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July 17, 2020

RE: ClearStak Report – The Efficacy of the ESP on Cordwood Stoves

To Whom it May Concern:

The Environmental Protection Agency (EPA) has designated a portion of the Fairbanks North Star Borough (FNSB) as 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_{2.5} emissions. There has been significant public interest in the potential for add-on retrofit controls, such as electrostatic precipitators (ESP), to help in reducing emissions within the nonattainment area and providing more flexibility to local residents that use wood for heat. To gain insight into the benefits of retrofit control devices, the FNSB has conducted a testing project which measured the effect of ESP and catalytic retrofit devices on pellet stoves. To provide some additional information in support of the Borough study, the Alaska Department of Environmental Conservation (ADEC) commissioned a small parallel study to measure the effect of ESPs on two EPA Step 2 cordwood stoves¹: non-catalytic and catalytic. The goal of this limited testing program was to provide initial information on ESP performance on cordwood stoves to aid the FNSB in their study efforts and to provide some insight on whether a broader more robust testing program is warranted.

The test program 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:

Non-catalytic Cordwood Stove Performance

- The ESP failed due to excessive creosote build-up after 34 hours of operation with dry fuel in a controlled environment. The excessive creosote buildup coupled with an ignition source, such as electrical arcing, is believed to present a potential safety hazard for homeowners.
- It is recommended that the manufacturer update its device design to address the creosote concerns and demonstrate performance using test protocols approved by FNSB, ADEC and/or EPA. It is further recommended that thorough testing on a new design be conducted by the manufacturer on noncatalytic devices of the size used in FNSB prior to further use or testing by FNSB.
- When creosote impacted measurements are ignored, ESP control efficiency was found to range between 66 – 73% (filter based versus TEOM measurements) for relatively high emitting non-catalyst

cordwood stoves. TEOM measurements showed significant variability in ESP control efficiency ranging from 33 – 92% depending on the test phase of the IDC.

- If the creosote concerns can be addressed, ESP's offer significant emission reduction potential for non-catalyst cordwood stoves, which could aid community efforts to improve air quality.

Catalytic Cordwood Stove Performance

- The test results for the ESP equipped catalytic cordwood stove indicate a control efficiency of 1%.
- The low emission levels of catalytic cordwood stoves combined with poor ESP performance during the startup test phase and the almost nonexistent reduction in overall emissions suggest that ESP control for these stoves offers little benefit to the community. However, other variables such as typical number of start-ups influence the overall emission reduction and additional data gathered through simultaneous measurement of PM before and after the ESP could provide additional insight to the efficacy of ESPs on catalytically controlled cordwood appliances.

This test program did not collect the data required to develop emission factors (lb/MMBtu) needed for a formal comparison with fuel oil stove values. However, the results for both appliance categories indicate they are at least one order of magnitude higher than fuel oil equivalency, which means if operated during Alerts they would worsen air quality and therefore cannot be exempt from burn bans in their current design.

All the above findings are based on limited testing and a more robust program employing simultaneous measurements based on both filter and TEOM methods is recommended and needed to confirm the above and provide additional insight into the potential benefits of any redesigned ESP for cordwood stove control.

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

Sincerely,



Cindy Heil
Program Manager
Air Non-Point and Mobile Sources

Enclosures:

Executive Summary
The Efficacy of ESP on Cordwood Stoves (July 15, 2020)

EXECUTIVE SUMMARY

Overview

A limited testing program was conducted to measure the effect of a commercially available electrostatic precipitator (ESP) on PM (particulate matter) emitted from cordwood stoves in support of the Fairbanks North Star Borough (FNSB) testing project, which studied the effect of ESP and catalytic retrofit control devices on pellet stoves. The study focus was to collect initial measurements with an ESP to assist in providing additional information to the decision-making processes within the Borough related to consideration of retrofit controls and potential needs for further testing by the Borough. Two EPA Step 2 appliances¹ were tested: a non-catalytic stove and catalytic stove, designated in this report as Stoves 9 and 19, respectively. Both were selected to be representative of their categories operated in Fairbanks North Star Borough (FNSB). The test fuel used was seasoned silver maple, sourced in Connecticut with 19-25% moisture content.

The testing program, conducted by ClearStak and Air Tox Environmental, evaluated the performance of an OkeoTube ESP. The testing was performed in a collaboration with ongoing testing under separate contract with FNSB and the Northeast States for Coordinated Air Use Management (NESCAUM). The test protocol used for operating the cordwood stoves was the Integrated Duty Cycle Method for Cordwood Stoves (IDC), developed by New York State Energy Research & Development Agency (NYSERDA) and NESCAUM. It specifies four phases of operation at two different heat output settings, high and low, designed to represent realistic stove operation: Startup, High Fire, Maintenance Fire and Overnight Fire.

Given the limited scope of the program, insufficient resources were available to support the collection of simultaneous measurements of PM up and downstream of the ESP unit. Instead, non-simultaneous measurements were collected from baseline (no ESP) and controlled (ESP installed) tests; average differences between the baseline and controlled tests were used to calculate the estimated efficiency in reducing emissions. Care must be taken in interpreting these values as test to test variability is imbedded in the average values used to calculate efficiency. For this reason, the findings are limited and preliminary. Additional and more robust testing with simultaneous measurements and larger sample sizes would need to be conducted to produce more complete findings on cordwood stoves.

Two different methods of PM measurement were employed in the program: the primary method used a modified ASTM E2515 protocol with dual filter train systems 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 minute by minute measurements of PM and provides insight into the performance of controls during different phases of the IDC as well as total operation, while the ASTM E2515 method only provides a single data point—the average of all test phases. Both measurement methods, filter based and

¹ Certified to 2.5 g/hr when tested with cordwood)

TEOM were used to measure PM emitted from the higher emitting non-catalytic cordwood stove (Stove 9). Measurements for the lower emitting catalytic cordwood stove (Stove 19) were

collected by the TEOM method, as it provides insight into differences in temporal performance; no filter measurements were collected for Stove 19.

Findings

Stove 9 (Non-Catalytic Cordwood Stove) – A total of 9 tests were conducted. Two of the 5 baseline tests (#'s 1 & 2) were invalidated due to test method deviations, leaving 3 valid baseline tests; their measurements along with average values are presented below in Table ES-1. One of the 4 ESP tests (# 3) had numerous error codes and it was observed that the voltage at the electrode was in the 3,000-voltage range, not at the maximum specified 30,000 voltage, which meant the ESP was not fully functioning to its capacity. At the end of the test, technicians removed the ESP from the test stand and found excessive buildup of creosote on the ESP walls significantly restricting air flow (see photo in test report). The result was a dramatic reduction in control efficiency and concern about operation as testing could not continue without intervention. ESP #3 was considered an anomaly for the purposes of estimating average removal efficiency, but it was a valid test and the results must be considered when assessing ESP as a control device on cordwood appliances.

The ESP was cleaned out with a wire chimney brush² and then re-installed back on the test stand. It was then confirmed that the ESP was still operational using ESP data which indicated that no errors existed and maximum voltage at the electrode was present. A thin layer of hard tacky coating of buildup did remain on the ESP walls even after the cleaning. The results for the remaining 3 ESP tests are also presented in Table ES-1 along average values.

Table ES-1				
Non-Catalytic Cordwood Stove				
Non-Simultaneous PM Test Measurements and Average Efficiency by Test Method				
(g/hr)				
TEOM				
Test Type/#				Average
Baseline	29.35	18.51	26.74	24.87
ESP	5.59	7.11	7.22	6.64
Control Efficiency				73.3%
Filter				
Test Type/#				Average
Baseline	34.85	22.03	32.40	29.76
ESP	8.21	11.25	10.63	10.03
Control Efficiency				66.3%

The average baseline values are an order of magnitude higher than the levels to which the stoves were certified. The cause of the discrepancy is the difference between the EPA test protocol and the IDC.

² While the manufacturer's manual recommends the use of a synthetic brush for cleaning, the thickness of the creosote dictated the use of metal brush to remove the restricting material.

Since the IDC is considered more representative of real-world operation, the actual emission rates for these appliances are substantially higher than indicated by the certification levels (this finding parallels motor vehicle owner experience with the difference between EPA and on-road fuel economy – people drive differently from EPA test procedures – people also operate their stoves differently from EPA test procedures). Despite the significant reductions achieved by ESPs (not impeded by creosote buildup), the resulting average values are still multiples of the levels to which the stoves are certified.

The particulate control efficiency is calculated based on the differences between the baseline and ESP tests. Both test methods showed significant PM reductions ranging from 66 percent for the primary filter method to 73 percent for the TEOM method. The cause of the 11 percent control efficiency difference is not known. For comparison purposes, the manufacturer claims a particulate control efficiency of 70-80% for European operation.

Regardless of the percent difference between the two PM measuring methods, the TEOM provides more data with regard to ESP performance with 1-minute average values. This is especially helpful when comparing ESP performance during burn phase changes. TEOM results for each burn phase are displayed in Table ES-2. As can be seen, test run ESP #3 in which the device errored out is an outlier compared to the other three runs (ESP #'s 1, 2, and 4). ESP #3 was a valid test and reflects what can happen to device performance and emissions due to excessive build-up of creosote (discovered after the test).

Test Phase	Baseline			ESP				Average Baseline	Average ESP*	Control Efficiency
	#3	#4	#5	#1	#2	#3	#4			
Startup	4.03	10.73	4.83	4.31	3.83	112.03	4.91	6.53	4.35	33.4%
High	23.13	13.07	30.91	5.18	6.30	20.22	9.14	22.37	6.87	69.3%
Maintenance	47.95	43.64	40.57	1.77	5.66	16.58	2.65	44.05	3.36	92.4%
Overnight	26.14	6.18	20.86	9.00	8.70	9.53	9.54	17.83	9.08	48.8%

*Does not include ESP #3, where ESP was not functioning.

In the Startup phase of ESP #3, the device emitted more than 17 times the amount of PM than was emitted by the stove on average during the Baseline testing. While later phases show a net reduction from Baseline levels, the total TEOM measured removal efficiency in ESP #3 is only 31% versus the tabulated 73% for the average of the other three test runs. In contrast, the table shows that test runs ESP #'s 1, 2 and 4 are relatively consistent in emission rates from the device and removal efficiencies both overall and by phase. The average of these three runs describes what can be called “normal performance” but it must be realized that the discrepant performance in ESP #3 is still possible in field service.

As can be seen in Table ES-2, the average PM removal efficiency of the ESP across the three runs is lowest (33%) in the Startup phase, which may be due to the ESP's delayed operational start.³ The ESP was most effective during the Maintenance Fire phase where the PM removal efficiency averaged 92% across the three test runs. Its performance was intermediate (69%) in the High Fire phase and second lowest (49%) in the Overnight Fire phase.

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; an explanation of the methodology and graphs for all ESP tests is presented in Appendix G. Test run ESP #4 was selected as representative of the ESP's overall performance in the testing and, specifically, of device performance with a light creosote coating lining the ESP walls.

Figure ES-1 shows Baseline and Post-ESP emission rates along with EPS power⁴ and arcing events⁵ for the entire test cycle. Average Baseline emissions from the stove (dashed red line) were not measured concurrently with emissions out of the ESP. The baseline is shown for reference as an approximate indicator of stove emission levels, but it does not represent stove-out emissions *during* the ESP test and, thus, does not match up minute by minute with Post-ESP emissions as measurements were not collected simultaneously.

As seen in the figure, the ESP powers up during minute 4 of the test (green line) and remains there through the end of Startup at minute 35. Post-ESP emissions are reduced once the ESP powers on. There is an uptick of PM emissions (blue line) at the start of the High Burn phase when the stove is reloaded. ESP power drops below full-power between minutes 48 and 63 during which emissions rise consistently until the device returns to full power and good emission control is restored. Running average PM emissions (double blue line) continue on a decline course into and through the Maintenance Fire phase. The ESP operates below full power but successfully limits emissions to an average of 6 g/hr since the start of the test (again more than twice the 2.5 g/hr certification level).

This level of performance continues into the start of the Overnight Fire phase, but is interrupted at minute 240 by the first in a sequence of arcing events (8 Reported and 3 Suspected). The first is associated with a spike in emissions from the ESP that nearly reaches the highest level of emissions observed during Baseline testing. Cumulative PM emissions tick up during the initial arcing events but decline thereafter to zero levels to end up at an average rate of 7.2 g/hr over the entire test. In this phase, ESP performance is reduced somewhat by arcing events compared to the Maintenance Fire phase. While not evident in Figure ES-1, a review of the minute specific values reported for the Overnight Fire phase

³ 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, it was observed that the ESP was activated when the stack temperature approached 100°F.

⁴ 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 G to this report. The curve for power 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.

⁵ 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.

of the other ESP tests found similar reductions in power, increased emissions and arcing indicating a problem with ESP control during this phase of operation.

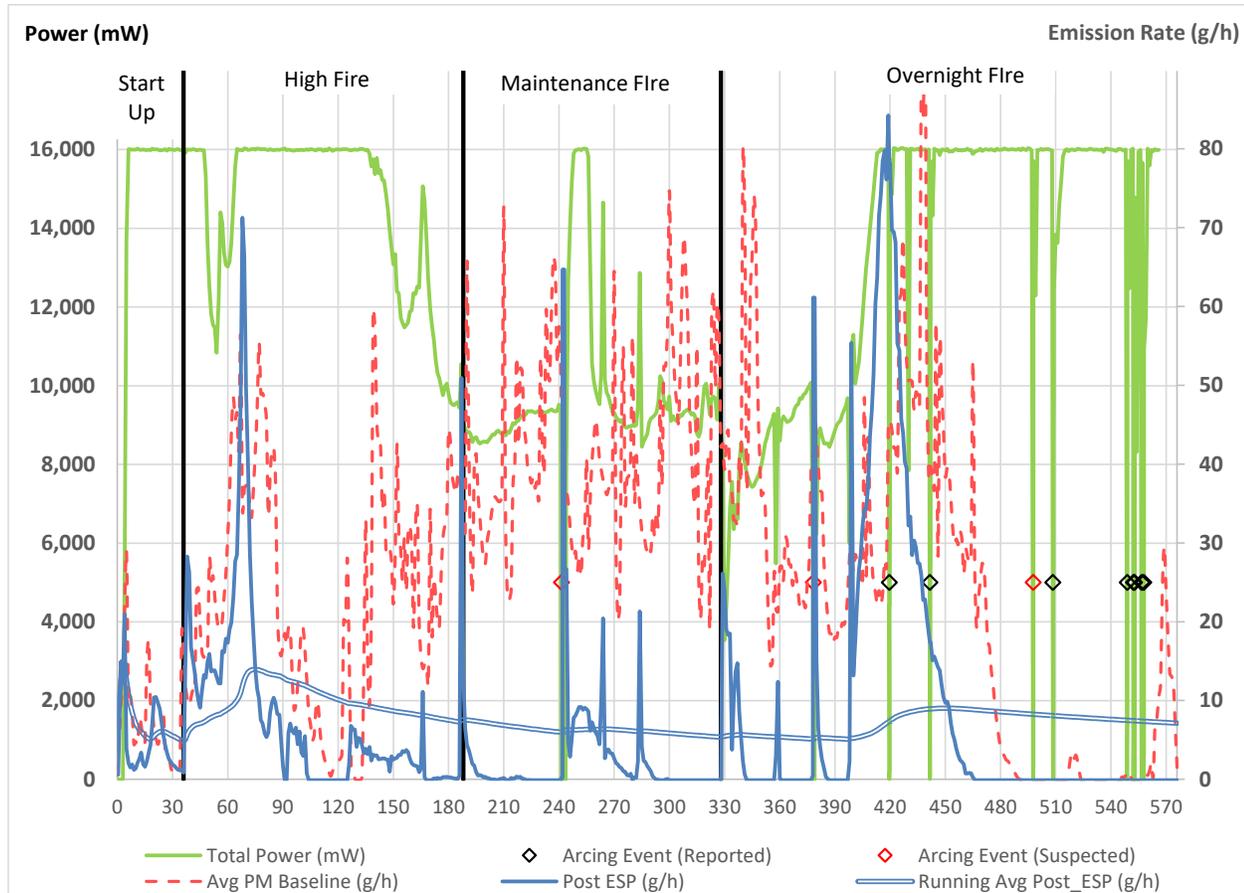


Figure ES-1. Non-Catalytic Stove 9 with ESP, Run 4, Entire Run (minutes 0-576)

A key finding from the testing is that the ESP performs relatively well on the non-catalytic cordwood stove as long as an excessive build-up of creosote is not present. During such operation, it is successful in reducing total PM emissions to 7.2 g/hr compared to average (uncontrolled) stove emissions of 24.9 g/hr during Baseline testing. One limiting factor is the 4-minute delay at the start of the test before the ESP begins to operate, which is determined by the device’s design. A second limiting factor is the occurrence of arcing during the Overnight Fire phase. These factors, however pale in comparison to the effect of creosote build-up on ESP performance, which occurred after 34 hours of dry cordwood use. Removal efficiency calculated for ESP #3 depends on the measurement method but ranged from zero for the filter values (actually there was a slight increase in average PM relative to the Baseline) to 31% for the TEOM values.

Stove 19 (Catalytic Cordwood Stove) – A total of 7 tests were conducted. One of the 3 baseline tests (#1) was invalidated due to test method deviations, leaving 2 tests valid baseline tests; their measurements

along with average values are presented below in Table ES-3. One of the 4 ESP tests (#1) also invalidated due to test method deviations. The results for the 3 remaining tests are also presented in Table ES-3. For all test runs, the average PM rate was under 5 g/hr using the IDC protocol. The difference in the average baseline and ESP values is only recorded at the second decimal place and provides an overall control efficiency of 1%.

Table ES-3							
Catalytic Cordwood Stove							
TEOM Test Measurements and Control Efficiency							
(g/hr)							
Baseline		ESP			Average Baseline	Average ESP	Control Efficiency
#2	#3	#2	#3	#4			
2.38	4.17	1.86	3.57	4.29	3.28	3.24	1.13%

When looking at the individual phases presented in Table ES-4 it is evident that the ESP had the least influence during Startup (8.9%), where PM emissions were higher than the High Fire and Maintenance Fire phases for test runs both with and without an ESP. This can be explained by both the internal catalyst and external ESP being inactive during the beginning portion of this phase. From a cold start, the catalyst has to be heated to activation temperature to become operational; until then, the gases bypass the catalyst through a manual mechanism. The ESP remains inactive until a temperature differential in the stack triggers the powering of the electrode.

Also shown in Table ES-4, startup emissions account for the large majority (87%) of the overall test emissions. Stove emissions drop off significantly once the catalyst reaches light off temperature after startup. Thus, the later High Fire and Maintenance Fire phases combined account for only 16% of overall emissions. Given the relatively low emission levels compared to start-up, the 50-60% ESP removal efficiency of these phases does little to further reduce PM emissions and makes a small contribution to overall PM control.

Table ES-4			
Catalytic Cordwood Stove			
TEOM Test Measurements and Control Efficiency by IDC Test Phase			
(g/hr)			
Test Phase	Baseline	ESP	Control Efficiency
Startup	19.21	17.5	8.9%
High Fire	0.32	0.14	56.1%
Maintenance Fire	2.02	0.80	60.4%
Overnight Fire	n/a	n/a	n/a

Figure ES-2 illustrates this using test run ESP #3 which was most representative of the average ESP performance. Post-ESP emissions (blue line) were very high in the first few minutes of the test. By

minute 16, Post-ESP emissions fall significantly, suggesting that the catalyst has reached light-off. The ESP powers on (green line) during minute 24 of the test, but with post-ESP emissions already at diminished levels it contributes relatively small incremental emissions control. PM emissions tick up at the start of the High Fire and Maintenance Fire phases when the stove is reloaded, but they start at the already low Baseline (uncontrolled) levels during those phases. The two arcing events during the High Fire phase have no detectable impact on PM emissions, unlike the non-catalytic stove tested.

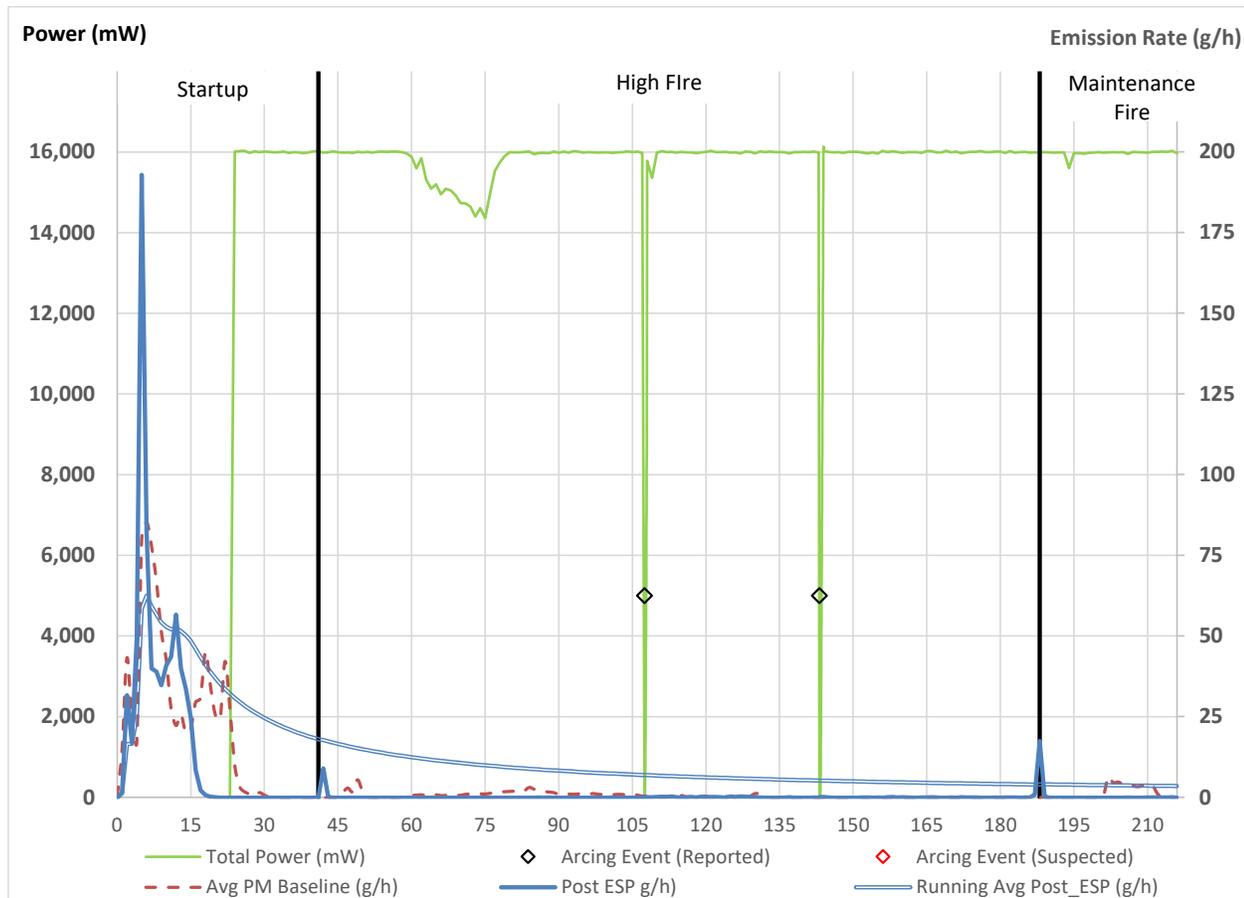


Figure ES-3 Catalytic Stove with ESP, Entire Run (minutes 0-216)

Summary

The performance of the ESP is of considerable interest to the Borough and ADEC as EPA has designated FNSB as 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_{2.5} emissions. The goal of this limited test program has been to provide some information on ESP performance and its potential use to reduce PM levels with cordwood stoves. Key insights gained from this limited test program include:

For the ESP on a noncatalytic woodstove:

- The ESP failed due to excessive creosote build-up after 34 hours of operation with dry fuel in a controlled environment. The excessive creosote buildup coupled with an ignition source, such as electrical arcing, is believed to present a potential safety hazard for homeowners. Therefore, it is recommended that the manufacturer update its device design to address this issue. It is further recommended that thorough testing on a new design be conducted by the manufacturer on noncatalytic devices of the size used in FNSB prior to further use or testing by the community or FNSB. Prior to conducting testing, it is recommended that the manufacturer prepare test protocols for review and/or approval by FNSB, ADEC, and/or EPA.
- ESP control efficiency was found to range between 66 – 73% (filter based versus TEOM measurements) for relatively high emitting non-catalyst cordwood stoves. TEOM measurements showed significant variability in ESP control efficiency ranging from 33 – 92% depending on the test phase of the IDC. The control efficiency observed for the overnight fire phase was less than 50%, which is of concern since it represents a significant category of stove operation in FNSB.
- All of the non-catalyst cordwood findings reported above, ignore test measurements collected when ESP operation was determined to be severely restricted due to excessive build-up of creosote. The overall average removal efficiency of this test ranged from zero to 31% (filter based versus TEOM measurements). The results reported above represent what can be called “normal performance” but it must be realized that the discrepant performance in ESP #3 will likely occur in field service.
- The requirement to manually clean the ESP after a limited number of tests raises concern about the design, its ability to handle higher levels of PM emissions, durability, and the public’s interest in regularly removing, cleaning and replacing the device to achieve continued control performance.
- If the creosote concern could be addressed, ESP’s offer significant emission reduction potential for non-catalyst cordwood stoves, which could aid community efforts to improve air quality.
- Additional testing of the existing ESP units on non-catalyst stoves can provide more insight into creosote build-up and its impact of control efficiency, but it is unlikely to eliminate the performance/safety concerns. The only way those concerns will be eliminated is for the ESP unit to be redesigned to address the higher emission loadings produced by non-catalyst cordwood stoves and for subsequent testing to document its performance.

For the ESP on catalytic woodstove:

- The test results for the ESP equipped catalytic cordwood stove indicate a control efficiency of 1%. The TEOM measurements show control efficiency varies by test phase ranging from 9 – 60% for 3 of the 4 test phases, with the lowest level of performance occurring during the highest emitting mode of operation (startup prior to catalyst light off).
- The relatively low emission levels of catalytic cordwood stoves combined with poor ESP performance during the high emitting startup test phase suggest that ESP control for these stoves offers little benefit to the community. In other words, an ESP coupled with an existing catalyst appears to provide limited additional benefit. Emission benefits could be greater if the number

of start-ups are small in comparison to other burn phases, however the burn practices of residents are unknown at this time. ADEC and the FNSB do not have data on how often residents start a catalytic woodstove ‘cold’ during the course of a winter; the fewer start-ups of the stove the more emission benefits from the use of the ESP. Simultaneous PM measurements taken upstream and downstream of the ESP could also provide more insight to the efficacy of ESPs on catalytic cordwood appliances.

Overall:

- The findings are based on limited testing and a more robust program employing simultaneous measurements based on both filter and TEOM methods is recommended and needed to confirm the above and provide additional insight into the potential benefits of any redesigned ESP for cordwood stove control.

This test program was developed by ClearStak in coordination with ADEC and FNSB in 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 ADEC/FNSB in consultation with EPA.

By sponsoring the testing, ADEC and FNSB have 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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The Efficacy of the ESP on Cordwood Stoves

Report 20.02.01

Prepared for:
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&
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1 Introduction

1.1 Background

A portion of the Fairbanks North Star Borough (FNSB) has been designated as a non-attainment area for fine particulate (PM_{2.5}) 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 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_{2.5} 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 particulate control efficiency of electrostatic precipitators (ESPs) on cordwood stoves. Evaluation of the results will allow the State of Alaska Department of Environmental Conservation (DEC) to determine if ESPs are a viable control option for reducing PM_{2.5} emissions for residential wood heaters in the Fairbanks North Star Borough.

Trinity Consultants, a contractor of the ADEC, subcontracted ClearStak, an accredited lab, for testing the performance of a commercially available ESP on non-catalytic and catalytic cordwood stoves. This testing was performed in a collaboration with ongoing testing in a separate contract with Fairbanks North Star Borough and the Northeast States for Coordinated Air Use Management (NESCAUM).

Assessing the performance of the cordwood stoves was not the objective of this research and therefore the stove manufacturers and models will remain anonymous in all documentation. The non-catalytic stove is an EPA Step 2 appliance and is designated as Stove 9 in this test report. The catalytic stove is an EPA Step 2 appliance and is designated as Stove 19 in this report. The test fuel used was seasoned silver maple, sourced locally with 19-25% moisture content.

2 ESP Description

2.1 The OekoTube Electrostatic Precipitator (ESP) by OekoSolve AG

The OekoTube ESP, Figure 1, 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%.

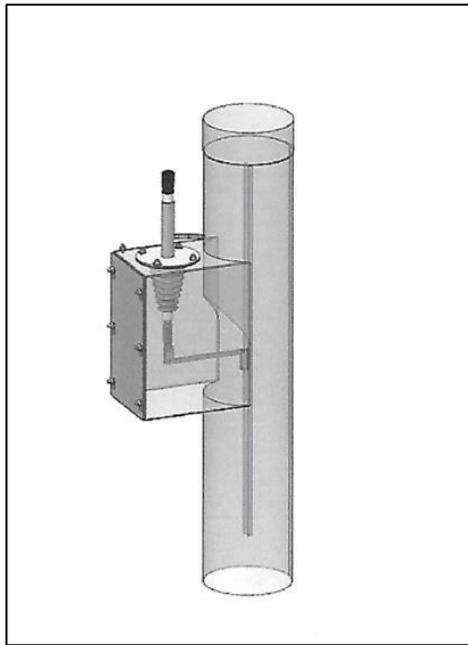


Figure 1. OekoTube Electrostatic Precipitator¹

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 outside on the chimney rooftop or installed indoors. The OekoTube ESP has a maximum power consumption of 30 Watts and becomes 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 A of this report.

¹ One World Resource Management, FNSB RFP 19047, 2.

3 Sampling and Analytical Procedures

ESP testing in the collaborative effort with Fairbanks North Star Borough and NESCAUM, as mentioned in 1.2 used simultaneous sampling pre and post ESP to determine particulate matter control efficiency. Simultaneous sampling pre and post ESP was considered but deemed infeasible due to a variety of non-technical issues; therefore, emissions were measured after the ESP in a dilution tunnel. Replicate test runs were completed with and without an ESP. Averaged baseline test runs (No ESP) were then compared to averaged ESP test runs (with an ESP).

3.1 Operational Methods

The operational protocol used for operating the cordwood stoves was NYSERDA and NESCAUM's Integrated Duty Cycle Method for Cordwood Stoves (IDC). The IDC protocol uses realistic operational procedures by providing data on four test fuel loads at two different heat output settings, high and low. It also utilizes different fuel load sizes in order to provide the most accurate and robust emission measurement data in a laboratory setting. Data on this fueling and operational protocol can be found on NESCAUM's website: <https://www.nescaum.org/topics/test-methods>.

3.1.1 Deviation from IDC – Stove 19

After baseline testing of Stove 19, it was concluded that PM emissions from this particular catalytic stove model were too low for the ESP to make a significant, if any, impact on reducing PM emissions due to the stove's ability to burn at a very slow burn rate while still maintaining an active catalyst (Figure 2). Therefore, it was decided to perform a modified and shortened version of the IDC to compare PM emissions during phases with higher burn rates where PM is present at higher quantities. The test runs included a normal Startup, a modified High Fire with air damper completely open for the full phase, and a partial Maintenance Fire with air damper open at ~10% and the test ending after 30 minutes from the fuel loading PM spike in Maintenance Fire. Overnight Fire burn phase, a long period of sometimes 8 hours or more of low heat demand, was not included in the modified IDC for Stove 19.

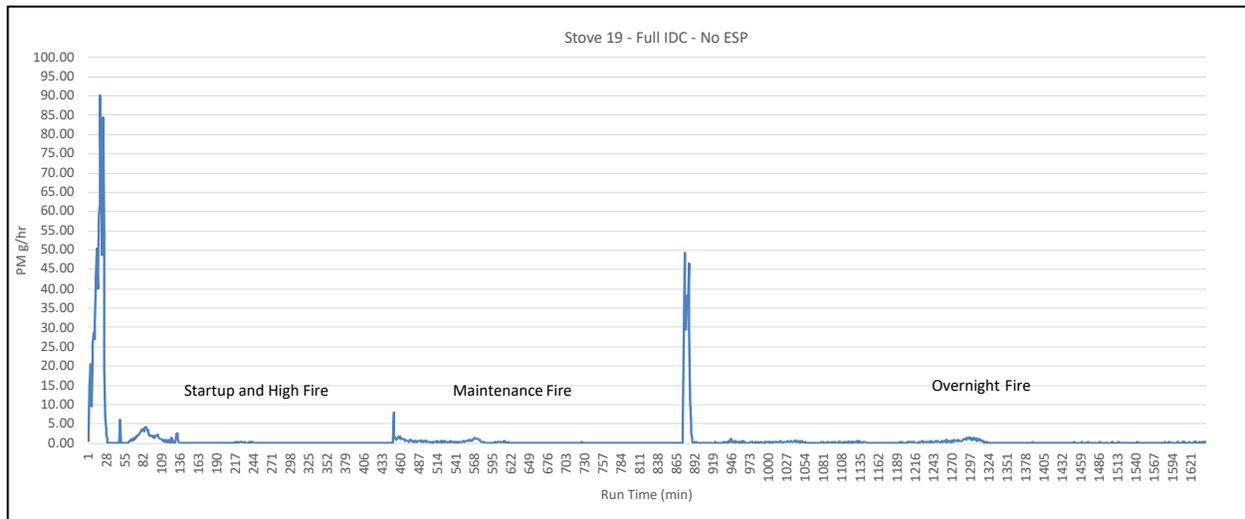


Figure 2. Catalytic Stove 19 IDC Test Example

3.2 Sampling Methods

Two methods for measuring PM were used for Stove 9, ASTM E2515 and NESCAUM's SOP for TEOM 1405. However, due to the natural variability of cordwood stove testing it was determined that the TEOM provided a more valuable insight to how the ESP affected PM emissions. Therefore, it was decided to move forward with TEOM testing only for Stove 19.

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

Two dual filter dry sampling train systems were used in collecting particulate samples. Two sampling trains collected particulate from an 8-inch diameter dilution tunnel and one sampling train collected particulate from ambient air. All particulate sampling conditions were in compliance with ASTM E2515-11. At the end of each test run, filters were removed from their housings; filters were desiccated for 24 hours, and then weighed to a constant weight per ASTM E2515-11 section 10. Other sampling and analytical procedures followed EPA Methods 1,2,3,4,5, and 28 and CSA B-415.10. PM from front half filter probe assemblies were collected from acetone rinses based on Method 5 through 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 a 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 B of this report. This document covers operational

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 options. 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 C, *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

4.1 Conditioning

The OekoTube ESP was used in previous tests in a collaborative effort with Fairbanks North Star Borough and NESCAUM and had a total run time of 105 hours. The ESP was conditioned on a Step 1 certified cord wood stove for 24 hours and then cleaned for testing on a Step 2 certified Pellet stove. Cleaning involved using a wire chimney brush and a vacuum to gently remove build up on the ESP's walls without disturbing the centered electrode. The ESP was not cleaned after pellet stove testing because of little to no buildup on the ESP walls. The light buildup that remained was a feathery and dusty texture that was not hard coated on the walls, but rather was fragile and easily fell out between movement during install. Below is an image of the ESP after use on a pellet stove and before this test series (Figure 3).



Figure 3. ESP At Start of Test Series

4.1.1 Installation OekoTube ESP

Representatives of OekoTube ESP products visited ClearStak on multiple occasions to train on ESP installation and operation. They also provided the lab with the ability to electronically record ESP data,

such as power, voltage, temperature, and errors through use of an Excel macro worksheet that logged 1 second interval data.

The 6-inch diameter and 39-inch length OekoTube ESP was installed at 48 inches from the stove flu collar per recommendation of Oekotube. The stack pipe used before and after the ESP was single wall black stove pipe. The following ESP was used for all test runs and details are in Figure 4 and the installation for the ESP is displayed in Figure 5. A stack k-type thermocouple was placed above the ESP at about 24 inches, to prevent short circuiting of the electrode. The stack pipe and ESP combination extended 15 feet from the base of the woodstove and top of floor scale.



Figure 4. ESP Identification



Figure 5. ESP installed on Cordwood Stove

4.2 Testing Instrumentation

The specification and placement of sampling instrumentation followed ASTM E2515 with an 8-inch diameter sampling section of the dilution tunnel. Instrumentation used for determining fuel loads and phase changes followed IDC. Surface temperature sensors were not used because performance of the stove was not the objective.

5 Results and Data Summary

5.1 Stove 9 – Non-catalytic

There were five baseline (No ESP installed) tests and four ESP (ESP installed) tests completed in a one-month timeframe between February 4th and March 3rd, 2020. ASTM E2515 results and testing conditions can be found in Table 1. Results from Baseline 1 and 2 and ESP 3 have been excluded from averages for determining ESP particulate control efficiency at PM capturing displayed in Table 2. Baseline 1 did not have filters per ASTM E2515 associated with the test run and technicians had difficulty maintaining a fire in the stove. This resulted in longer periods of fuel adjustments to provide air to keep the fire alive, which went against the fueling procedures in the IDC protocol. Baseline 2 test run is an outlier because startup fuel was added to the stove in batches after the initial firing of the kindling. The protocol was then revised to combine startup fuel and kindling together in the firebox at the start of the test. This revised fueling portion of the protocol was adopted and used for all of Baseline 3-5 and ESP 1-4 test runs. During ESP 3 test run, the ESP errored out and it was observed that the voltage at the electrode was in the 3,000 Voltage range, not at the maximum specified 30,000 voltage, which meant the ESP was not fully functioning to its capacity. Upon removing the ESP from the test stand, technicians found excessive buildup of creosote on the ESP walls significantly restricting air flow. The ESP was cleaned out with a wire chimney brush² and then re-installed back on the test stand. It was then confirmed that the ESP was still operational using ESP data which indicated that no LED errors existed and maximum voltage at the electrode was present. A thin layer of hard tacky coating of buildup did remain on the ESP walls even after the cleaning.

The particulate control efficiency of the ESP to reduce PM emissions was determined by comparing the average PM emissions from baseline tests and ESP test runs. PM was measured with the TEOM and filters per ASTM E2515 and results did differ as evident in Table 2. The percent difference between the two PM measuring protocols differed at a higher percentage in the ESP test runs (32-42%) than in the Baseline test runs (14-17%) and the reasoning has not been determined. This difference in PM results in two different average efficiencies for ESP PM capturing. Overall, TEOM results show the ESP having a higher efficiency of 73% compared to the ASTM filter results of 66%. The overall percent difference between the two PM

² While the manufacturer's manual recommends the use of a synthetic brush for cleaning, the thickness of the creosote dictated the use of metal brush to remove the restricting material.

measuring protocols is 11%. For comparison purposes, the manufacturer claims a particulate control efficiency of 70-80%.

Regardless of the percent difference between the two PM measuring methods, the TEOM provides more insightful data with regard to ESP performance due to the 1-minute data intervals. This is especially helpful when comparing ESP performance during burn phase changes. The phase results from the TEOM data are displayed in Table 3 and visually displayed in Figure 6. As can be seen there, test run ESP 3 in which the device errored out is an outlier compared to the other three runs (ESP 1, ESP 2, and ESP 4). ESP 3 was a valid test and reflects what can happen to device performance and emissions due to excessive build-up of creosote (discovered after the test). In the Startup phase of ESP 3, the device emitted more than 17 times the amount of PM than was emitted by the stove on average during the Baseline testing. While later phases show a net reduction from Baseline levels, the total removal efficiency in ESP 3 is only 31% versus the tabulated 73% for the average of the other three test runs. In contrast, the table and figure show that test runs ESP 1, ESP 2 and ESP 4 are relatively consistent in emission rates from the device and removal efficiencies both overall and by phase. The average of these three runs describes what can be called “normal performance” but it must be realized that the discrepant performance in ESP 3 is still possible in field service.

As can be seen in Table 3, the average PM removal efficiency of the ESP across the three runs is lowest (33%) in the Startup phase, which may be due to the ESP’s delayed operational start at a time which tends to show elevated emissions³. The ESP was most effective during the Maintenance Fire phase where the PM removal efficiency averaged 92% across the three test runs. Its performance was intermediate (69%) in the High Fire phase and second lowest (49%) in the Overnight Fire phase.

³ 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, it was observed that the ESP was activated when the stack temperature approached 100°F.

Table 1. Non-Catalytic Stove 9 PM Testing

Filter Test Results									
Test ID	Baseline 1*	Baseline 2	Baseline 3	Baseline 4	Baseline 5	ESP 1	ESP 2	ESP 3	ESP 4
Date	2/4/20	2/6/20	2/25/20	2/26/20	2/27/20	2/11/20	2/12/20	2/13/20	3/3/20
Average Dilution Tunnel flow (cfm)	491	503	521	521	517	530	516	521	526
Average Sampling Rate (cfm)	n/a	0.112	0.118	0.116	0.109	0.119	0.116	0.112	0.114
Total PM Emissions (g)	n/a	24.56	343.83	197.94	363.42	81.00	155.08	299.18	102.26
Test Duration (min)	n/a	390	592	539	673	592	827	611	577
PM Rate (g/hr.)	n/a	3.78	34.85	22.03	32.40	8.21	11.25	29.38	10.63
Uncertainty of Filter Emissions Et +/- @ 95% confidence (g)		2.30	8.02	4.99	8.48	2.95	4.16	7.12	3.26
Uncertainty of Filter Emissions Et in +/- (%)		9	2	3	2	4	3	2	3
Baseline 1* Invalid test run, had difficulty with the stove and did not have filter data.									

Table 2. Non-Catalytic Stove 9 Average ESP Particulate Control Efficiency at Reducing PM

Filter / TEOM Comparison																
Test ID	Baseline 1	Baseline 2	Baseline 3	Baseline 4	Baseline 5	ESP 1	ESP 2	ESP 3	ESP 4	Average Baseline**	Average ESP***	Average Efficiency	Baseline Standard Deviation**	Baseline, % CV**	ESP Standard Deviation***	ESP % CV***
TEOM PM (g/hr)*	14.89	3.25	29.35	18.51	26.74	5.59	7.11	17.16	7.22	24.87	6.64	73.3	4.6	18.6	0.7	11.2
Filter PM (g/hr)	n/a	3.78	34.85	22.03	32.40	8.21	11.25	29.38	10.63	29.76	10.03	66.3	5.6	18.7	1.3	13.1
Percent Difference (%)		14	16	16	17	32	37	42	32	16	34	11	-	-	-	-

*Negative TEOM values were set to 0 per TEOM protocol
 **Does not include Baseline 1 and Baseline 2 because they used a different startup procedure
 ***Does not include ESP 3 where ESP was not functioning

Table 3. Non-Catalytic Stove 9 Average PM Rates Per Burn Phase – TEOM Only

IDC Breakdown PM in g/hr* - TEOM Only														
	Baseline 1	Baseline 2	Baseline 3	Baseline 4	Baseline 5	ESP 1	ESP 2	ESP 3	ESP 4	Average Baseline g/hr**	Average ESP g/hr***	Baseline Avg. % of Total PM	ESP Avg, % of Total PM	% Average Efficiency
Startup	6.14	3.20	4.03	10.73	4.83	4.31	3.83	112.03	4.91	6.53	4.35	2.0	4.3	33.4
High Fire	20.25	1.80	23.13	13.07	30.91	5.18	6.30	20.22	9.14	22.37	6.87	19.1	23.7	69.3
Maintenance Fire	27.25	3.02	47.95	43.64	40.57	1.77	5.66	16.58	2.65	44.05	3.36	48.9	12.8	92.4
Overnight Fire	7.54	4.10	26.14	6.18	20.86	9.00	8.70	9.53	9.54	17.73	9.08	29.9	59.2	48.8

*Negative TEOM values were set to 0 per TEOM protocol
 **Does not include Baseline 1 and Baseline 2 because they used a different startup procedure
 ***Does not include ESP 3 where ESP was not functioning

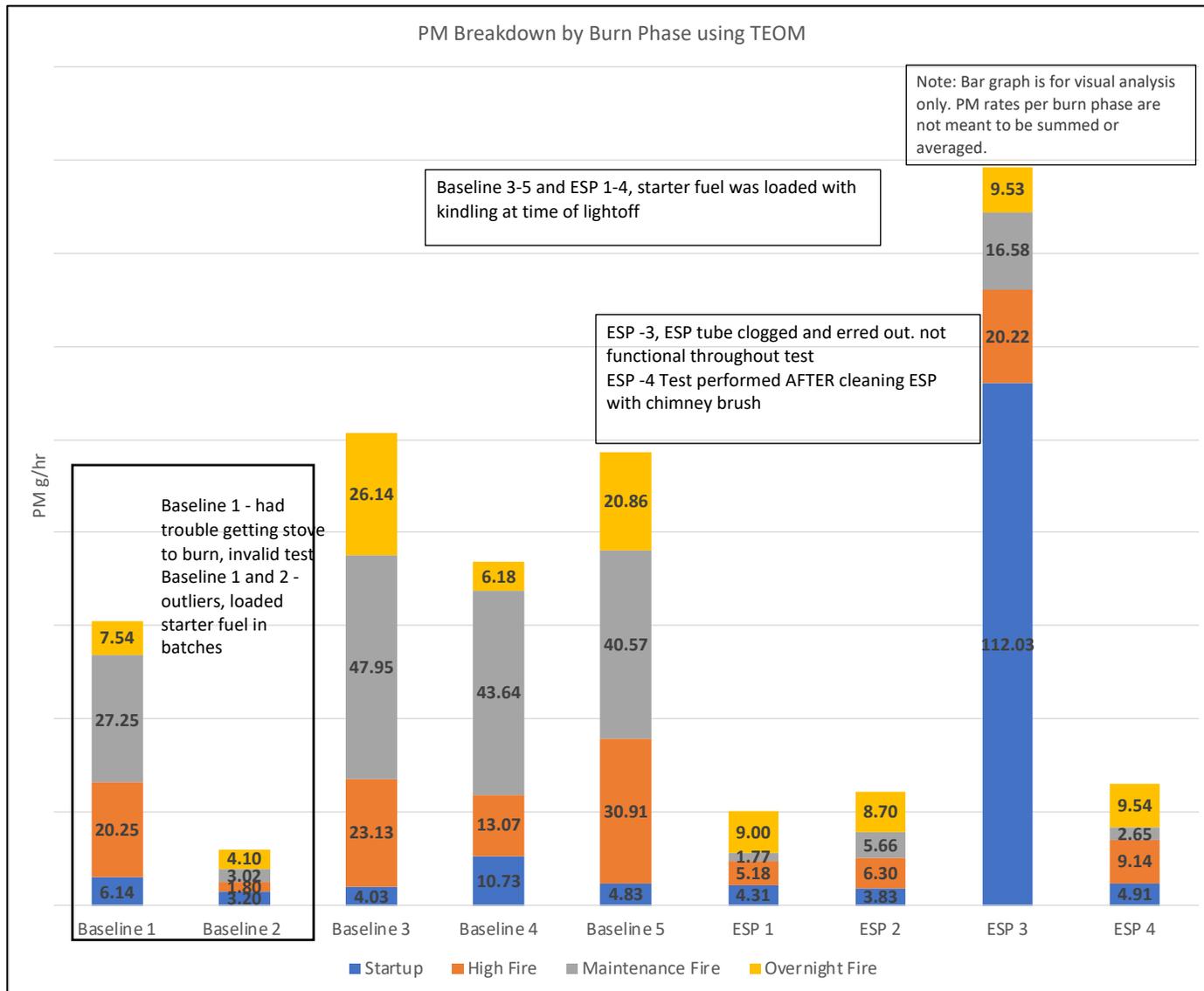


Figure 6. Non-Catalytic Stove 9 PM Phase Comparison

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 Consultants on behalf of the Alaska Department of Environmental Conservation (ADEC) and is included in this report at the request of ADEC; an explanation of the methodology and graphs for all ESP tests is presented in Appendix G. Test run ESP 4 was selected as representative of the ESP's overall performance in the testing and, specifically, of device performance with a light creosote coating lining the ESP walls. Figure 7 shows Baseline and Post-ESP emission rates along with EPS power⁴ and arcing events⁵ for the entire test cycle. Average Baseline emissions from the stove (dashed red line) were not measured concurrently with emissions out of the ESP. The baseline is shown for reference as an approximate indicator of stove emission levels, but it does not represent stove-out emissions *during* the ESP test and, thus, does not match up minute by minute with Post-ESP emissions.

⁴ 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.

⁵ 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.

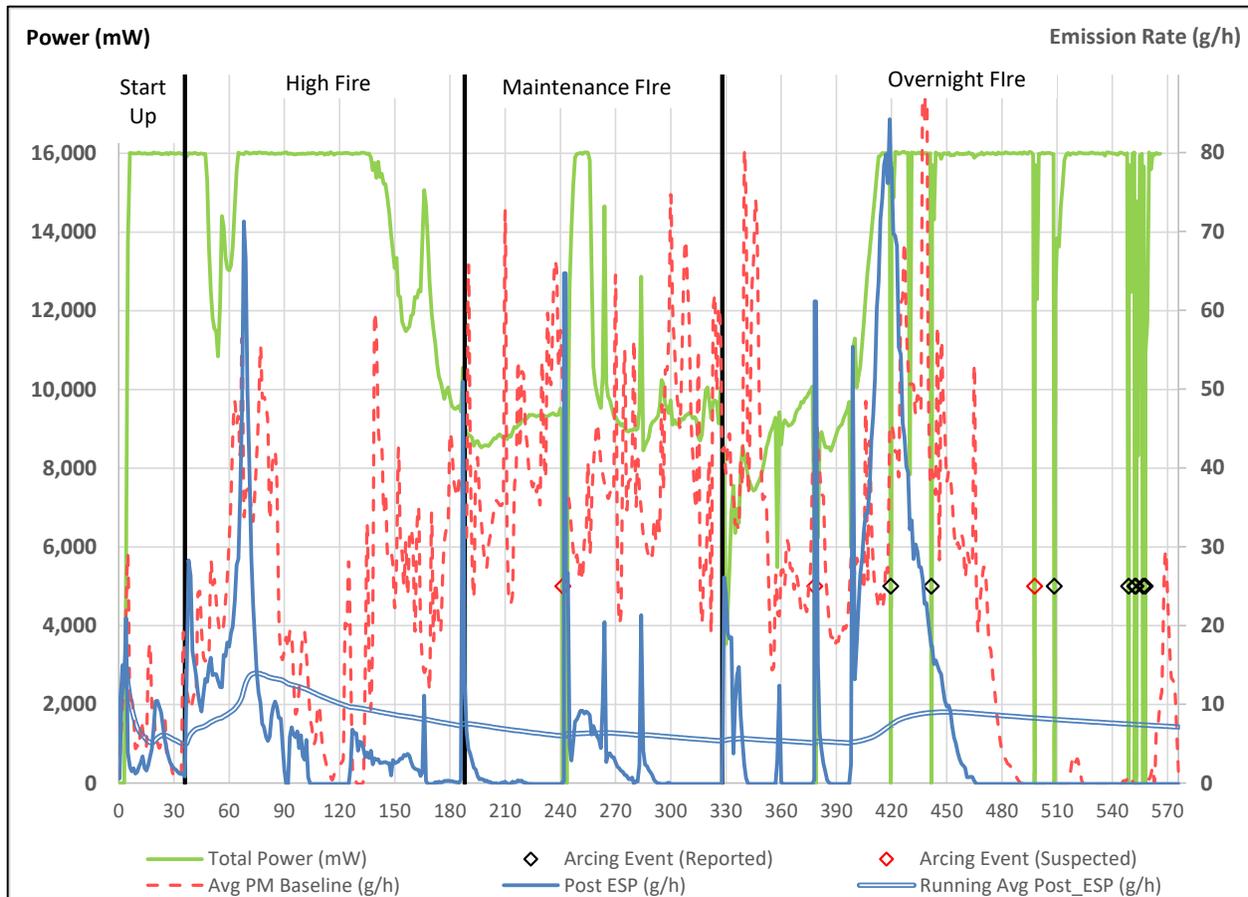


Figure 7. Non-Catalytic Stove 9 with ESP, Run 4, Entire Run (minutes 0 -575)

As seen in Figure 7, the ESP powers up during minute 4 of the test (green line) and remains there through the end of Startup at minute 35. Post-ESP emissions are reduced once the ESP powers on. There is an uptick of PM emissions (blue line) at the start of the High Burn phase when the stove is reloaded. ESP power drops below full-power between minutes 48 and 63 during which emissions rise consistently until the device returns to full power and good emission control is restored. Running average PM emissions (double blue line) continue on a decline course into and through the Maintenance Fire phase. The ESP operates below full power but successfully limits emissions to an average to 6 g/hr. since the start of the test.

This level of performance continues into the start of the Overnight Fire phase, but is interrupted at minute 240 by the first in a sequence of arcing events (8 Reported and 3 Suspected). The first is associated with a spike in emissions from the ESP that nearly reaches the highest level of emissions observed during Baseline testing. Cumulative PM emissions tick up during the initial arcing events but decline thereafter to zero levels to end up at an average rate of 7.2 g/hr over the entire test. In this phase, ESP performance is reduced somewhat by arcing events compared to the Maintenance Fire phase

A key finding from the testing is that the ESP performs relatively well on the non-catalytic cordwood stove as long as an excessive build-up of creosote is not present. During such operation, it is successful in reducing total PM emissions to 7.2 g/hr. compared to average (uncontrolled) stove emissions of 24.9 g/hr. during Baseline testing. One limiting factor is the 4-minute delay at the start of the test before the ESP begins to operate, which is determined by the device's design. A second limiting factor is the occurrence of arcing during the Overnight Fire phase. However, when creosote builds up to excessive levels, the ESP suffers a significant degradation in removal efficiency as evidenced by test run ESP 3.

5.2 Stove 19 – Catalytic

There were two baseline tests and three ESP test runs completed between March 10th and March 20th, 2019 using the modified and shortened IDC protocol described in Section 3. Results from Baseline 1 and ESP 1 have been excluded from averages for determining ESP particulate control efficiency as displayed in Table 4 and Table 5.

By use of thermostatically controlled technology, this particular stove was designed to operate at low burn conditions for long periods of time without a visible flame and while still maintaining an activated catalyst. In Baseline 1, it was determined during the test that technicians may have actually influenced the stove operation in a negative way by making fuel adjustments in order to achieve a yellow flame. Therefore, after this test, the IDC protocol was revised to include no fuel adjustments unless there is no weight change for a period of at least 15 minutes. This revision rule was used for all tests moving forward after Baseline 1. ESP 1 test run was not included in the results because it followed a different protocol measuring PM in the stack through use of another test method but was not used moving forward for ESP test runs.

For all test runs, the average PM rate was under 5 g/hr. using the shortened IDC protocol. When looking at the individual phases in Table 5 and visually in Figure 8, it was evident that the ESP had the least influence during Startup (8.9%), where PM emissions were higher than High Fire and Maintenance Fire phases for test runs both with and without an ESP. This can be explained by both the catalyst and ESP being inactive during the beginning portion of this phase. The catalyst has to be heated to activation temperature from a cold start to be operational and until then the gases bypass the catalyst through a manual mechanism. The ESP remains inactive until a temperature differential in the stack triggers the powering of the electrode. Technicians have observed that the ESP was activated when the stack neared 100°F from ambient.

As Figure 8 demonstrates, Startup emissions account for the large majority, (> 85%) of the overall test emissions. In this phase, the ESP achieves a removal efficiency of only 8.9%. Stove emissions drop

significantly once the catalyst reaches light off temperature after startup. Thus, the later High Fire and Maintenance Fire phases combined account for less than 15% of overall emissions. Given this, even a 50% ESP removal efficiency in these phases does little to further reduce PM emissions and so makes little contribution to overall PM control.

Figure 9 illustrates this clearly using test run ESP 3 which was most representative of the average ESP performances. Post-ESP emissions (blue line) were very high in the first few minutes of the test. By minute 16, post-ESP emissions fall to emission levels comparable to a pellet appliance, suggesting that the catalyst has reached light-off. The ESP powers on (green line) during minute 24 of the test, but with post-ESP emissions already relatively low the emission reductions achieved are over shadowed by the uncontrolled high start-up emissions. PM emissions tick up at the start of the High Fire and Maintenance Fire phases when the stove is reloaded, but there is a low level of Baseline (uncontrolled) PM emissions during those phases. The two arcing events during the High Fire phase have no detectable impact on PM emissions, unlike the non-catalytic stove tested. This may be due to the low PM emissions into the ESP due to the action of the catalyst combined with only small amounts of PM adhered to the ESP walls because of the catalytic stove's inherently low level of emissions.

⁶ Figures 7 and 9 are drawn from the work by Rincon Ranch Consulting to create a basis for understanding the performance of the ESP device.

Table 4. Catalytic Stove 19 Average ESP Particulate Control Efficiency

TEOM Comparison								
	Baseline 2	Baseline 3	ESP 2	ESP 3	ESP 4	Average Baseline*	Average ESP**	Average Efficiency
TEOM PM (g/hr)*	2.38	4.17	1.86	3.56	4.25	3.27	3.22	1.55
Average Dilution Tunnel flow (cfm)	539	525	519	530	531			
Test Duration (min)	478	231	222	216	238			

*Negative TEOM values were set to 0 per TEOM protocol

Table 5. Catalytic Stove 19 Average ESP Particulate Control Efficiency

IDC Breakdown PM in g/hr* - TEOM Only						Average Baseline g/hr**	Average ESP g/hr**	Baseline Avg. % of Total PM	ESP Avg. % of Total PM	% Average ESP Efficiency
	Baseline 2	Baseline 3	ESP 2	ESP 3	ESP 4					
Startup	21.10	17.31	9.16	18.06	25.27	19.21	17.50	85.4	91.0	8.9
High Fire	0.34	0.31	0.18	0.11	0.14	0.32	0.14	8.5	3.7	56.0
Maintenance Fire**	1.17	2.88	1.32	0.62	1.27	2.02	1.07	6.1	5.2	47.0
Overnight Fire (Not part of test)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

*Negative TEOM values were set to 0 per TEOM protocol

**Maintenance fire was only first 30 min.

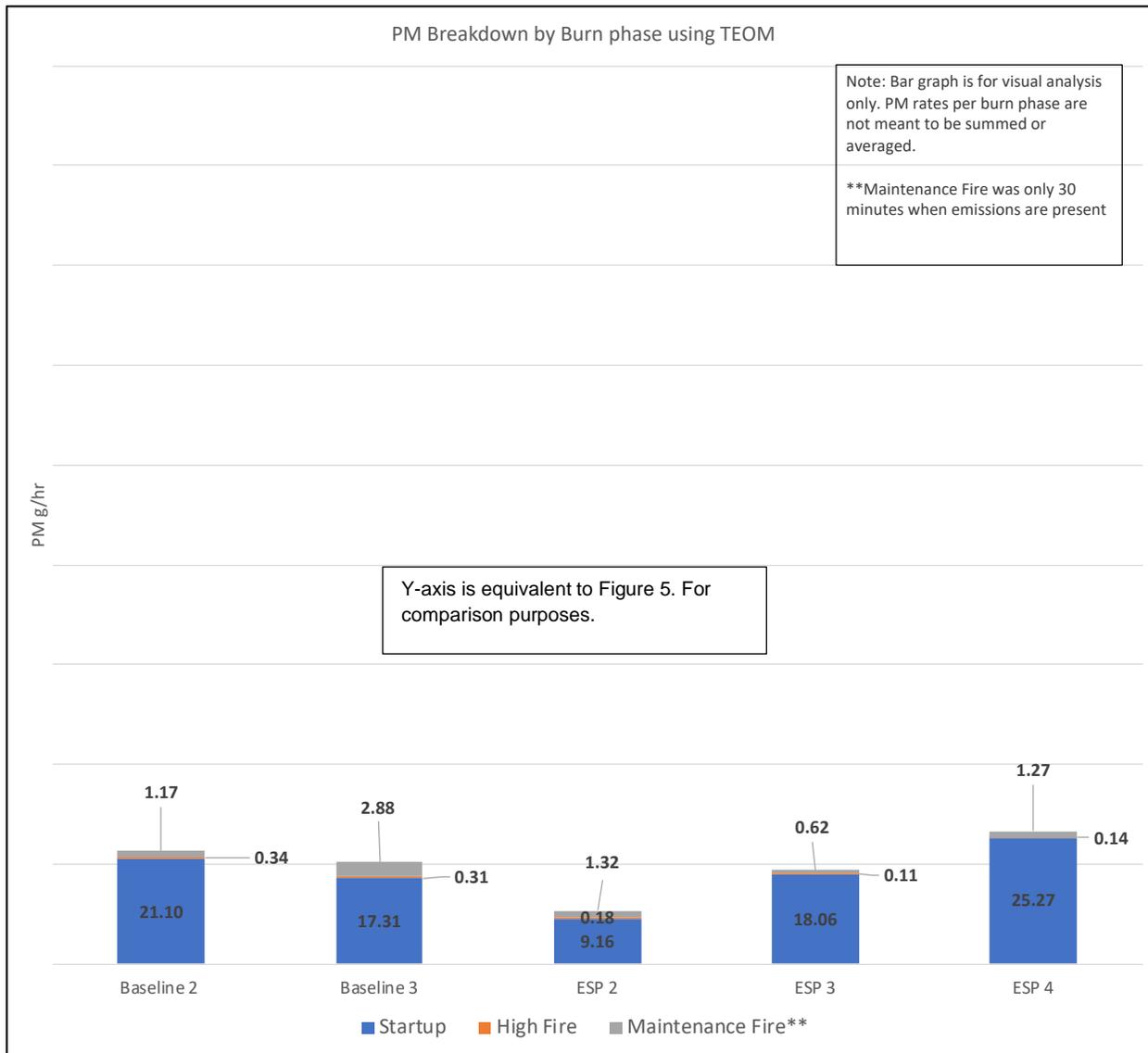


Figure 8. Catalytic Stove 19 PM Phase Comparison

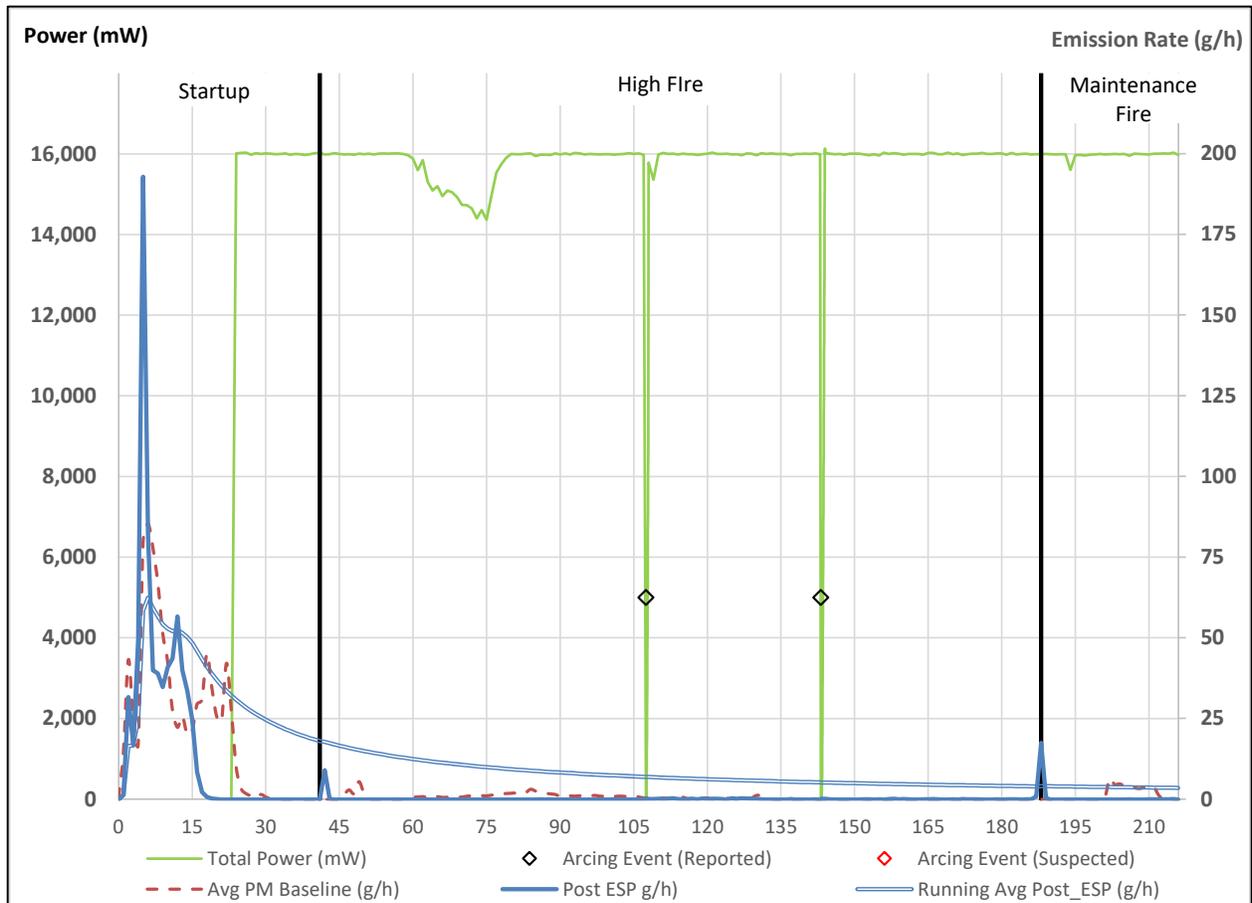


Figure 9 Catalytic Stove 19 with ESP, Run 3, Entire Run (minutes 0-216)

6 ESP Performance Observations

This section is dedicated to observations made while operating the ESP on Stove 9 and Stove 19 that may or may not be PM emission related.

6.1 ESP LED Errors

ESP Test Run 3 was run on February 13th, 2020 on Stove 9, a Step 2 certified cordwood stove. The test began at 7:31 AM. Data collected by the ESP, including power, voltage, error codes, and temperature are stored on a live Excel macro worksheet at 1 second intervals. The maximum voltage at the electrode during steady state should be 30,000 Volts and tends to vary based on stove operation and may drop to 0 briefly during arcing events before ramping back up, which has been observed in previous tests. Around 11 AM a technician observed that the voltage readings were very low. Scrolling through earlier data from the morning, it was observed that the electrode had been functioning at this low voltage for hours. It was not until 2:41 PM that the LED light on the ESP went from solid green (active) to a solid red indicating an error. Despite the error, the ESP continued to operate even at its low functional state instead of shutting down and powering off the electrode. According to the manual, a solid red light could mean a myriad of faults, such as a dirty insulator or insulator box, excessive deposits in the flue, an uncentered electrode, damaged voltage cables, damaged voltage module, or problem with the temperature sensor. Upon removal of the ESP, it was discovered that excessive deposits of creosote had partially restricted flow. See Figure 10, Figure 11, and Figure 12 for pictures of the ESP after ESP 3 test run and then after cleaning. Unfortunately, while trying to review the second by second data in the live feed from the ESP, the macro sheet crashed and data from that event was lost. However, an image of the screen was taken that day by technicians trying to troubleshoot during the test and can be viewed in Figure 13.

By reviewing TEOM PM concentration data it was noticeable that the ESP did not have much of, if any effect at capturing PM while the ESP was poorly functioning as evident in Figure 14. This test run also had the highest PM spike five minutes into the test at 1,202 g/hr., therefore, it is possible that the ESP was not functioning the entire test run or it is also possible that this high PM emitting start was the final event that affected the ESP in a way that it no longer could function to capacity. Unfortunately, without the ESP data we cannot provide a definitive reason.

This buildup was after three cordwood test runs for a total of 34 hours. After cleaning the ESP, a black tacky thin coating remained clinging to the ESP walls. Technicians were instructed to clean the ESP in a way that would mimic what a typical homeowner may be capable of and have available in their home.

Therefore, we used a wire chimney brush down the sides of the walls. Technicians could have used a lab grade acetone or other reagent to try to remove the tacky hard coating on the walls, but it was not recommended in the user manual and it was decided that this was not something a typical user may think to do on their own.



Figure 10. ESP Failure Picture 1



Figure 11. Amount of Buildup that Came Out



Figure 12. ESP After Cleaning

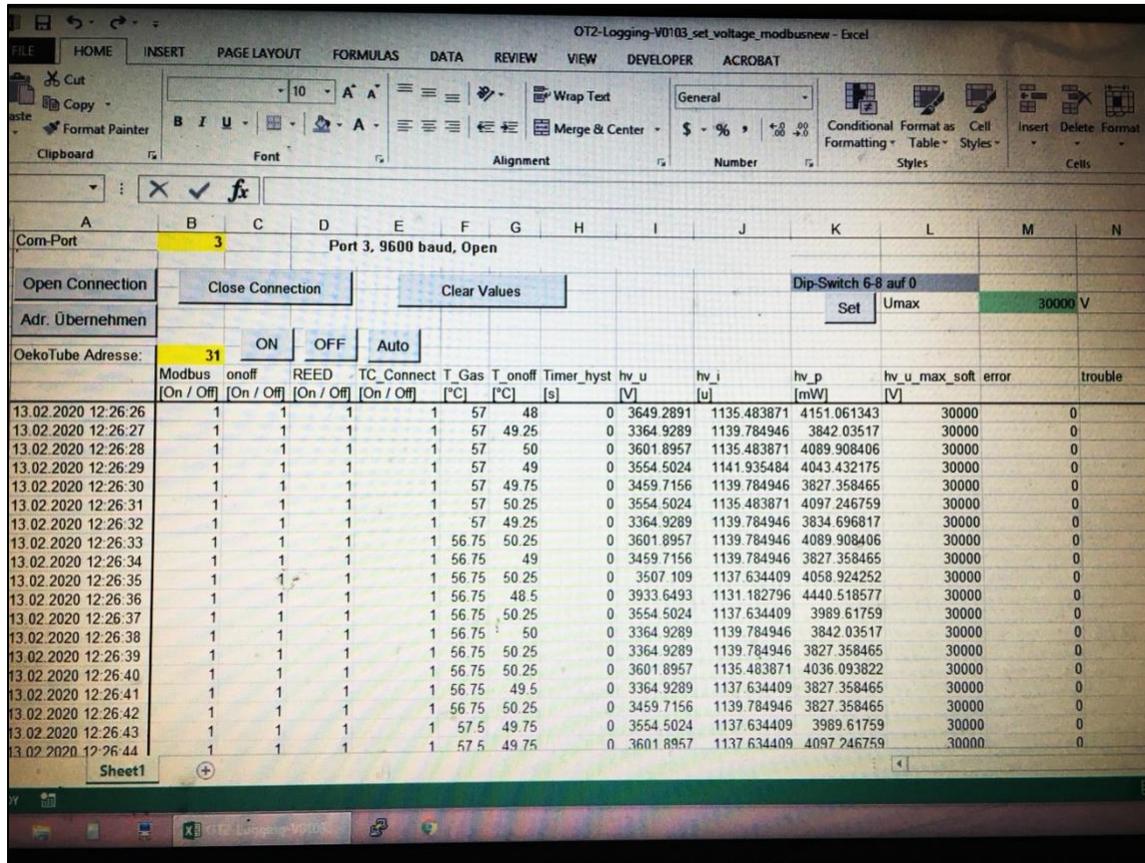


Figure 13. ESP Macro Worksheet Snapshot Feb 13, 2020

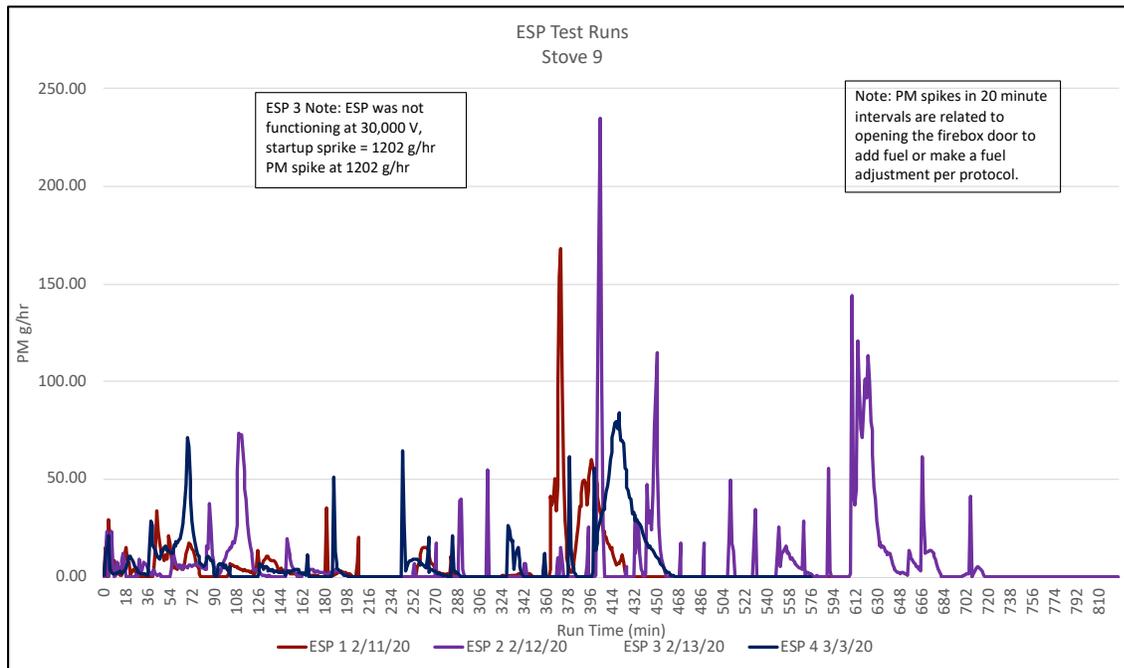


Figure 14. Non-Catalytic Stove 9 ESP Test Runs PM Rates

6.2 ESP Differential Temperature Control

Technicians observed that sometimes the ESP would go inactive during the tail end of a phase or shortly after the beginning of a new phase during testing of Stove 19. Stove 19 is designed to burn long and slow during a low demand burn, like in the Maintenance Fire phase. This slow burn allows the Stove 19 to operate at low stack temperatures. It is possible that a decreasing stack temperature rate or low steady stack temperature may trick the ESP logic into thinking that the fire has gone out and signal the ESP to power down. This is important to note because it is possible that the ESP could potentially fail to capture PM emissions during transitional periods of low to high heat demands with low stack temperatures. An example is displayed in Figure 15 .

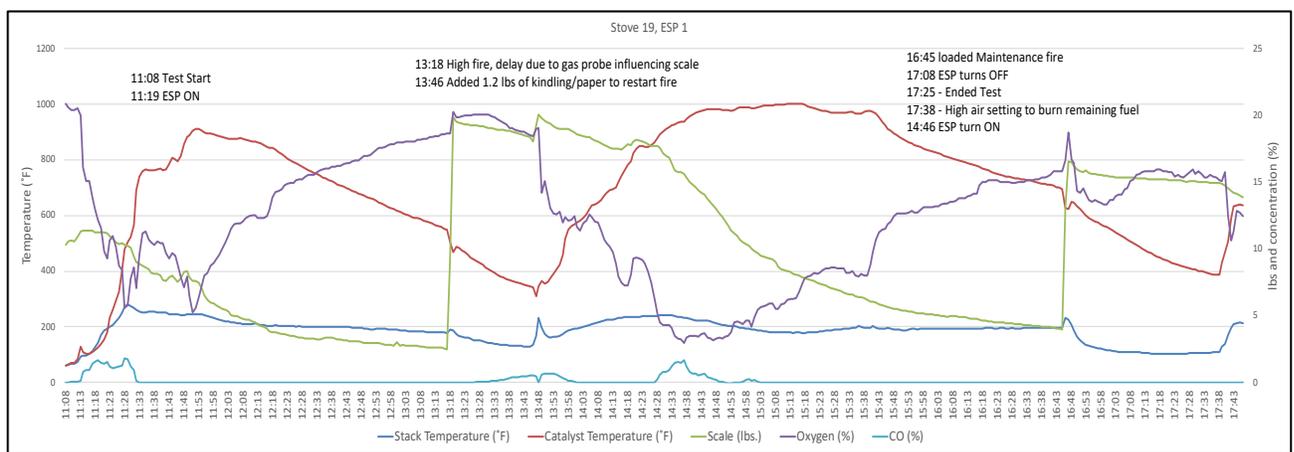


Figure 15. Catalytic Stove 19 ESP Test Run

6.3 ESP Arcing events

During operation, the ESP had electrical arcing events that would not be visible to the user unless reviewing ESP data or live TEOM data. ESP arcing events are recorded as trouble code and voltage drops to 0 immediately for a brief second before climbing back up to maximum operating capacity. Micro-arcing events, when voltage does not drop to 0 signaling an error code to document the event, are less obvious, but can be observed by inconsistencies in the power of the ESP. Such events, arcing or micro-arcing, are random and cannot be predicted. By observing live TEOM data, ESP arcing events may coincide with spikes in PM concentration.

7 Recommendations for Future Research

ClearStak recommends future testing should focus on using multiple cordwood appliances and use multiple ESP models to further investigate the particulate control efficiency of the ESP. Using multiple stove models will provide a more accurate range of ESP performance based on a large variability of operation among different appliances as well as with replicates of the same appliance. Using multiple ESP models during testing will help determine how reproducible the ESP is and make variability within operation from model to model known.

8 Quality Control and Assurance Procedures and Results

8.1 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 D.

9 Appendices

Appendix A. OekoTube ESP Installation Guide

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

Appendix C. *Particulate Matter Emission Measurement Methods*

Appendix D. Instrumentation Calibrations

Appendix E. Datasets Per Test Run

Appendix F. ESP Software Data

Appendix G. Analysis of Device Performance