



# Fairbanks North Star Borough

Air Quality Division

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July 7, 2020

RE: ClearStak Report – Pellet Stove Retrofit Emission Control Device Testing

To Whom it May Concern,

The implementation of a curtailment program to restrict particulate matter (PM) emitted from solid-fuel heating appliances during air quality alerts, also known as “burn bans,” requires the use of alternative heat sources which can be more expensive than heating with wood. This has generated considerable community interest in determining whether the addition of Retrofit Control Devices (RCDs) would allow wood-burning to continue when burn bans are in effect, specifically Stage 2 Alerts where only those with No Other Adequate Source of Heat (NOASH) are allowed to operate solid fuel appliances. To address this interest, the Borough commissioned a testing project to measure the effect of RCDs on PM emitted from a pellet stove and develop an emission factor suitable for use in a State Implementation Plan (SIP). The project evaluated the performance of two RCDs: an OkeoTube electrostatic precipitator (ESP) and a Grace Fire StoveCAT catalyst. In a cooperative study, the State of Alaska commissioned testing of cordwood appliances with an ESP which is covered in a separate report.

Control devices that reduce PM have been available for over a century and are successfully employed on numerous applications in the U.S., and throughout the world, with high control efficiencies in the 90-99% range. In fact, several residential wood stove manufacturers have successfully integrated catalytic emission reduction into model design. Central to achieving high performance in all applications is the incorporation of the control device within the structure of the appliance, periodic maintenance, periodic monitoring, and proper operation. Existing residential wood heaters encompass several appliance types including stove, insert, and hydronic heater, multiple fuels including pellet and cordwood, differing control methods including catalyst, combustion controls, and hybrid models. All manufactured to varying standards in the past 32 years creating a dizzying array of unique characteristics to be accounted for in the design of an externally mounted control device to be used on existing appliances.

The Borough-commissioned test program for an RCD on a pellet stove appliance employed two different methods of PM measurement: an EPA filter based method, which collects total PM emitted over the entire test and a not yet EPA certified method that uses a tapered element oscillating microbalance (TEOM) that collect time-resolved measurements of PM emitted

during the test. The former is the primary measurement method but provides no insight into performance during different phases of operation (startup, high, medium, and low burn). Key findings include:

#### ESP Performance

- The overall reduction in PM measured by the primary filter method was 72%; the average TEOM reduction was 47%.
- TEOM measurements found particulate removal varied by phase of operation ranging from 25% during medium burn to 74% during high burn.
- TEOM measurements showed that ESP performance is significantly limited by the occurrence of arcing events, which are caused when the electric field responsible for trapping particles collapses.
- Sufficient data was gathered to support development of an emission factor for an ESP equipped Step 2 pellet appliance.

#### StoveCAT Performance

- The catalyst did not activate and had no effect on PM emissions.
- Testing data does not support development of an emission factor.
- This finding was confirmed by temperature data collected upstream and downstream from the catalyst which showed post-catalyst temperatures always cooler than upstream catalyst temperatures.

#### Summary

- To ensure that operation of pellet stoves during Stage 2 Alerts does not increase the PM emitted, they must emit levels that are equivalent to the primary heating source in the community – fuel oil furnaces.
- In the test, pellet stoves equipped with ESPs emitted PM levels an order of magnitude higher than emitted by fuel oil furnaces. This means allowing the operation of ESP equipped pellet stoves during a Stage 2 Alert would increase the PM emitted. The testing results do not support an exemption for ESP-equipped pellet stoves from Stage 2 Alerts.
- Although the test results do not support a Stage 2 exemption for ESP-equipped pellet stoves it does not preclude their use in the Borough. If determined to be durable in Alaska winters along with proper maintenance, cleaning, and monitoring requirements ESP-equipped pellet stoves could provide a quantifiable air quality benefit to the area.
- ESPs perform well under certain steady state conditions. Relative to cordwood a pellet appliance exhibits steady state operation with auger fed fuel, automatic air settings, and dry fuel. However, even the relatively steady state operation of a pellet appliance shows decreased control efficiencies during different burn phases, highlighting the challenge to design an ESP capable of maintaining high control efficiencies under variable conditions.
- The StoveCAT testing demonstrates that it is not designed for the operating conditions of a pellet stove and should not be considered a control device for pellet stoves.
- The testing performance of externally mounted RCDs does not support operation of pellet stoves during Stage 2 Alerts.

A copy of the test report is attached. Also attached is an executive summary prepared by Borough staff which discusses test findings and their implications for the community.

Sincerely,

*Nick Czarnecki*

Nick Czarnecki  
FNSB Air Quality Manager

# EXECUTIVE SUMMARY

## Overview

A testing program was conducted to measure the effect of aftermarket emission control devices on PM (particulate matter) emitted from a Step 2 pellet stove, selected to be representative of that category of solid fuel burning appliances operated in the Fairbanks North Star Borough (FNSB). The testing program, conducted by ClearStak, in collaboration with Northeast States for Coordinated Air Use Management (NESCAUM) and Air Tox Environmental, evaluated the performance of two aftermarket retrofit control devices: an OkeoTube electrostatic precipitator (ESP) and a Grace Fire StoveCAT catalyst.

The program collected data on PM emitted upstream and downstream from the ESP unit simultaneously to allow a calculation of the efficiency of the unit in reducing emissions. The manufacturer's recommended placement of the StoveCAT catalyst did not allow sufficient space for the measurement of upstream emissions. Therefore, non-simultaneous measurements were collected from baseline (no catalyst) and controlled (catalyst installed) tests; average differences between the baseline and controlled tests provide the basis to calculate the efficiency in reducing emissions.

Two different methods of PM measurement were employed in the program: the primary method used a modified ASTM E2515 protocol with dual train filters to collect the total PM emitted over the course of the test; and a secondary method, not yet certified by EPA, that used a tapered element oscillating microbalance (TEOM) to collect time-resolved measurements of PM emitted during the test. Data collected by the TEOM method provides insight into the performance of controls during different phases of operation (i.e., startup, low, medium, and high burn) as well as total operation, while the ASTM E2515 method only provides a single data point—the average of all phases. Multiple replicate tests were conducted to assess variance in the performance of the retrofit controls.

## Findings

*ESP Performance* – A total of 6 controlled tests were conducted. Particulate control efficiency varied between test runs and the method used to measure emissions. As shown in Table ES-1, the overall reduction in emissions measured by the primary filter method was 72%; the average TEOM measured reduction was 47%. Large differences in PM emissions measured downstream occur between the TEOM and filter trains of ASTM E2515 and are likely related to the limitations of the filter-based instrumentation's ability to measure small filter catches (i.e., 0.2 mg and less) with precision and accuracy. This led to unusually large uncertainties in measured PM and the calculated control efficiency. Although ASTM E2515 is the primary method for PM measurement, the TEOM measurements may provide a more accurate representation of ESP performance.

<b>Table ES-1 ESP PM Control Efficiency (% reduction)</b>							
Test Run	ESP 2**	ESP 3	ESP 7	ESP 8	ESP 9	ESP 10	Average
Filter	90	38	51	70	94	86	72
TEOM	69	60	37	49	41	24	47

\*\* Missing 10 min. of stack flow; used average minute data from the interval prior to and after the missing interval.

Table ES-2 below presents TEOM-measured average emission rates and removal efficiencies over the entire test cycle and by test phase to summarize ESP performance over different phases of operation.

<b>Table ES-2 Average TEOM Measurements</b>					
	Entire Cycle	Startup	High Burn	Medium Burn	Low Burn
Average Emissions (g/hr)					
Pre ESP	1.0	1.3	1.1	0.8	0.9
Post ESP	0.5	0.9	0.3	0.6	0.4
Average Efficiency (% reduction)					
Mean Value	47	30	74	25	55
Std. Deviation	16	24	12	36	15

On average, the ESP removes 47% of the pellet stove's emissions over the test cycle, reducing its average emission rate from 0.97 g/h before the device to 0.51 g/h after the device. However, its overall performance varies from 24% to 69% across the six test runs. Particulate removal is consistently high only in the High Burn Phase where it averages 74%. It is low (30%) in the Startup phase largely because the ESP does not begin to operate until it senses a sufficient temperature rise to indicate the presence of smoke. Thus, it offers no control for up to 15 minutes after the stove is first fired. Particulate removal is lowest (25%) and highly variable in the Medium Burn phase due to the occurrence of arcing events that reduce the availability of control and re-entrain particulate matter (previously captured within the ESP) which is then emitted to the atmosphere<sup>1</sup>. Particulate removal in the Low Burn Phase (55%) is intermediate between the High and Medium Burn phases but is consistent across test runs.

A key finding from the testing is that the ESP's performance is significantly limited by the occurrence of arcing events. Arcing is observed in all phases except the High Burn with the greatest frequency of arcing occurring during the Medium Burn phase. Arcing has a twofold

<sup>1</sup> Arcing and re-entrainment is a normal phenomenon that occurs in ESP devices across many applications. An arcing event occurs when conditions within the device discharge the high-voltage electrode and cause the electric field responsible for trapping particulates to collapse. In the testing and analysis reported here, emissions of re-entrained particulates are counted against the removal efficiency following the precedent set by EPA regulation for ESPs in the industrial sector.

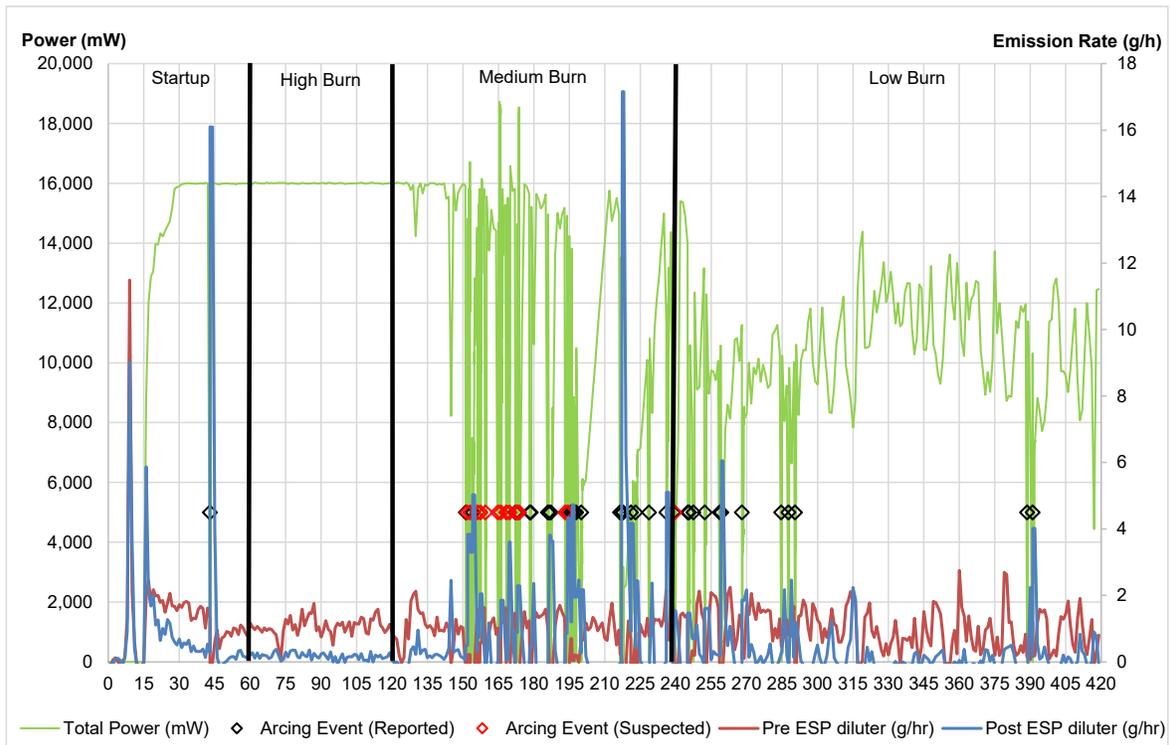
impact on ESP performance. First the electric field required to trap particles collapses causing an electric discharge to the stack wall (arcing event) which disturbs the collected dust layer accumulated on the stack wall re-entraining the PM into the exhaust stream. Second, it takes time for the lost electric field to be reestablished; particulate control is lost during that time and diminishes ESP performance. The number of arcing events varies from test to test, but periodic arcing is a phenomenon in ESPs that can be expected to routinely occur in service. Another limiting factor occurs at the start of the test while the ESP's control logic waits to detect the presence of smoke to indicate the start of a burn. Based on the six test runs, the ESP may wait for up to 15 minutes after the stove is started before turning on to control emissions.

While it is clear that ESP performance varies by phase of operation, little information is currently available to characterize how pellet stoves are actually operated during the heating season. The current average values reported reflect the weighting of each minute of operation in the test. Once data is collected on how pellet stoves are operated, the data collected in this program can be re-weighted to better represent ESP performance in the Borough and provide a better picture of its potential value to the community.

The summary presented in the tables above is limited to average values and does not convey the range of data collected in the testing or how ESP performance varies across the phases of operation. To fill this gap, Figure ES-1 presents a representative example of ESP operation and emissions over a complete test run. It shows pre- and post-ESP emission rates along with ESP power and arcing events for the entire test cycle. As can be seen, the ESP does not power up until minute 15 of the test (green line). An emissions spike of nearly 12 g/hr out of the stove (red line) occurs in minute 9 before the ESP powers on and is followed by a smaller spike from the stove in minute 16 just as the ESP powers on. The ESP approaches its full operating power of 16,000 mW by minute 30, but an arcing event occurs at minute 43 leading to a spike of 16 g/hr out of the ESP. When compared to emissions out of the stove, which were ~1 g/hr in the minutes before and after the spike, it is clear that previously-captured PM is being expelled from the ESP.

As the test moves into the High Burn phase, stove emissions vary in the range of 1–2 g/hr. The ESP operates consistently at its full operating power and successfully limits emissions from the ESP to a maximum of 0.5 g/hr during the High Burn. This level of performance continues into the start of the Medium Burn phase but is interrupted at minute 151 by the first of a long series of arcing events (22 Reported and 16 Suspected). Each of these is associated with a spike in emissions from the ESP that is in excess of emissions from the stove at that point in time. The largest spike occurs at minute 217 and reaches 17 g/hr. Arcing events continue into the Low Burn phase with an additional 12 events reported. These are associated with smaller emission spikes, but the events at minutes 260 and 392 rise well above emissions from the stove. Once arcing begins to happen, the ESP often operates well below full power which leads to lower removal efficiency. These general trends were repeated across all six replicate tests.

In summary, the information presented in Figure ES-1 provides a representative picture of how the ESP responds to changes in both stove emission rates and arcing events over the course of a complete test cycle that average efficiency values fail to convey.



**Figure ES-1. Pre and Post Emission Rate with ESP Power for Step 2 Pellet Appliance with ESP (Run 9)**

*StoveCAT Performance* – All emission testing was done downstream of the catalyst. When it was observed that the catalyst did not operate during more than 94% of the conditioning period, the decision was made to reduce the replicates of baseline and catalyst test runs. Two baseline tests, without the catalyst installed, were performed. After one test with the catalyst installed, it was determined that that the catalyst never activated and, therefore, had no effect on PM emissions as evidenced by the catalyst temperature data showing that post-catalyst temperatures were always cooler than pre-catalyst temperatures for the entire test run. This finding is not surprising since catalyst operation requires a combination of fuel in the form of hydrocarbons (HC), oxygen and a sufficiently high temperature to light off and continue operation. The pellet stove emission levels are low to begin with, which limits the HC needed to support combustion, and the placement of the catalyst outside of the stove (rather than within) reduces the flue gas temperature to less than is needed for catalyst light-off and continued combustion.

### Summary

The performance of these control devices is of considerable interest to the Borough as EPA has designated it a nonattainment area for fine particulate matter (less than 2.5 microns in diameter) and residential wood burning has been identified as the largest source of PM<sub>2.5</sub> emissions. This finding led to implementation of a curtailment program (burn bans) to restrict the PM emitted by solid-fuel burning appliances on days when concentrations are forecast to exceed regulatory thresholds; when burn bans are in effect, homeowners are forced to use more expensive heating alternatives. There is considerable interest in the community in determining whether the addition of control devices would allow wood-burning to continue when burn bans are in effect.

To ensure that no “backsliding” occurs, PM emitted from solid-fuel burning appliances configured with retrofit devices must not exceed the levels emitted by fuel oil furnaces. Table ES-3 lists the emission factors<sup>2</sup> calculated by ClearStak for the Step 2 EPA-certified pellet stove without control and for the same stove equipped with an ESP based on TEOM measurements and filter measurements, which produced removal efficiencies of 47% and 72% respectively. Below this, emission factors are listed for a residential fuel oil furnace, which is the chief alternative for home heating during burn bans, and for a natural gas furnace. Because fuel oil furnaces are currently the primary heat source in most of the area’s homes, the residential fuel oil furnace defines the emissions level that must be reached to achieve fuel-oil equivalency.

As the table shows, the PM reductions achieved with a pellet stove plus ESP are insufficient to achieve equivalency with fuel oil appliances. To do so would require reductions of more than 90% with the ESP. Moreover, the gap between ESP performance on the test and the level required for fuel-oil equivalency depends on whether pellet stoves are used continuously as the primary heating source for the household or are used infrequently as a backup heating source with frequent startups when ESPs perform poorly. More insight into how pellet stoves are operated will be needed to judge the size of this gap. A further consideration is that the testing does not provide information on the cleaning frequency needed to maintain collection efficiency, the deterioration in ESP performance over time or the device’s durability in Alaskan winters. Overall, the data show that ESP control efficiency on a pellet appliance is highly variable ranging from poor to good. The testing results do not support an exemption for ESP-equipped pellet stoves from the curtailment program. Sufficient data was gathered to support development of an emission factor for an ESP equipped Step 2 pellet appliance.

The test results for the StoveCAT demonstrate that it is not designed for the operating conditions of a pellet stove and should not be considered as a control device.

This test program was developed by ClearStak and NESCAUM in coordination with FNSB and consultation with EPA to provide an engineering—not regulatory—assessment. The New Source Performance Standards (NSPS) for residential wood heaters does not contain emission standards or certification processes for wood stove retrofit control devices. The lack of a regulatory framework required the selection of test procedures, placement of control devices, and specification of data collection requirements by ClearStak and FNSB in consultation with EPA.

By sponsoring the testing, FNSB has taken the lead in establishing a framework for assessing retrofit control device performance. Before emission factors for inventory development can be prepared and accepted by EPA for use in regulatory planning, considerable additional testing will be required to confirm the data collected in this program, to establish maintenance requirements for the ESP, and to determine deterioration in control efficiency over time. The overall burden of these requirements would be challenging for one community to address on its own within a reasonable time frame.

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<sup>2</sup> Emission *factors* in lbs/MMBtu should not be confused with the emission *rates* in g/hr from which they are derived.

<b>Table ES-3 Comparison of Pellet Stove Emission Factors to Other Residential Heating Sources</b>		
	<b>PM<sub>2.5</sub> Emission Factor<sup>a</sup> (lb/MMBtu)</b>	<b>Source</b>
<b>Pellet Stove (EPA Certified)</b>		
No Control	0.090	ClearStak
with ESP Control (TEOM removal efficiency)	0.047	ClearStak
With ESP Control (Filter removal efficiency)	0.031	ClearStak
<b>Other Residual Heating Sources</b>		
#1 / #2 Fuel Oil Furnace (weighted 31.8% #1, 68.2%, #2)	0.0034	OMNI run #17 <sup>b</sup>
Natural Gas Furnace	0.0000488	Brookhaven Report <sup>c</sup>

<sup>a</sup> All particulate matter for all sources is assumed to be less than 2.5 micrometer in diameter. Therefore, the PM emission factors presented here may be used to represent PM<sub>10</sub>, PM<sub>2.5</sub>, or total PM.

<sup>b</sup> "Measurement of Space Heating Emissions," OMNI-Test Laboratories, Inc., May 23, 2013.

<sup>c</sup> R. McDonald, "Evaluation of Gas, Oil and Wood Pellet Fueled Residential Heating System Emissions Characteristics," Brookhaven National Laboratory, BNL-91286-2009-IR, December 2009. Average of natural gas furnace, conventional and condensing boiler tests.

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# Pellet Stove Retrofit Emission Control Device Emission Reduction Testing

Report 20.01

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July 7, 2020

# 1 Table of Contents

## Contents

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<b>1</b>	<b>Table of Contents .....</b>	<b>ii</b>
<b>2</b>	<b>List of Figures .....</b>	<b>iii</b>
<b>3</b>	<b>List of Tables.....</b>	<b>iv</b>
<b>1</b>	<b>Introduction .....</b>	<b>1</b>
1.1	Background.....	1
1.2	Summary of Test Program.....	1
<b>2</b>	<b>RCD Description .....</b>	<b>2</b>
2.1	The Grace Fire StoveCAT™ Emission Control Device Retro-Fit by Healthy Hearth, LLC .....	2
2.2	The OekoTube Electrostatic Precipitator (ESP) by OekoSolve AG .....	3
<b>3</b>	<b>Sampling and Analytical Procedures.....</b>	<b>4</b>
3.1	Operational Methods.....	4
3.2	PM2.5 Sampling Methods .....	4
<b>4</b>	<b>Test Arrangements and Set-Up .....</b>	<b>6</b>
4.1	Conditioning .....	6
4.2	Installation .....	6
<b>5</b>	<b>Results and Data Summary .....</b>	<b>13</b>
5.1	OekoTube ESP Results .....	13
5.2	Graphical Display of OekoTube ESP Results.....	13
5.3	Grace Fire StoveCAT™ Results .....	16
5.4	Unexpected Deviations from Test Methods.....	18
<b>6</b>	<b>Quality Control and Assurance Procedures and Results .....</b>	<b>21</b>
6.1	ASTM E2515 and ASTM E2779 .....	21
6.2	Dekati® eDiluter™.....	21
6.3	Sample Calculations .....	22
<b>7</b>	<b>Appendices .....</b>	<b>24</b>

## 2 List of Figures

---

Figure 1. StoveCAT™ Three State Technology .....	2
Figure 2. OekoTube Electrostatic Precipitator.....	3
Figure 3. StoveCAT™ Install -serial number unknown/not labeled .....	8
Figure 4. StoveCAT™ Install Schematic .....	9
Figure 5. StoveCAT™ Install Schematic 2 .....	10
Figure 6. ESP Identification .....	11
Figure 7. Pre and Post ESP Test Setup .....	12
Figure 8 PM Per Burn Phase .....	12
Figure 9. Pre and Post Emission Rate with ESP Power for Pellet Appliance with ESP (Run 9).....	15
Figure 10. Cumulative Emission Rates and Mass Removal for Pellet Appliance with ESP (Run 9) .....	15
Figure 11. StoveCAT and Baseline TEOM Data .....	16
Figure 12. PM Per Burn Phase.....	17
Figure 13. StoveCAT™ Temperature Data.....	17

### **3 List of Tables**

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Table 1 ESP Particulate Control Efficiency Per Test Run .....	10
Table 2 Filter Train Test Results.....	11
Table 3 Average ESP Particulate Control Efficiency Per Burn Phase .....	12

# 1 Introduction

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## 1.1 Background

A portion of Fairbanks North Star Borough (FNSB) has been designated as a non-attainment area for fine particulate (PM<sub>2.5</sub>) pollution. The largest contributing source sector has been determined to be residential wood space heating. Over 13,000 wood-burning devices are estimated to operate within the non-attainment area including: fireplaces, fireplace inserts, wood stoves, pellet stoves, and outdoor wood-fired hydronic heaters. As a result of the non-attainment designation, the residential wood space heating sector will be subject to more stringent regulatory requirements until attainment is achieved. Due to the high and varying cost of fuel oil, the main source of heating in Fairbanks homes, there is considerable interest in identifying technologies capable of reducing PM<sub>2.5</sub> emissions from wood-burning devices so they can continue to operate within the more stringent regulatory structure.

## 1.2 Summary of Test Program

The primary purpose of this study was to evaluate the efficacy of retrofit emission control devices (RCDs) on the ability to reduce PM<sub>2.5</sub> emissions and obtain information to be used to create an RCD emission factor, which will be used for a State Implementation Plan (SIP) for the FNSB. An RCD is defined as an after-market device used in conjunction with a solid fuel burning appliance (SFBA) and designed to reduce particulate matter (PM) emissions. Examples of RCDs include, but are not limited to, electrostatic precipitators (ESPs) and catalysts. The results will allow FNSB to determine if RCDs can provide quantifiable and verifiable emission reductions for their State Implementation Plan.

The FNSB contracted with the EPA accredited lab, ClearStak, for testing the performance of two commercially available RCDs on a Step 2 certified pellet stove. ClearStak, in a collaboration with Northeast States for Coordinated Air Use Management (NESCAUM) and Air Tox Environmental, measured PM<sub>2.5</sub> emissions before and after the installed RCD to quantify particulate control efficiency.

For assessing the RCDs, an EPA Step 2 Certified pellet stove was selected based on common pellet stoves listed in changeout programs in Fairbanks, Alaska. Assessing the performance of the pellet stove selected was not an objective of this research and therefore the stove manufacturer and model will remain anonymous by being specified as Pellet Stove 14 for all documentation. The test pellet fuel used was selected and provided by FNSB and is representative of pellet fuel used by homeowners in Fairbanks.

## 2 RCD Description

### 2.1 The Grace Fire StoveCAT™ Emission Control Device Retro-Fit by Healthy Hearth, LLC

The StoveCAT™ Retro-Fit Device is a stationary catalytic system designed for wood burning appliances, such as wood stoves. It is powered by a patented three stage catalytic cartridge, Figure 1, designed to capture pollutants without causing backpressure from harmful blockages of organic particulates. Any buildup of organic material on the catalytic components is burned off during the next high-burn period making the StoveCAT™ a self-cleaning device requiring no maintenance from users.

The StoveCAT™ can be installed to any appliance in under an hour by a professional chimney sweep or by the user. More information of the StoveCAT™ will be provided in the installation guide document as Appendix A of this protocol.

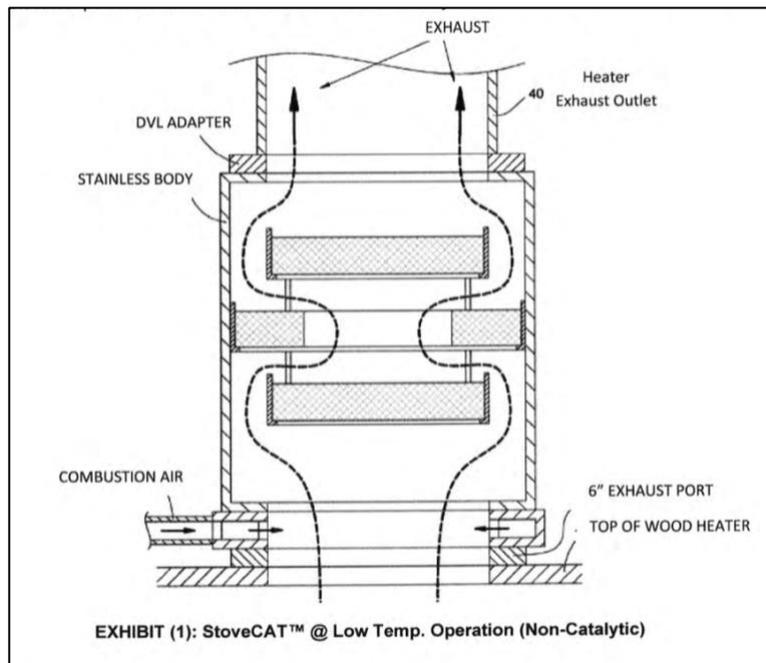


Figure 1. StoveCAT™ Three State Technology<sup>1</sup>

<sup>1</sup> Healthy Hearth, LLC, StoveCAT™ Retro-Fit Installation Guide, 3.

## 2.2 The OekoTube Electrostatic Precipitator (ESP) by OekoSolve AG

The OekoTube ESP, Figure 2, is designed as a retrofit device to reduce harmful PM emissions from wood and coal burning appliances. It uses a high voltage electrode to release electrons that adhere to the walls of the chimney by electrostatic forces where they collect large PM flakes. The PM separating efficiency is documented in the manual as 70-80%.

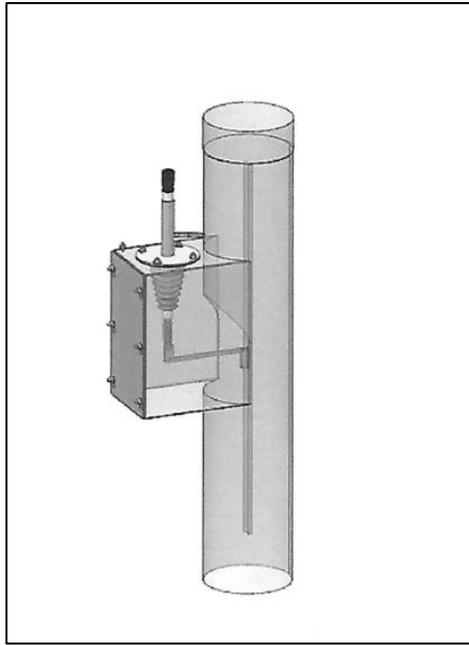


Figure 2. OekoTube Electrostatic Precipitator<sup>2</sup>

The technology for the OekoTube ESP is all the same despite varying models and sizes. The OekoTube ESP is adaptable to various installations and can be inserted on the chimney rooftop or installed indoors. The OekoTube ESP has a maximum power consumption 30 Watts and is active when an internal temperature sensor, installed in the stack tube portion just above the insulator box, detects a change in temperature within the stack. During standby, power consumption reduces to as low as 0.7 Watts. For the purpose of this research, the indoor 39-inch model will be used. More information of the OekoTube ESP will be provided as Appendix B of this report.

<sup>2</sup> One World Resource Management, FNSB RFP 19047, 2.

## 3 Sampling and Analytical Procedures

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### 3.1 Operational Methods

The operational protocol used for operating the pellet stove was ASTM E2779 *Standard Test Method for Determining Particulate Matter Emissions from Pellet Heaters*.

ASTM E2779 was modified to begin PM<sub>2.5</sub> emission sampling the moment the appliance begins operation instead of waiting a minimum of 1-hour for the pellet stove to reach steady state. This modification provides quantifiable startup emissions.

### 3.2 PM<sub>2.5</sub> Sampling Methods

The objective of the testing is to determine the PM control efficiency of two aftermarket retrofit devices, which requires measuring PM upstream and downstream of the retrofit. ASTM E2515, the current protocol for measuring PM emissions of residential wood stoves, involves sampling known diluted stack gas through a dilution tunnel and is limited to measuring downstream of the device. The choice to modify ASTM E2515 to sample off of a portable diluter provided the necessary capabilities to measure PM both upstream and downstream of a retrofit. After receiving the retrofit devices, reviewing formal specification documents, and discussion with manufacture representatives it was determined that measuring PM up and downstream was feasible for the ESP, but not for the catalyst retrofit. The required close proximity installation to the flue collar of a stove made upstream PM measuring unobtainable.

#### 3.2.1 SOP for Dekati® eDiluter™ in a wood stove stack with the Höntzsch vane anemometer

This SOP is still a draft and is not EPA approved. A copy will be included as Appendix C of this report. This stack PM measurement method is for measuring PM emission rates in a wood or pellet stove stack and covers the stack sample dilution and measurement of the stack flow, not the measurement of the PM from the outlet of the diluter. PM measures are obtained with two techniques: (1) total run PM using Method 5G or ASTM E2515 filter measurement, and (2) real-time PM measurements with a Thermo model 1405 TEOM. Operation of the TEOM is covered in Section 3.2.3.

### **3.2.2 ASTM E2515 Standard Test Method for Determination of Particulate Matter Emissions by a Dilution Tunnel**

A modified ASTM E2515 protocol serves as the primary source of PM measurement for this project. Single particulate sampling trains with dual 47-mm Emfab filters were used to determine total PM up and downstream of the ESP and downstream of the StoveCAT™. A dual train comparison test was done during a Baseline test run with no RCD and confirmed that the total emissions determined between the two trains were within 5% from the average total emissions value, which is within the acceptable range of ASTM E2515, section 11.7.

ASTM E2515 was modified to sample off of a portable diluter inserted in the stack instead of a dilution tunnel as required in ASTM E2515. Sampling trains operated according to Sections 9.8 of ASTM E2515, with the exception that sampling was from the diluter and was proportionate to stack flowrate, not the dilution tunnel.

All recoveries of filterable PM<sub>2.5</sub> followed Section 10, Analytical Procedures, of ASTM E2515 and EPA ALT-126.

### **3.2.3 Standard Operation Procedures for Thermo 1405 TEOM® for use in a dilution tunnel or with an extractive dilution system Version**

The TEOM is the secondary source of PM data. TEOM data was used to show time resolved PM rates per test run. The current SOP will be included as Appendix D of this report. This document covers operation concepts and procedures for use of the TEOM model 1405 to measure and report continuous PM measurements in EPA Method 5G dilution tunnel or equivalent dilution method. The Thermo Scientific model 1405 TEOM is designed for ambient real-time PM measurements. It is an inertial microbalance - a true continuous mass measurement method with resolution of 0.01 µg (0.00001 mg). The TEOM is highly configurable, allowing the instrument to be “tuned” to best meet the needs of a specific application. The version of the TEOM used here is the simplest, without any sample conditioning. TEOM flows, temperatures, and timing settings are changed from the normal ambient settings, but there are no hardware modifications needed. Instrument manuals, software, and related support information are available from the NESCAUM TEOM document collection. This SOP is not EPA approved, however, previous PM comparisons between traditional filter pull data and TEOM is described in Appendix E, *Particulate Matter Emission Measurement Methods*, and show a high degree of comparability between ASTM E2515 or EPA Method 5G filter results and TEOM data.

## 4 Test Arrangements and Set-Up

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### 4.1 Conditioning

Pellet Stove 14 was provided by NESCAUM and has had over 50 hours of run time prior to being at ClearStak. 50 hours of conditioning for appliances and catalysts are a requirement of fueling and operational protocols listed in the 2015 Standards of Performance for New Residential Wood Heaters, New Residential Hydronic Heaters and Forced-Air Furnaces (NSPS), such as ASTM E2779 (which only recommends 48 hours). Conditioning or aging of the catalyst and stove at operating temperatures and PM emissions ensures consistency in performance and operation during testing. There are currently no operational and fueling protocols under the NSPS that provide guidance for conditioning of an ESP, which does not contain catalytic substrate in need of aging. For this reason, the team's (ClearStak, NESCAUM, and FNSB project managers) best engineering judgement was used to decide a condition period of 24 hours of the ESP to reach consistent performance.

#### 4.1.1 Grace Fire StoveCAT™

The StoveCAT™ was conditioned for 50 hours on Pellet Stove 14 at a medium and high burn rate settings from November 14<sup>th</sup> – November 21<sup>st</sup> of 2019. Out of the 50 hours of conditioning, the catalyst was only active intermittently within one 3-hour timeframe during a high burn rate.

#### 4.1.2 OekoTube ESP

The OekoTube ESP was conditioned for 24 hours on an EPA Step 1 cordwood stove from December 11<sup>th</sup> – December 16<sup>th</sup> of 2019. The ESP was then removed from the stack and cleaned with a wire chimney brush and vacuumed before use in ESP replicate testing on Pellet Stove 14. There was no manual cleaning between replicate testing on Pellet Stove 14.

### 4.2 Installation

The two RCDs were installed, operated, and maintained, per manufacturers' instructions. The manuals and any other documentation provided by the manufacture for testing can be found in the appendices. The manufacturer of each of the RCDs were given the option to assist in the installation and verify that the RCD is operating to specification.

### **4.2.3 Grace Fire StoveCAT™**

The StoveCAT™ was installed for testing March 23, 2020. The manufacturer was not able to observe the install at ClearStak due to the 2020 pandemic restrictions. Per manufacturer's request, it was installed as close as possible to the pellet stove flue collar. The piping out of the flue collar was 3-inch diameter double-wall and then transitioned to 4-inch diameter double-wall, which is the diameter of the StoveCAT™ connection (Figure 3). After the StoveCAT™, 4-inch diameter double-wall stack pipe continued 7 feet before transitioning to 6-inch diameter pipe (Figure 4 and Figure 5). The overall length of the stove pipe extended 15 feet +/- 1 foot from the stove platform. Stack temperature sensors were installed near the flue collar, immediately before and after the StoveCAT™ and then at the top of the stack. The temperature gauges on the catalyst retrofit are part of the product and was installed by the manufacture. There was not enough stack piping between the flue collar and StoveCAT™ to do upstream PM sampling therefore PM sampling was done only downstream and required testing with and without the StoveCAT™.

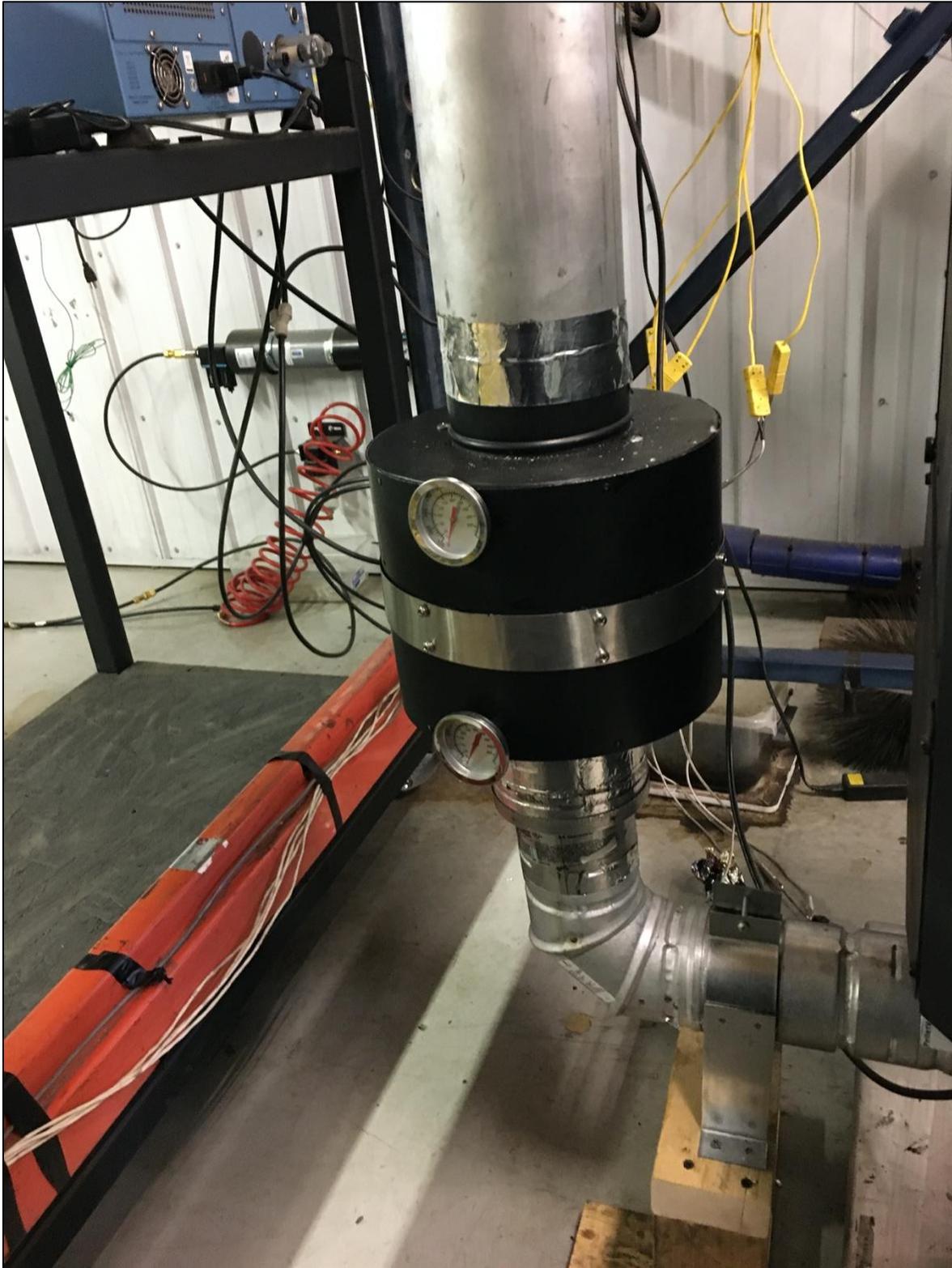


Figure 3. StoveCAT™ Install -serial number unknown/not labeled

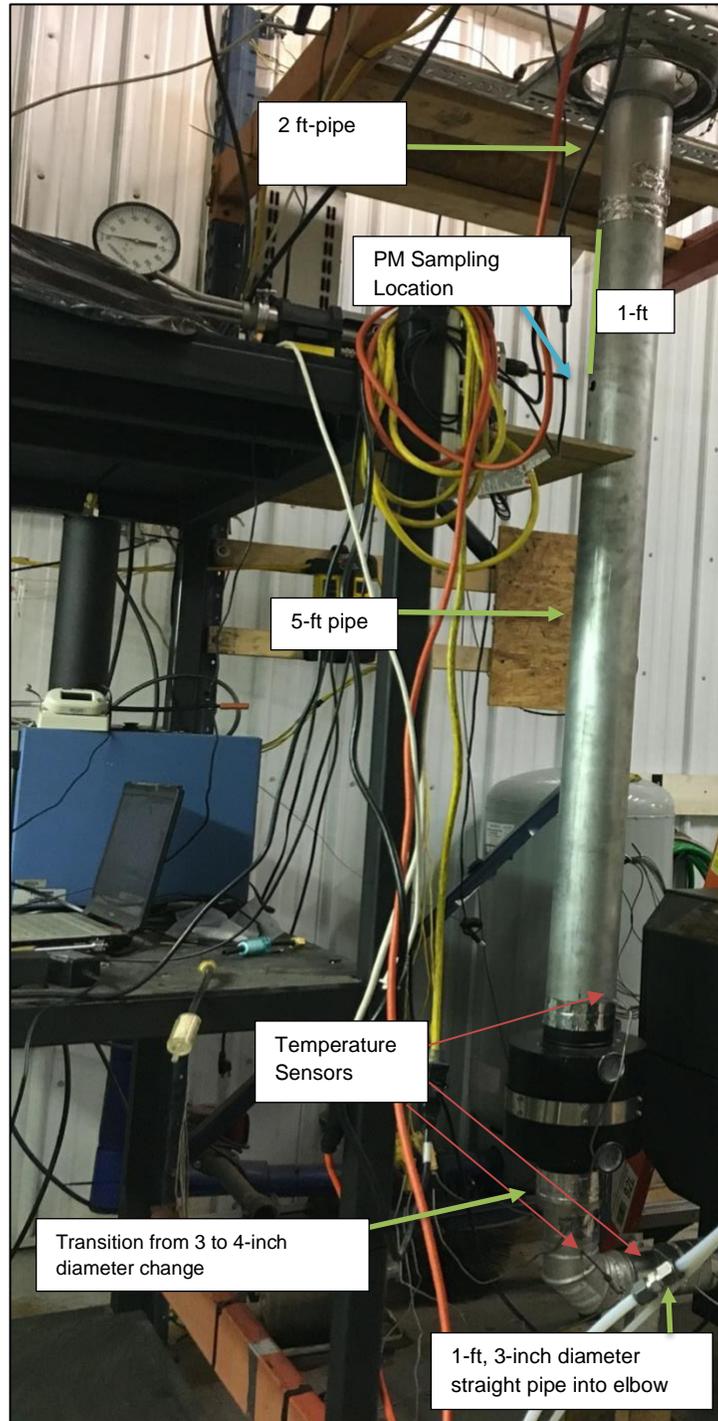


Figure 4. StoveCAT™ Install Schematic

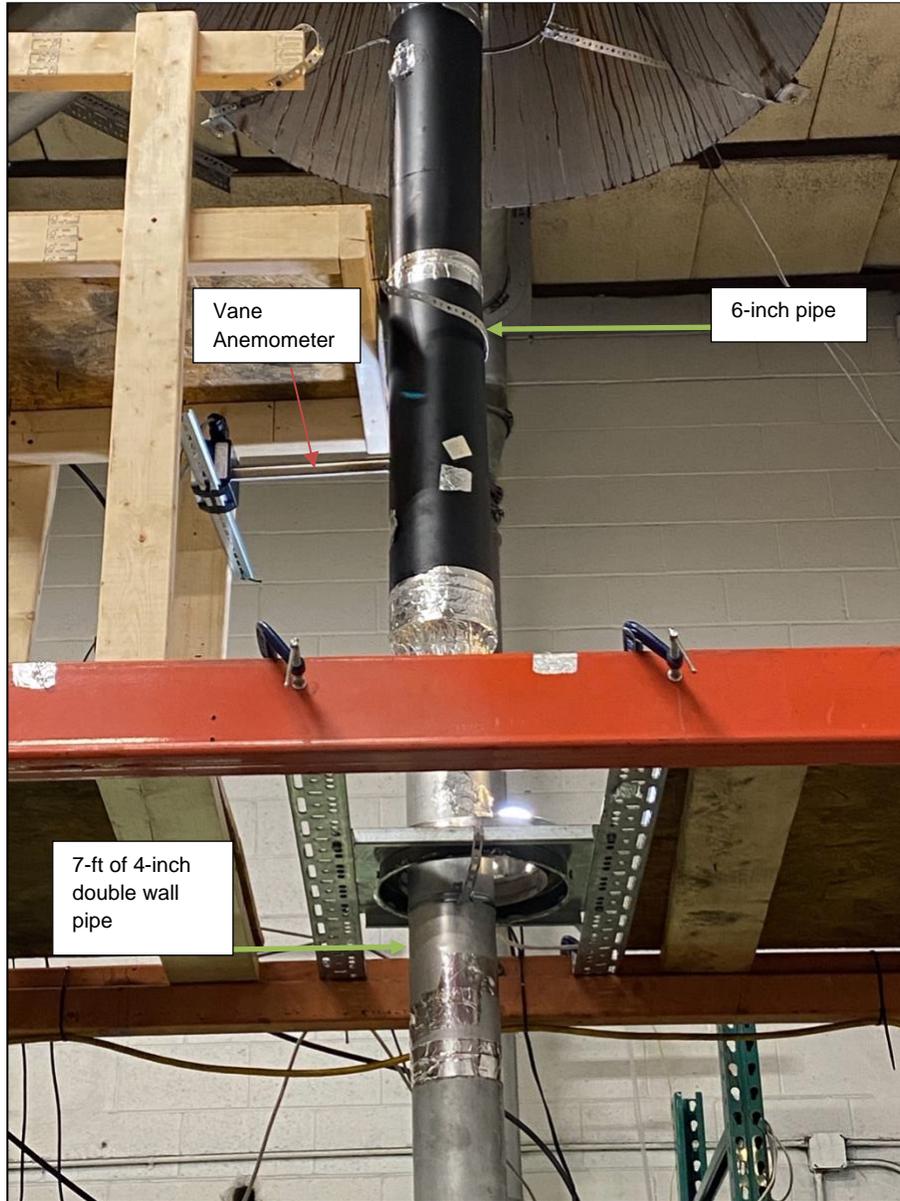


Figure 5. StoveCAT™ Install Schematic 2

#### 4.2.4 OekoTube ESP

Representatives of OekoTube ESP products visited ClearStak on different occasions to train on ESP installation, operation, and to observe testing of ESP 2 and ESP 3 test runs. They also provided the lab with the ability to electronically record ESP data, such as power, voltage, temperature, and errors.

The 6-inch diameter and 39-inch length OekoTube ESP was installed at 48 inches from the stove flue collar per recommendation of Oekotube. The pipe coming out of the flue collar, similar to the StoveCAT™ install, was a 3-inch diameter double wall pipe and elbow before transitioning to 6-inch diameter. The stack pipe used before and after the ESP was 6-inch diameter single wall black stove pipe. Originally, the ESP was installed with double wall black stove pipe, but it was determined that the connections between double wall stove pipe and ESP was a source of air leaks. Oxygen and anemometer measurements upstream and downstream of the ESP were used to confirm there were no leaks between the single wall stack and ESP connections. The overall length of the stove pipe extended 15 feet +/- 1 foot from the stove platform. The following ESP was used for all test runs and details are in Figure 6.



Figure 6. ESP Identification

To measure upstream and downstream emissions, PM measuring instrumentation was installed pre and post ESP (Figure 7). Instrumentation above the ESP, which includes the anemometer, downstream diluter, and stack temperature sensor, were installed at greater than 24-inches from the ESP, to prevent short circuiting of the electrode. This is greater than the minimum distance requirement (2x duct diameter) of the electrode to minimize electrostatic influence. The upstream diluter was installed eight inches below the ESP.

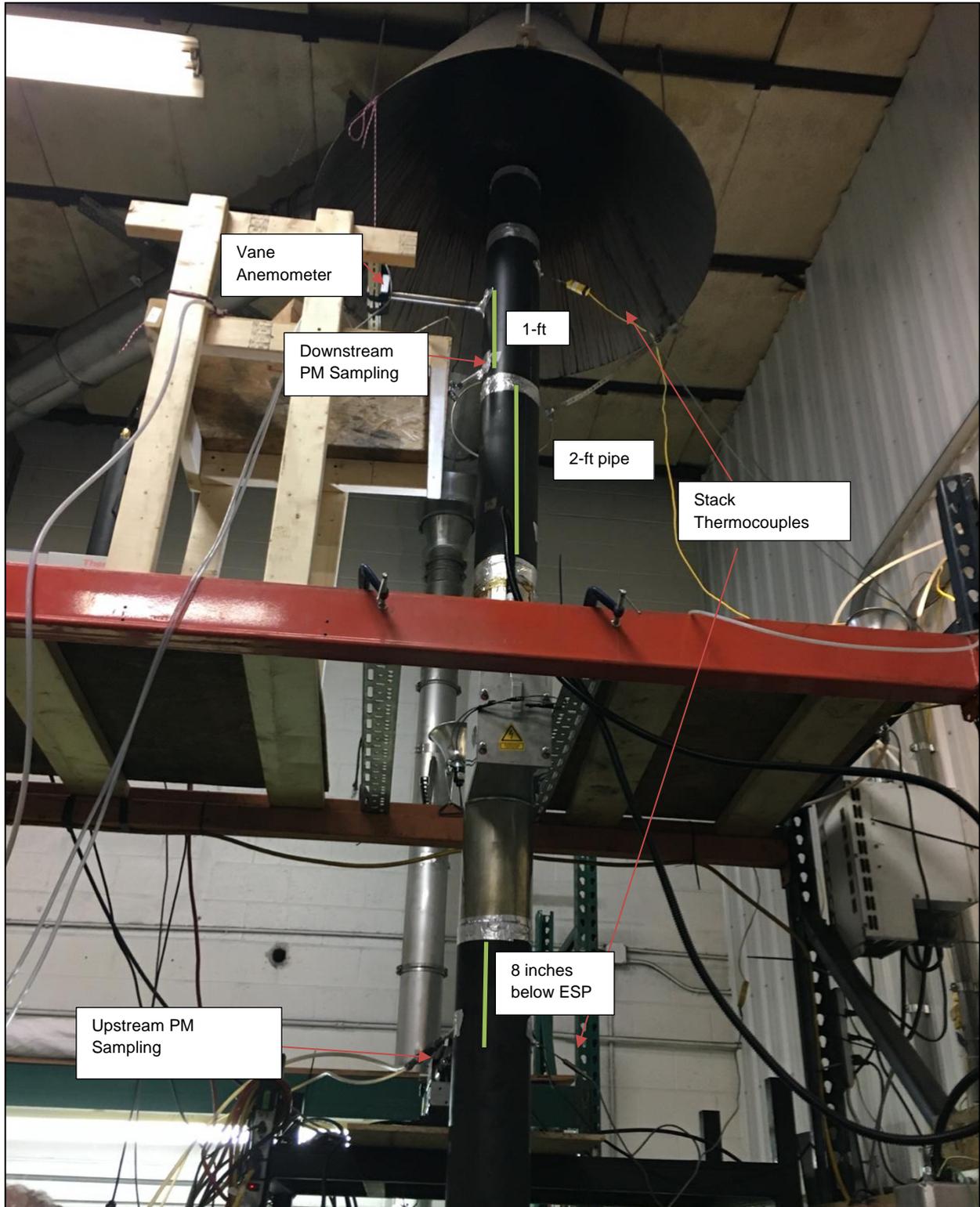


Figure 7. Pre and Post ESP Test Setup

## 5 Results and Data Summary

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### 5.1 OekoTube ESP Results

Testing took place over a month timeframe in January 2020. Particulate control efficiency of the ESP varied between test runs regardless of methods used to determine PM, evident in Table 1.

The wide range of variability of measured emissions downstream between the TEOM and filter trains of ASTM E2515 may be explained by the limitations of the ASTM E2515 test methodology and instrumentation in the inability to measure stoves with minimal filter PM catch of 0.2 mg or less. Thus, leading to unusually large uncertainties in determining overall PM emissions shown in Table 2. Although the filter data is the primary measurement method for PM, the TEOM results may actually provide better or more accurate picture of how well the ESP performs.

The TEOM provides time resolved PM rates over the course of the test run to provide performance evaluation of the ESP per phase of ASTM E2779 and startup are displayed in Table 3 and Figure 8. The ESP was most efficient at reducing PM emissions during the high burn rate setting with an average reduction rate of 74% and least efficient during the medium burn rate phase with an average reduction rate of 25%. PM removal in the Low Burn Phase (55%) is intermediate between the High and Medium Burn phases but is consistent across test runs.

The variability in the ESP's efficiency at reducing startup PM may be due to the ESP's inability to control initial startup emissions, which tends to be the highest PM spikes of many stoves. The ESP remains in a standby state until a pre-set temperature differential in the stack signals the activation of the electrode. By reviewing the ESP logged data per test (Appendix H), it was observed that the ESP was activated when the stack temperature approached 100°F, minutes after the pellet had stove ignited.

The ESP's low particulate control efficiency ratings during medium and low burn rates may be explained by the ESPs unstable performance during these phases. As observed in the ESP data, it appears that the ESP was arcing frequently during medium and low burn rates. Arcing is a short-term drop of ESP power, voltage and current to zero that is associated with emissions spikes from the ESP. Arcing occurs when the electric field between the electrode and the collection plate becomes strong enough to induce electrical breakdown and current flow between electrode and collection plate. Causes include over-voltage to the electrode and build-up of a high-resistance dust layer on the collection plate that tends to strengthen the internal electric field. When arcing occurs, the electric field responsible for trapping particulates collapses leading to loss

of emissions control; previously-trapped particulates can be re-entrained at this time and expelled from the device. These arcing events were also visually displayed in the TEOM PM data where dramatic spikes in PM emissions downstream of the ESP exceeded the PM emissions upstream of the ESP. Without more testing and analysis of this phenomenon it is unknown if the frequency of arcing is typical operation.

Table 1 ESP Particulate Control Efficiency Per Test Run

	Filter / TEOM Comparison											
	Pre ESP 2**	Post ESP 2**	Pre ESP 3	Post ESP 3	Pre ESP 7	Post ESP 7	Pre ESP 8	Post ESP 8	Pre ESP 9	Post ESP 9	Pre ESP 10	Post ESP 10
TEOM PM (g/hr)*	1.15	0.36	0.73	0.29	1.00	0.64	1.06	0.54	1.10	0.64	0.78	0.60
Filter PM (g/hr)	1.11	0.11	0.77	0.48	1.76	0.86	1.47	0.45	0.89	0.05	0.80	0.11
ESP Efficiency (Filter only)	90.4		37.9		51.2		69.7		94.2		86.2	
ESP Efficiency (TEOM only)	68.9		60.2		36.7		49.4		41.3		24.0	
*Negative TEOM values were set to 0 per TEOM protocol												
** missing 10 min. of stack flow, used average minute data from interval before and after missing 10 minute interval												

By comparing the two sources of PM, Pre ESP test data is typically within 10% of each other, however for unknown reasons, ESP 7 and ESP 8 are outliers.

Table 2 Filter Train Test Results

Filter Test Results														
Test ID	Baseline 3	Baseline 4*	Pre ESP 2**	Post ESP 2**	Pre ESP 3	Post ESP 3	Pre ESP 7	Post ESP 7	Pre ESP 8	Post ESP 8	Pre ESP 9	Post ESP 9	Pre ESP 10	Post ESP 10
Date	1/3/20	1/30/20	1/8/20	1/8/20	1/9/20	1/9/20	1/21/20	1/21/20	1/22/20	1/22/20	1/23/20	1/23/20	1/29/20	1/29/20
Average Stack flow (cfm)	35.40	31.50	31.19	31.19	30.90	30.90	31.49	31.49	30.91	30.91	30.19	30.19	30.32	30.32
Average Sampling Rate (cfm)	0.240	0.250	0.240	0.240	0.250	0.250	0.250	0.260	0.250	0.260	0.250	0.260	0.500	0.510
Test Duration (min)	420	420	420	420	420	420	420	420	420	420	420	420	420	420
PM Pre Dilution adjustment (g)	0.16	0.22	0.22	0.02	0.17	0.10	0.35	0.17	0.30	0.09	0.19	0.01	0.16	0.02
Avg. Dilution Factor from eDiluter	34.4	33.8	35.2	37.3	31.9	33.65	35.1	35.3	34.4	34.7	32.8	36.2	35.1	38.8
Adjusted PM with Dilution (g)	5.50	7.44	7.74	0.75	5.42	3.37	12.29	6.00	10.32	3.12	6.23	0.36	5.62	0.78
PM Rate (g/hr.)	0.79	1.06	1.11	0.11	0.77	0.48	1.76	0.86	1.47	0.45	0.89	0.05	0.80	0.11
ESP Efficiency %	n/a	n/a	90.4		37.9		51.2		69.7		94.2		86.2	
Uncertainty of Filter Emissions Et +/- @ 95% confidence (g)	0.018	0.016	0.016	0.015	0.015	0.015	0.017	0.015	0.016	0.014	0.015	0.014	0.0079	0.007
Uncertainty of Filter Emissions Et in +/- (%)	11	7	7	75	9	15	5	9	5	16	8	140	5	35
*2 sample trains for precision test, PM emissions per sample train were within 5% of the average PM emissions of the two trains and is acceptable by ASTM E2515 section 11.7														
** missing 10 min. of stack flow, used average minute data from interval before and after missing 10 minute interval														

ESP 1, ESP 4, ESP 5, ESP 6, Baseline 1, and Baseline 2 test runs were all invalid runs due to instrumentation malfunction or failed quality checks.

Table 3 Average ESP Particulate Control Efficiency Per Burn Phase

Average ESP Efficiency Per Burn Phase									
	ESP 2 (%)	ESP 3 (%)	ESP 7 (%)	ESP 8 (%)	ESP 9 (%)	ESP 10 (%)	Average (%)	Standard Deviation (%)	%CV
Startup High Burnrate Setting (1 hour)	62.6	32.2	-4.38	51.7	16.9	20.2	29.9	22.3	74.7
High Burnrate Setting (1 hour)	76.9	85.1	73.9	81.7	76.9	51.5	74.3	10.8	14.6
Medium Burnrate Setting (2 hours)	57.1	74.1	-2.60	37.3	1.02	-13.3	25.6	32.7	127.5
Low Burnrate Setting (3 hours)	74.6	57.1	61.2	41.2	63.6	34.2	55.3	13.7	24.7

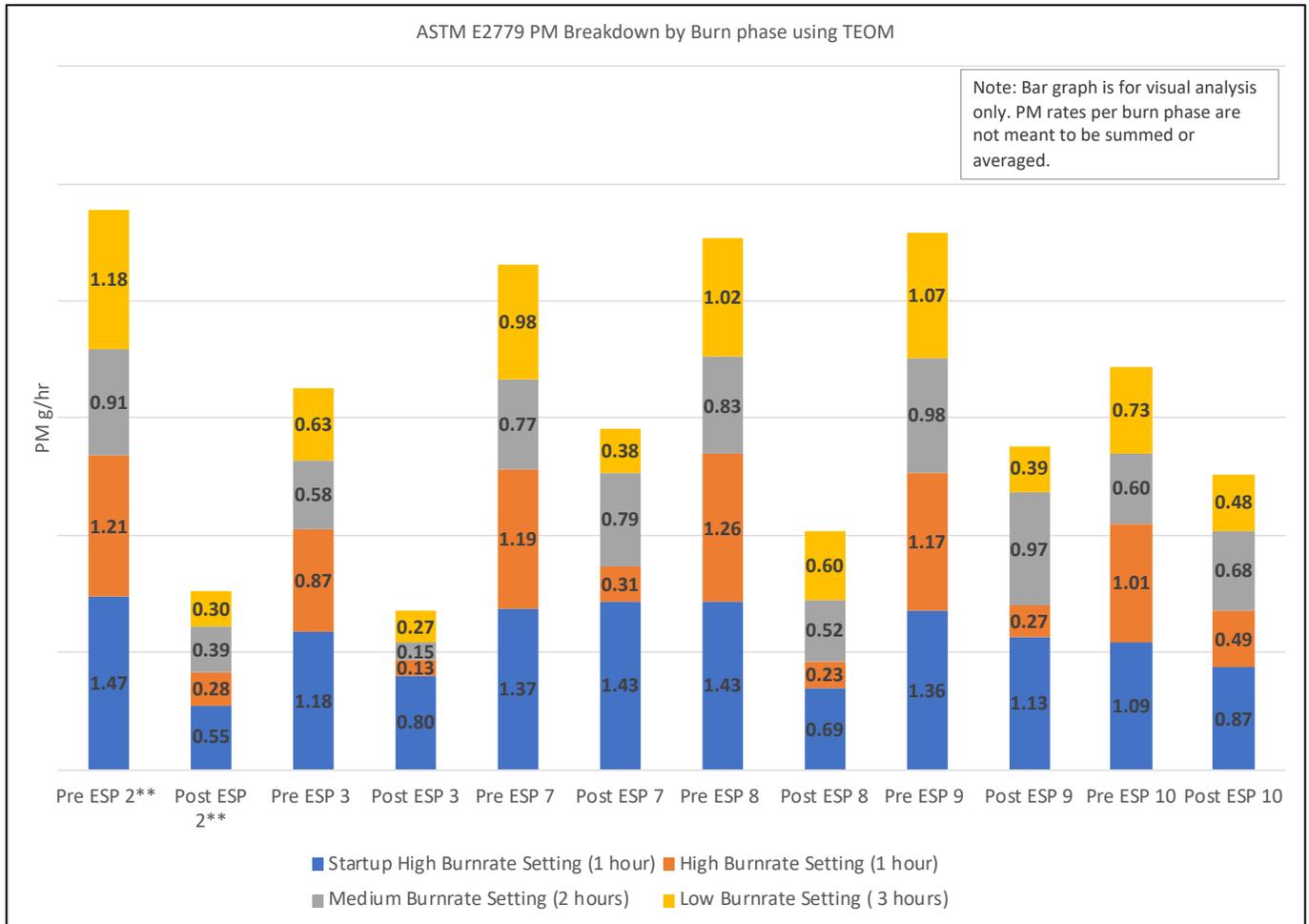


Figure 8 PM Per Burn Phase

## 5.2 Graphical Display of OekoTube ESP Results

To provide a basis to understand the performance of the ESP device, the TEOM and ESP operational data were combined and processed to permit a graphical display of emissions performance on a consistent basis during the test. This work was performed by Rincon Ranch Consulting, under subcontract to Trinity Consulting on behalf of the Fairbanks and North Star Borough (FNSB) and is included in this report at the request of FNSB; an explanation of the methodology and graphs for all ESP tests is presented in Appendix I.

Test run ESP9 is representative of the ESP's overall performance in the testing and illustrates the issues faced in pellet stove applications. Figure 9 shows pre- and post-ESP emission rates along with EPS power<sup>3</sup> and arcing events<sup>4</sup> for the entire test cycle. Figure 10 shows the trend of cumulative emissions (pre- and post-ESP) and cumulative and instantaneous PM removal during the test.

As seen in Figure 9, the ESP does not power up until minute 15 of the test (green line). An emissions spike of nearly 12 g/hr out of the stove (red line) occurs in minute 9 before the ESP powers on and is followed by a smaller spike from the stove in minute 16 just as the ESP powers on. The ESP approaches its full operating power of 16,000 mW by minute 30, but an arcing event occurs at minute 43 leading to a spike of 16 g/hr out of the ESP. When compared to emissions out of the stove, which were in the range of ~1 g/hr in the minutes before and after the spike, it is probable that previously-captured PM is being expelled from the ESP.

As the test moves into the High Burn phase, stove emissions vary in the range of 1–2 g/hr. The ESP operates consistently at its full operating power and successfully limits emissions from the ESP to a maximum of 0.5 g/hr during the High Burn. This level of performance continues into the start of the Medium Burn phase, but is interrupted at minute 151 by the first of long series of arcing events (22 Reported and 16 Suspected). Each of these is associated with a spike in emissions from the ESP that is in excess of emissions from the stove at that point in time. The largest spike occurs at minute 217 and reaches 17 g/hr. Arcing events continue into the Low Burn phase with an additional 12 events reported. These are associated with smaller

<sup>3</sup> ESP power and arcing events are indicative of operational conditions within the device, but more detail on operating parameters is available in the supplemental Appendix I to this report. The curve for power in Figure 9 shows minute-by-minute averages during the test but switches temporarily to a second-by-second basis to show more detail when an arcing event occurs.

<sup>4</sup> Arcing events are classified as Reported events when the ESP reports a trouble code of 8 and as Suspected events when power, voltage and current fall simultaneously to zero without a trouble code.

emission spikes, but the events at minutes 260 and 392 rise well above emissions from the stove. Once arcing begins to happen, the ESP often operates well below full power.

Figure 10 shows the variation of pre- and post-ESP emissions and removal efficiency during the test run and the effect of arcing events on ESP performance. Running average emissions and removal efficiency are calculated cumulatively from the start of the test. Whenever an arcing event occurs, cumulative removal is set back as emissions from the ESP are increased most likely by re-entrained PM. The ESP achieves a net emissions reduction during Startup, but this is significantly reduced by the one arcing event. Cumulative removal increases steadily during the High Burn phase but is significantly set back during the Medium Burn phase once the long sequence of arcing events begins. Some recovery is achieved during the Low Burn phase.

A key finding from the testing is that the ESP's performance is adversely affected by arcing events in all phases except the High Burns. A second limiting factor is the 15-minute delay at the start of the test before the ESP begins to operate. The delayed start-up is determined by the device's design. The number of arcing events varies from test to test, however the comparative frequency of arcing in various burn phases is consistent across all six replicate tests.

<sup>5</sup> In the testing and analysis reported here, emissions of re-entrained particulates are counted against the removal efficiency of the device following the precedent set by EPA regulation of ESPs in the industrial sector.

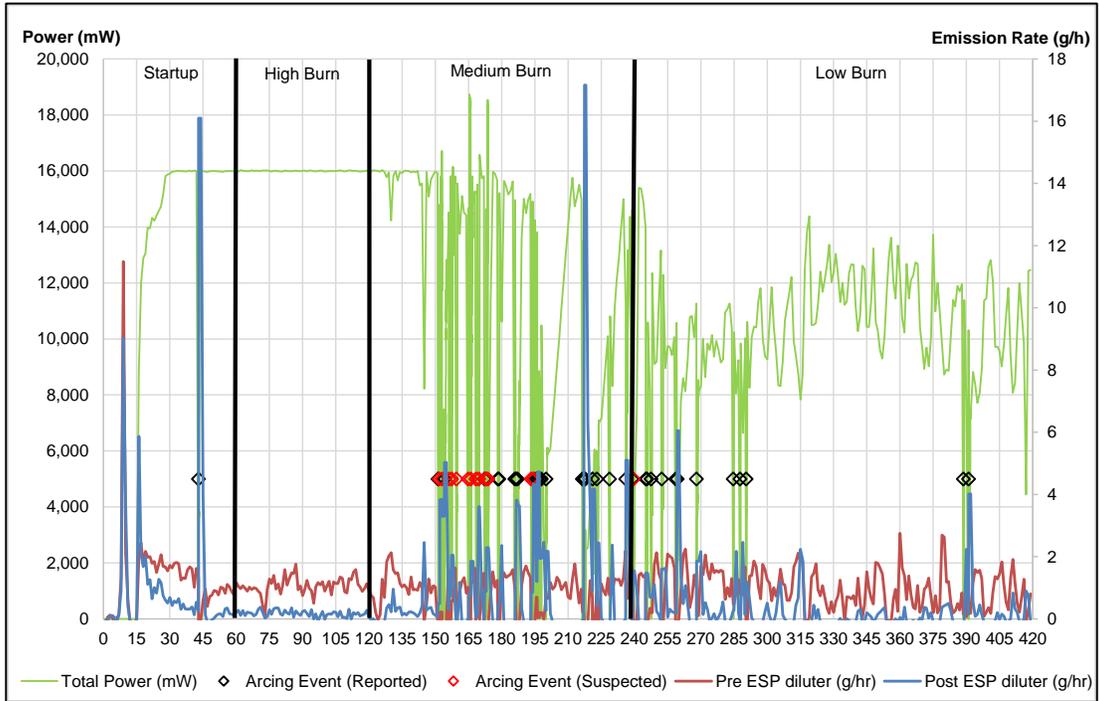


Figure 9. Pre and Post Emission Rate with ESP Power for Pellet Appliance with ESP (Run 9)

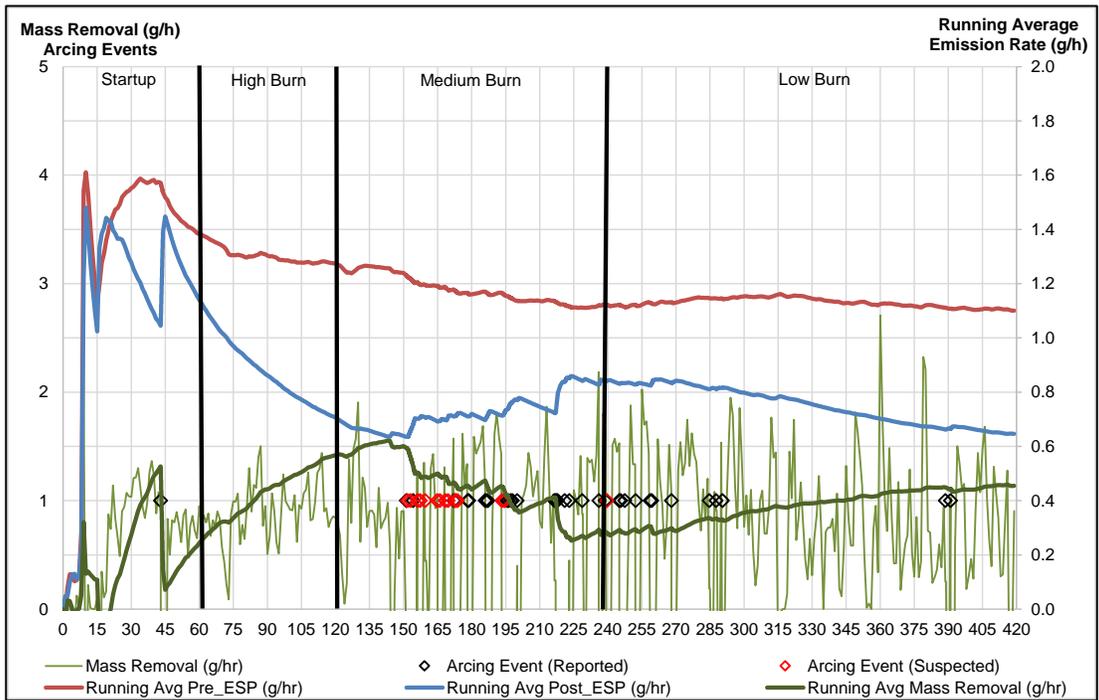


Figure 10. Cumulative Emission Rates and Mass Removal for Pellet Appliance with ESP (Run 9)

### 5.3 Grace Fire StoveCAT™ Results

All StoveCAT™ emission testing was done downstream of the catalyst. Considering it was observed that the catalyst was not operational during more than 94% of the conditioning period, the decision was made to reduce the replicates of baseline and catalyst test runs. Two baseline tests, without the catalyst installed, were performed January 3<sup>rd</sup> and January 30<sup>th</sup>, 2020 (Table 2). After one test with the catalyst installed, performed April 14<sup>th</sup>, 2020, it was determined that that the catalyst never activated and therefore, had no effect on emission performance for Pellet Stove 14 (Figure 11 and Figure 12). This is evident by the catalyst temperature sensor data showing that post catalyst temperatures were always cooler than pre catalyst temperatures for the entire test run (Figure 13).

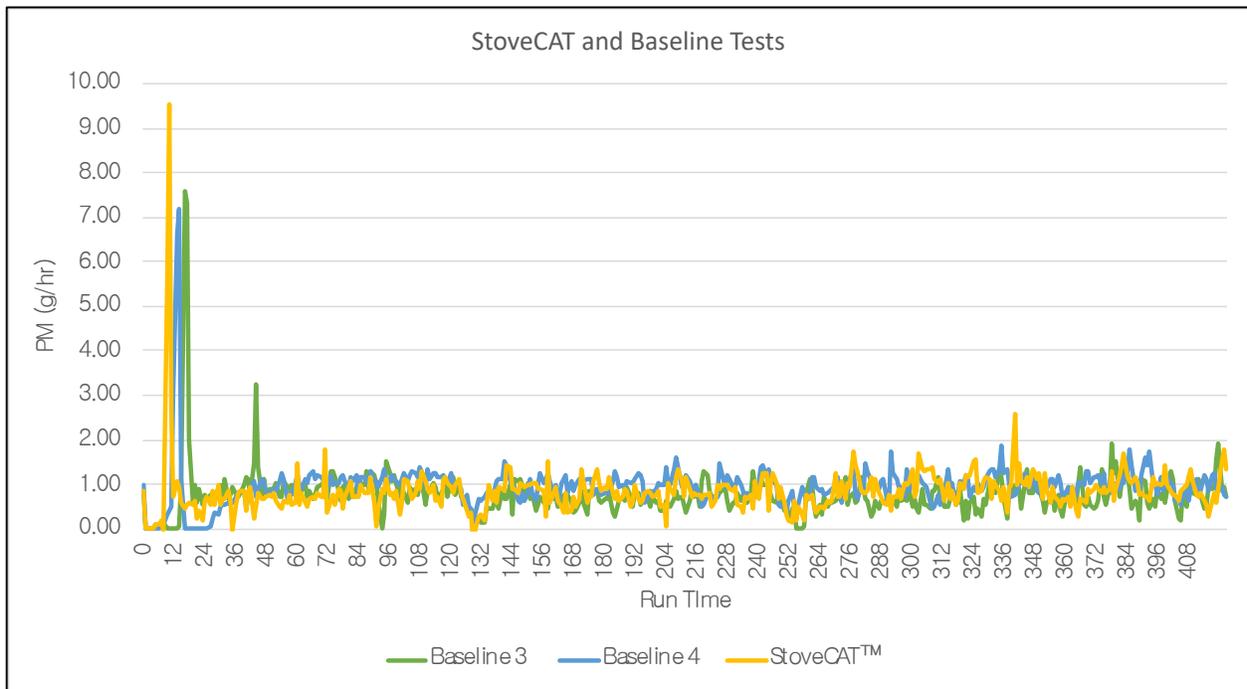


Figure 11. StoveCAT and Baseline TEOM Data

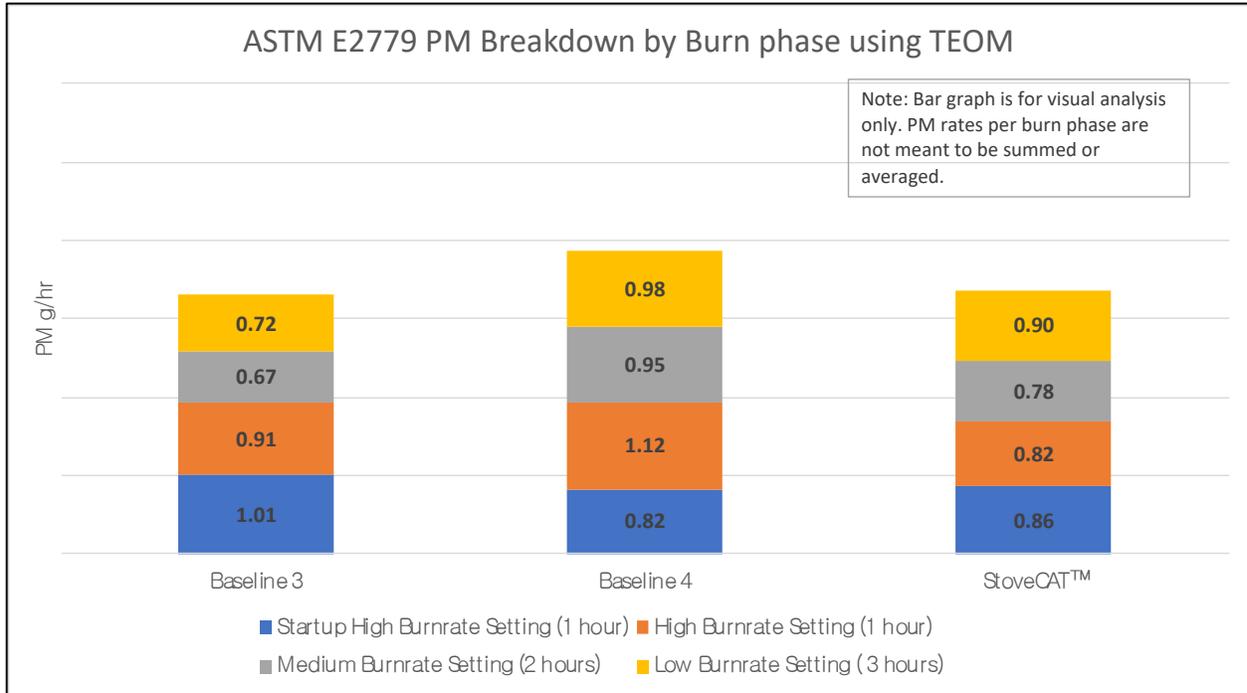


Figure 12. PM Per Burn Phase

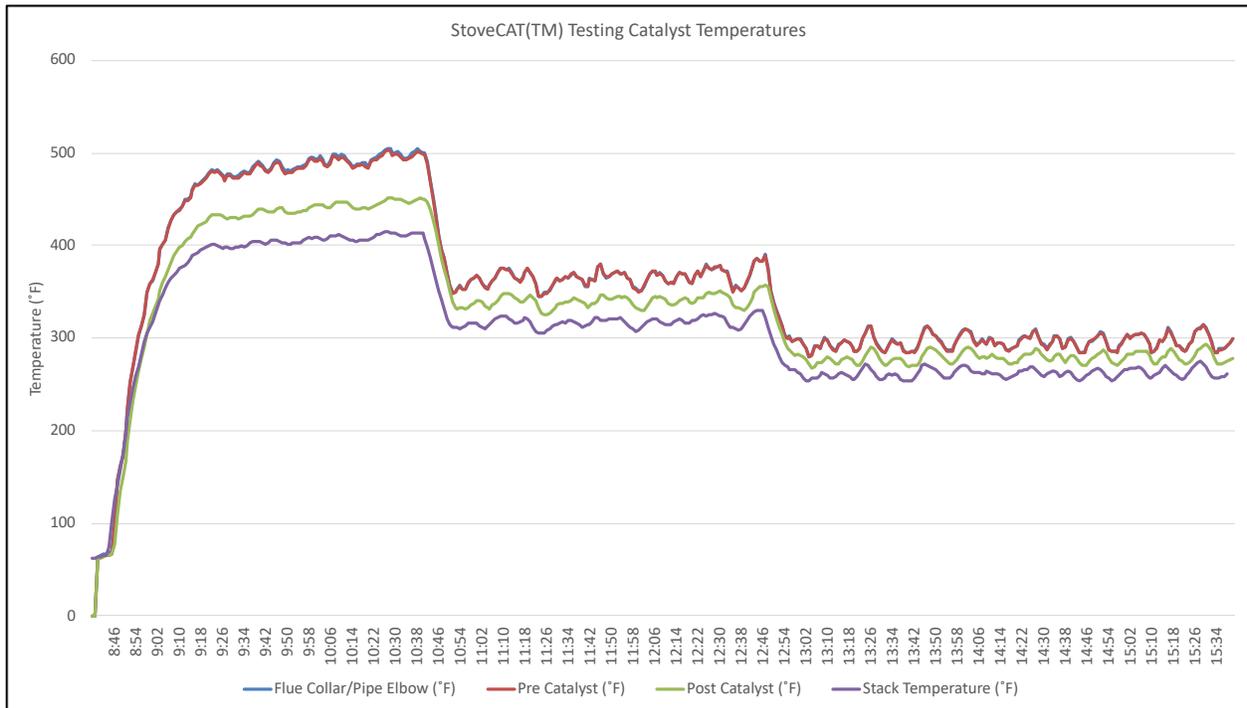


Figure 13. StoveCAT™ Temperature Data

## **5.4 Unexpected Deviations from Test Methods**

### **5.4.1 Stack Pressure and Velocity**

The vane anemometer was used as the main source of velocity measurements in the stack because differential pressure in the stack could not be accurately observed. It was determined during testing that the stack flow was too low and below the detection limit (0.005 in WC) for the micro pitot tube and quarter inch manometer for use of determining stack velocity. The vane anemometer is calibrated and specified for low range stack flows with a 1% accuracy making it a valid source for measuring velocity per the calibration report attached in Appendix F.

Minute velocity measurements were combined into 10-minute averages to compare to filter train sampling rate for proportionate rate sampling. Vane anemometer 10-minute averages were not corrected to moisture and therefore may be biased high by 10%, but it is assumed that moisture is the same throughout the flow in the stack and therefore does not affect ESP particulate control efficiency.

### **5.4.2 ASTM E2515 Filter Train Sampling Rates**

Due to limitations of ASTM E2515 combined with low emitting emissions from an EPA Step 2 pellet stove, PM catch on filters used for measuring downstream RCD emissions were too low to measure accurately even when sampling at an average of 0.250 cfm. For ESP 10 test run, the sampling rate was doubled to 0.500 cfm to double PM filter catch. This exceeds the sample flowrate specified in ASTM E2515, but does not exceed the filter face velocity of 30 ft/min. and therefore does not invalidate the test run.

### **5.4.3 Proportionality Sampling**

The pellet stove stack velocity was not always steady throughout the test run and sometimes differed by more than 10% when transitioning between high, medium, and low burn rates. Proportionality was maintained by manually calculating minute anemometer and stack temperature data to 10-minute averages and comparing to the past manually collected 10-minute sample volume.

Originally, at the start of the test series, proportionality was determined using on the minute average anemometer and stack temperature data at each 10-minute interval and then comparing to the past manually collected 10-minute sample volume. However, Pellet Stove 14's stack velocity and temperature was not always stable throughout a 10-minute interval resulting in false proportionality rates (PR). This problem did not arise until data compilation and analysis after test runs were completed. The test runs affected were ESP 2 and ESP 3 where 94% of PR values are within 85% - 100% for ESP test run 2 and 96% of PR values

are within 85% - 105% for ESP test run 3. Performance of Pellet Stove 14 is not the focus of this test series' objective and both sampling rates of the filter trains were operated in unison. Therefore, determined PM emissions for ESP 2 test run and ESP 3 test run may be biased low, but it does not affect the ratio of PM reduction for gauging ESP performance.

ESP test run 10 also has a lower overall PR due to the higher filter train sampling rate of 0.500 cfm. The goal for ESP 10 was to double the average sampling rate to double PM catch on the filter and decrease uncertainty in PM emissions determined downstream of the ESP. In the low burn rate phase of the test run, the filter train sampling flowrate hit the maximum achievable without exceeding the maximum filter face velocity of 30 ft/min. Both sampling rates of the filter trains were operated in unison. Therefore, determined PM emissions may be biased low, but it does not affect the ratio of PM reduction for gauging ESP performance.

#### **5.4.4 eDiluter Rinses**

eDiluter acetone rinses were completed using eDiluter serial number 86106, paired with TEOM serial number 20291 during a catalyst test run on 3/26/20 and 4/14/20. 4/14/20 was a valid catalyst test run and 3/26/20 test run was invalidated due to interruptions to anemometer flow recordings. However, the anemometer data is not needed to assess diluter rinse PM catch and therefore does not affect the result. The eDiluter rinses were performed by breaking down the eDiluter into the two stages per Appendix C. Both test days showed a PM loss of in the 1st stage of range 8-10% of total PM. The second stage rinse results were high for undetermined reasons. On 3/26, the second stage rinse was more than the total PM collected and the catch from 4/14/20 was 38% of total PM, which is not consistent with the reasonably good agreement of PM measured from the dilution tunnel (spare TEOM) and diluter systems for testing of this pellet stove.

It should also be noted that eDiluter rinses are a new concept and has never been performed before by the lab nor NESCAUM, the owners of the instrument. It is possible that unknown variables are being overlooked in the calculations of diluter rinse catch. It is also possible, that the execution of the rinse was not handled properly. Without an established procedure by the manufacture, NESCAUM and ClearStak were forced to draft one based on what is known in handling the instrument and the known specification.

See calculations below.

**Diluter is 2 stages with nominal Dilution Factor(DF) of 6 for both.****3/26/20 diluter rinse catch:**

Total nominal flow (dilution + sample) in each stage: 40+8 = 48 lpm

Average inlet flow = 7.835 slpm; target = 7.605

Average DF = 34.15; target = 36.8

$34.15/36 = 0.9486$ , acceptable DF

1st stage is 2.65 mg

2nd stage is 5.25 mg

Run Time: 440

avg stack pm: 7.39 mg/m<sup>3</sup>, from avg Teom pm x actual DF

**Simplified calcs with default flows and Dilution Factor:**

Average Concentration in 1st stage =  $7.39 \text{ mg/m}^3 / 6 = 1.25 \text{ mg/m}^3$

volume in 1st stage =  $440 \text{ min} * .048 \text{ m}^3/\text{min} = 21.12 \text{ m}^3$

total pm =  $1.25 \text{ mg/m}^3 * 21.12 \text{ m}^3 = 26.4 \text{ mg}$

Result =====>  $2.69 \text{ mg} / 26.4 \text{ mg} = 10.2\%$  of sampled PM is in the diluter catch

Average concentration in 2nd stage is directly measured by Teom: 0.2160 mg/m<sup>3</sup>

Total PM =  $0.2160 \text{ mg/m}^3 * 21.12 \text{ m}^3 = 4.56 \text{ mg}$

**4/14/20 Actual diluter performance:**

Average inlet flow: 7.94 standard lpm; target = 7.63 lpm

Average Dilution Factor = 32.7 ; target = 36.65

$32.7/36 = 0.908$ , acceptable DF

**4/14/20 diluter rinse raw mass catch:**

1st stage is 3.16 mg

2nd stage is 2.53 mg

Run Time: 440 minutes

Average stack PM: 10.39 mg/m<sup>3</sup>, from average Teom pm x actual Dilution Factor

**Simplified Calculations with default flows and Dilution Factor:**

Total stage flow = 48 lpm (0.048 m<sup>3</sup>/min), with a first stage conc. of (stack concentration/DF), and 2nd stage conc. is actual PM measured by Teom.

Average Concentration in 1st stage =  $10.39 \text{ mg/m}^3 / 6 = 1.73 \text{ mg/m}^3$

Volume in 1st stage =  $440 \text{ min} * .048 \text{ m}^3/\text{min} = 21.12 \text{ m}^3$

Total pm =  $1.73 \text{ mg/m}^3 * 21.12 \text{ m}^3 = 36.57 \text{ mg}$

RESULT =====>  $3.16 \text{ mg} / 36.57 \text{ mg} = 8.6\%$  of sampled PM is in the diluter catch

Avg conc in 2nd stage is directly measured by Teom: 0.3177 mg/m<sup>3</sup>

Total PM =  $0.3177 \text{ mg/m}^3 * 21.12 \text{ m}^3 = 6.71 \text{ mg}$

RESULT =====>  $2.53 \text{ mg} / 6.71 \text{ mg} = 37.7\%$  of sampled PM is in the diluter catch

## 6 Quality Control and Assurance Procedures and Results

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### 6.1 ASTM E2515 and ASTM E2779

All instrumentation used are calibrated according to sections 7 and 8 of ASTM E2779 and sections 6-8 of ASTM E2515. Quality performance check procedures and acceptable tolerances on test instrumentation described in sections 9.4, 9.6, 9.7, and 9.9 of ASTM E2515 were followed as directed and documented. All calibration and verification data can be found in Appendix F.

### 6.2 Dekati® eDiluter™

The Dekati® eDiluter™ calibrations were verified at the start and end of each test run by comparing CO measured by the eDiluter using an enhanced trace level NDIR gas analyzer and EPA Protocol Gases. Further information is provided under “eDiluter Performance Checks” in the *SOP for Dekati® eDiluter™ in a Wood Stove Stack with the Höntzsch Vane Anemometer*.

The primary quality check validation for TEOM PM data was the comparison of run-average emission rates with the filter pull off the eDiluter. Additional TEOM quality checks include flow and leak checks, and confirmation of the TEOM transducer  $K_0$  calibration factor.

All calibration and verification data can be found in Appendix F.

### 6.3 Sample Calculations

#### 6.3.1 From Anemometer Stack Flows Calculations Rev 19-12-05

Rev 12/5/19, G. Allen				<b>NOTE:</b> If Col. E Stack P is not in " Hg, the last term in H3 must be edited.						
			Anemometer		Velocity		Velocity	Velocity		
1/29/20	Stack T	Stack delta-p	Velocity	Stack P	m/s, cal.	Stack T	m/s	m/min	stack flow	stack flow
Time (hh:mm)	deg F	"H2O absolute	m/sec raw	" Hg	corrected	deg C	at STP	STP	m3/min STP	CFM@STP
8:45	60.2		0.00	29.675	0.16	16	0.165	9.89	0.166	5.9

#### Sample Calculation @ 9:45 Start Time (Line 7)

Velocity @ STP = 0.165 m/s = 0.16 m/sec x (298 K / (16°C +273) ) x (29.675 in Hg/29.92 in Hg)

Stack Flow = 5.9 cfm = 0.165 m/sec x (60 sec/min) x EFFECTIVE STACK AREA of 0.01683 m2 x (35.3147 ft3 / m3)

Avg. 1/29/20 Test Stack flow = 30.32 cfm

#### 6.3.2 Calculated PM from Raw Filter/probe Catch

Owner Title: Quality Manager   Type: Quality System   Status: ACTIVE Version: 08   Last Modified: January 31, 2018							
Test ID:		FNSB Stove 14 ESP 10					
Date:		1/29/20					
ISS# / AS#	Filter / FH ID #	Pre-Weight Avg (g)	Post Weight Avg (g)	Total Catch (g)	Total Catch (mg)		
Post ESP	ISS-2	FF-15 (CS-18)	Probe	63.604160	63.604070	-0.00009	0.000
	ISS-2	EM-19-00248	Front Filter	0.093815	0.093930	0.00011	0.115
	ISS-2	EM-19-00249	Back Filter	0.093815	0.093990	0.00017	0.175

#### Sample Calculation

Total Raw Filter Catch = 0.29 mg = 0.000 mg front half probe + 0.115 mg front filter + 0.175 mg back filter

PM Concentration =  $1.35 \times 10^{-6}$  g/dry standard ft<sup>3</sup> = (0.29 mg / 1000 mg) / 214.049 dry standard ft<sup>3</sup>  
(dscf) of gas volume sampled through filters

Total PM Emissions Pre dilution adjustment = 0.02 g =  $1.35 \times 10^{-6}$  g/dscf x 30.32 cfm x 420 min run  
time

Total Emissions Adjusted PM with dilution = 0.78 g = 0.02 g X 38.8 Avg. Dilution Factor from eDiluter  
(determined daily, see eDiluter logs in Appendices)

PM g/hr = 0.11 g/hr. = 0.76 g / 7-hour test

# 7 Appendices

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Appendix A. StoveCAT™ Installation Guide

Appendix B. OekoTube ESP Installation Guide

Appendix C. *SOP for Dekati® eDiluter™ in a wood stove stack with the Höntzsch vane anemometer*

Appendix D. *Standard Operation Procedures for Thermo 1405 TEOM® for use in a dilution tunnel or with an extractive dilution system Version*

Appendix E. *Particulate Matter Emission Measurement Methods*

Appendix F. Instrumentation Calibrations

Appendix G. Datasets Per Test Run: Note Spreadsheets are setup for dilution tunnel testing. Testing was done in the diluter and stack. All data references to the dilution tunnel are diluter and stack

Appendix H. ESP Software Data

Appendix I. Analysis of Device Performance