications Milestone	
4	HAZOP and Risk Analysis Milestone	
4	Comprehensive Project Review: Detail Design, Cost and Fabrication Schedule Milestone	
5	Prototype Installation Summary Milestone	
Go/No-Go	Go/No-Go Decision Point -Intermediate Validation Point	

- Budget Period 1 & 2 Milestone Deliverables Shown in Table
- BP3 – Not Shown

3 – Impact

- Introducing a novel approach to Residential Wood Heating using Fluidized Bed Technology
- Meet future PM and Efficiency targets and Reduce other emissions such as NOx / CO:
  - Fluid-bed operation improves air/fuel mixing, increases heat transfer which results in more complete fuel combustion.
  - Transients lead to the greatest emissions in current state of the art systems - Thermal Inertia of the fluid-bed helps maintain lower emissions during transient operation
  - Fluid bed uncontrolled NOx, CO and VOC emissions are typically 10% to 25% less for a given biomass fuel than for a stoker
- Fuel flexibility: An added benefit is the ability to use a wider selection of renewable fuels.
- Overcome challenges associated with operational complexity of fluidized bed systems via automation.

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3 – Impact

- The team includes a commercial/industrial partner and supplier of biomass combustion systems
  - Commercialization path includes potential to supply products directly
  - License IP to third party suppliers of Biomass heaters
- The team has put in place an IP Management Plan.
- Graduate students and post-doc researchers of diverse backgrounds are gaining experience in design, operation and prototype testing
- Team will continue to disseminate information via presentations including poster sessions and future publications
- An Industrial Review Committee to provide further input and guidance on the development approach and commercialization plan

Summary

- Project promotes the clean use of biomass fuels making new heaters significantly cleaner and improving the air quality in communities where people burn wood for heat.
- Allow the introduction of a technology that has proven superior performance and flexibility from competing system at industrial and utility scale
- Imbedded modern low-cost sensors and microprocessors to achieve automation objectives
- Design and Simulation efforts demonstrate that the design can meet desired performance and achieve aggressive targets for emissions control and efficiency
- A prototype will be built to demonstrate the benefits and allow introduction of a renewable fuel-based heating solution for residential applications
- The development of the technology has other potential marketable applications
  - Automation, Advanced Control and Data Monitoring Features,
  - Emissions Control
  - Alternate Fuels
  - Drying, heating and energy transfer applications

Quad Chart Overview

Timeline

- *10/01/2020*
- *12/31/2024*

	FY22 Costed	Total Award
DOE Funding	*(10/01/2021 – 9/30/2022)* *$271,160*	*(negotiated total federal share)* *$2,431,050*
Project Cost Share *	$84,608	$607,773

TRL at Project Start: 4

TRL at Project End: 6

Project Goal

Design, construct and test a low-emission and efficient residential wood-fired central heater based on the novel application of bubbling fluidized-bed (BFB) technology.

End of Project Milestone

Perform final verification test and assess whether project targets were achieved

Project target reducing particulate emissions by at least 25% from the EPA 2020 target of 0.1 lb/MMBTU heat output and increasing efficiency by 5-15% above the baseline.

Funding Mechanism

FOA: DE-FOA-0002203, Topic Area 5, 2020

Project Partners

- The Babcock & Wilcox Company
- The Ohio State University