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## Effect of Thermal Storage on the Performance of a Wood Pellet-fired Residential Boiler

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***Effect of Thermal Storage on the Performance of a Wood  
Pellet-fired Residential Boiler***

**Brookhaven National Laboratory  
Sustainable Energy Technologies Department  
Energy Conversion Group**

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## Abstract

Interest in the direct use of biomass for thermal applications as a renewable technology is increasing as is also focus on air pollutant emissions from these sources and methods to minimize the impact. This work has focused on wood pellet-fired residential boilers, which are the cleanest fuel in this category. In the residential application the load varies strongly over the course of a year and a high fraction of the load is typically under 15% of the maximum boiler capacity. Thermal storage can be used even with boilers which have modulation capacity typically to 30% of the boiler maximum.

One common pellet boiler was tested at full load and also at the minimum load used in the U.S. certification testing (15%). In these tests the load was steady over the test period. Testing was also done with an emulated load profile for a home in Albany, N.Y. on a typical January, March, and April day. In this case the load imposed on the boiler varied hourly under computer control, based on the modeled load for the example case used.

The boiler used has a nominal output of 25 kW and a common mixed hardwood/softwood commercial pellet was used. Moisture content was 3.77%. A dilution tunnel approach was used for the measurement of particulate emissions, in accordance with U.S. certification testing requirements.

The test results showed that the use of storage strongly reduces cycling rates under part load conditions. The transients which occur as these boilers cycle contribute to increased particulate emissions and reduced efficiency. The time period of a full cycle at a given load condition can be increased by increasing the storage tank volume and/or increasing the control differential range. It was shown that increasing the period strongly increased the measured efficiency and reduced the particulate emission (relative to the no storage case). The impact was most significant at the low load levels.

Storage tank heat loss is shown to be a significant factor in thermal efficiency, particularly at low load. Different methods to measure this heat loss were explored. For one of the tanks evaluated the efficiency loss at the 15% load point was found to be as high as 7.9%. Where storage is used good insulation on the tank, insulation on the piping, and attention to fittings are recommended.

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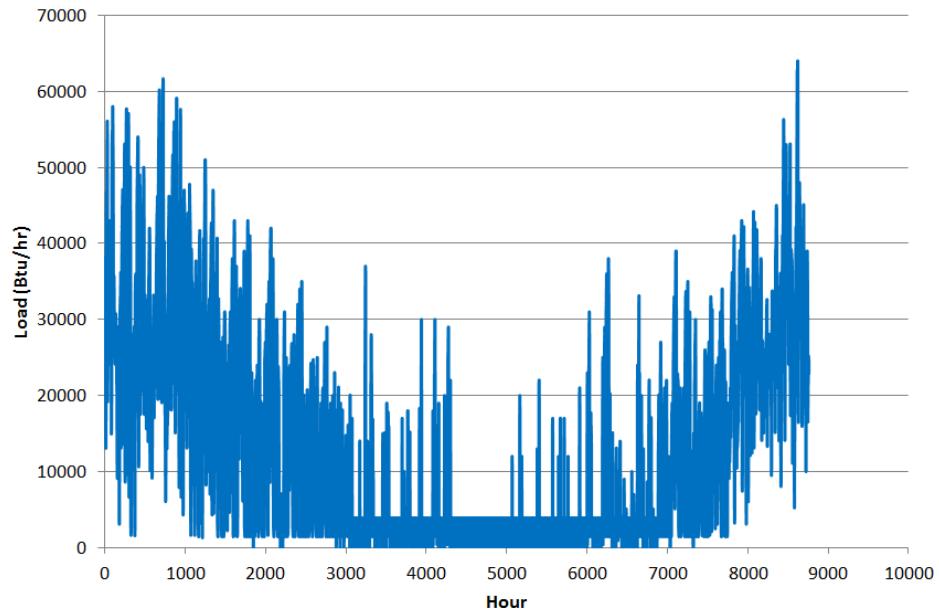
## Introduction

Increased direct use of biomass for heating applications in the U.S. offers significant promise including reduced use of imported fuels, regional job creation, reduced end user energy expenditures, and reduced climate impact. The scope of interest here includes cordwood, wood pellets, wood chips, potentially crop residues used in space heating stoves, central heating boilers, and warm air furnaces. The applications include homes, commercial and institutional buildings, and industrial applications. Over the past 10 years, the use of biomass fuels for such heating applications has been increasing [1].

In New York State, the Renewable Heat New York Program has been developed to support the growth of direct biomass heating [2]. There is clear recognition, however, that the combustion technologies traditionally used have higher emissions of air pollutants such as particulates, carbon monoxide, and hydrocarbons relative to oil and gas fueled heating systems. There is a critical need to ensure that the growth of biomass direct heating is done using technologies and fuels which do not create negative regional air quality impacts [1].

Of the fuels included, wood pellets typically have the lowest emissions [3, 4]. Pellets are drier, have a high surface to volume ratio, and can be fed into the combustion zone automatically in response to heating load roughly like oil and gas fuels. Pellet-fired boilers currently available on the market typically have the ability to modulate firing rate to 30% of the maximum. In residential applications, this modulation capability is important because heating load varies strongly during the year. However, this modulation capability is not adequate to avoid the need for these systems to cycle. For significant parts of the year the heating load is well below 30% of the maximum heating load. In addition, systems are typically oversized, leading to a large fraction of the year having a heating load under 30% of the boiler's maximum capacity[5].

Under cycling conditions, pellet boilers undergo start and shut down operations which may be expected to have higher air pollutant emissions than under steady state. The rate of cycling under a low load condition can be reduced through the use of thermal storage and many manufacturers now specify storage should or must be used with pellet-fired boilers. To illustrate this further, Figure 1 shows the results of an annual load analysis of a 2500 ft<sup>2</sup> ranch home located in Albany, N.Y.. This includes domestic hot water and so there is significant summer load on the system. This simulation was done using Energy 10 software. For this same case, Table 1 provides results of an analysis of the percentage of annual hours the load on the boiler is in different categories as a function of oversize factor, "OF". The oversize factor is the output capacity of the boiler divided by the maximum heating load on the building. The oversize factor of 1.7 has been historically used as the typical U.S. factor for heating systems.



**Figure 1 Annual distribution of heating load for a 2500 ft<sup>2</sup> home in Albany (simulation). Includes both heat and domestic hot water load.**

Table 1. Distribution of Annual Operating Hours Based on Oversize Factor (OF). 2500 ft<sup>2</sup> Ranch home in Albany New York.

| Load Range <sup>1</sup> | % of Annual Hours in Load Range |                      |                      |
|-------------------------|---------------------------------|----------------------|----------------------|
|                         | OF <sup>2</sup> =1.0            | OF <sup>2</sup> =1.7 | OF <sup>2</sup> =3.0 |
| <15%                    | 54                              | 62.1                 | 83                   |
| 16-25%                  | 8.3                             | 17.9                 | 15.4                 |
| 25-50%                  | 24                              | 20                   | 1.6                  |
| 50-100%                 | 13.9                            | 0                    | 0                    |

1. Load Range is based on a percentage of the boilers rated output capacity.
2. OF = Oversize Factor. Boiler output capacity divided by the homes maximum space heat demand.

In this study an examination of the performance of a modern wood pellet-fired residential heating boiler under different load conditions and with different levels of thermal storage has been completed. The objectives are to improve understanding of the cycling behavior of such a boiler and to quantify the effects of thermal storage under different load conditions. Currently, in the U.S. there isn't an accepted test method for evaluating the thermal efficiency and

emissions of an automatic-feed boiler (e.g. pellet or chip fueled) when integrated with thermal storage. Part of the motivation of this work was to develop experience and data which would provide a foundation for the development of such a test procedure.

## Experimental

### Boiler Description

The boiler used during the experiments was a residential wood pellet boiler with a nominal rated output capacity of 85,000 Btu/hr (25 kW). This boiler has a 10 gallon water capacity the manufacturer recommends use with a 119 gallon thermal storage (“buffer”) tank. The boiler is operated with a microprocessor controls with full text menus. The boiler is equipped with a lambda sensor in order to measure residual oxygen and adjust fuel feeding rates accordingly. Technical specifications include a secondary fan, exhaust fan, automatic ignition, automatic ash cleaning, a stainless steel firebox and a drop grate system.

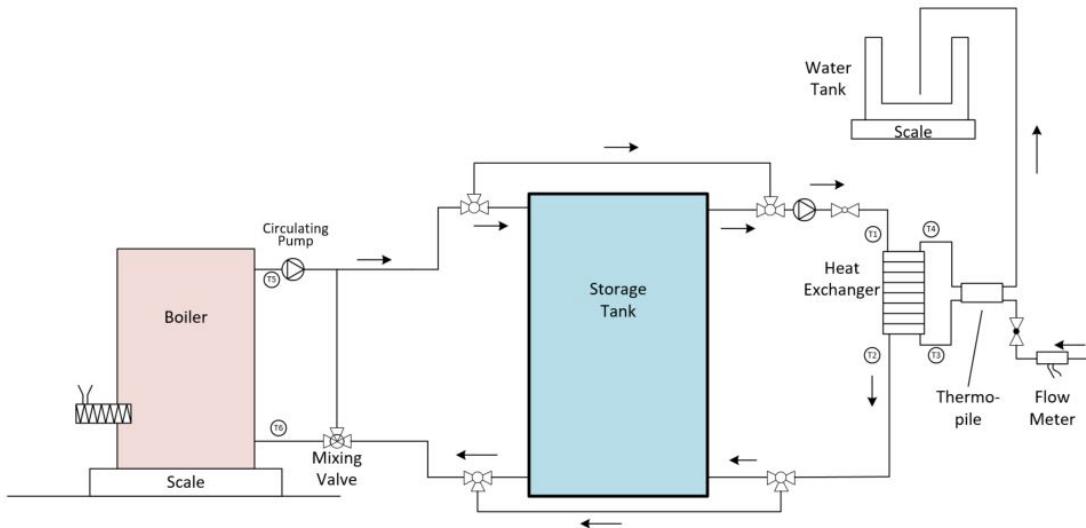
### BNL Lab Facilities

Figure 2 provides a sketch of the boiler hydronic setup in the lab. The boiler is installed on a weigh scale and has a small capacity pellet feed hopper attached so that the fuel burn rate can be directly determined from the mass change. This hopper may be refilled during test runs, depending on the load and cycling pattern. As per the manufacturer’s installation instructions the boiler has a piping loop with a mixing valve to ensure that cold water, below 130°F, does not return to the boiler. The system, as shown, includes a storage tank and the piping is arranged so that the flow from the boiler can either go into the storage tank or bypass the storage tank flowing directly to the load heat exchanger. This enables testing both with and without thermal storage. The heat exchanger consists of two plate type heat exchangers in parallel inside of a foam insulated box. On the other or open side of the heat exchanger cold “city” water flows at a controlled rate to impose the target load. Flow rate is controlled and measured using a Belimo model epiv control module. From the heat exchanger the cooling water is directed to a weigh scale located on the floor above for a direct mass measurement of the cooling water flow rate. The 50 gallon tank on the weigh scale must be periodically emptied and the flow meter output is used during these brief times to determine flow rate for energy output purposes.

The flow rate to the load heat exchanger was adjusted to provide a temperature drop across the heat exchanger of 20°F (supply-return) to approximate the performance expected in the field. The concern here was largely avoiding high flow rates which could unrealistically de-stratify the storage tank. Under variable load conditions this flow rate was set at a high output condition at the highest temperature observed during cyclic operation. This would give lower temperature changes at lower output and temperature conditions.

Table 2: Manufacturer's Specifications for the Test Boiler

| Component                    | Units               | P28                             |
|------------------------------|---------------------|---------------------------------|
| Rated output                 | kW<br>(Btu/hr)      | 24.9 (85,000)                   |
| Minimum Modulation           | %                   | 30                              |
| Efficiency                   | %                   | 85 (Higher Heating Value basis) |
| Consumption at max load      | lb/h<br>(kg/h)      | 7.3<br>(3.31)                   |
| Consumption at part load     | lb/h<br>(kg/h)      | 2.09<br>(0.95)                  |
| Max adjustable boiler temp   | °F (°C)             | 185 (85)                        |
| Permitted operating pressure | psig<br>(bar)       | 44.1<br>(3)                     |
| Total weight                 | lb (kg)             | 480 (218)                       |
| Boiler width                 | in (mm)             | 23.6 (600)                      |
| Boiler depth                 | in (mm)             | 29.9 (760)                      |
| Boiler height                | in (mm)             | 40.7 (1035)                     |
| Vent connector diameter      | in (mm)             | 5.9 (150)                       |
| Water content                | gal (L)             | 10.0 (38)                       |
| Ash box volume               | ft <sup>3</sup> (L) | 0.97 (27.5)                     |
| Flow connection              | inch                | 1 NPT                           |
| Return connection            | inch                | 1 NPT                           |
| Electrical supply            | V                   | 230                             |



**Figure 2 Test arrangement in BNL lab**

Two different storage tanks were used during this project one with 119 gallons of storage and the second with 210 gallons of storage. The smaller of these two tanks represents the manufacturer's specified storage volume for this unit. The larger tank was tested to evaluate the impact of increasing the storage volume.

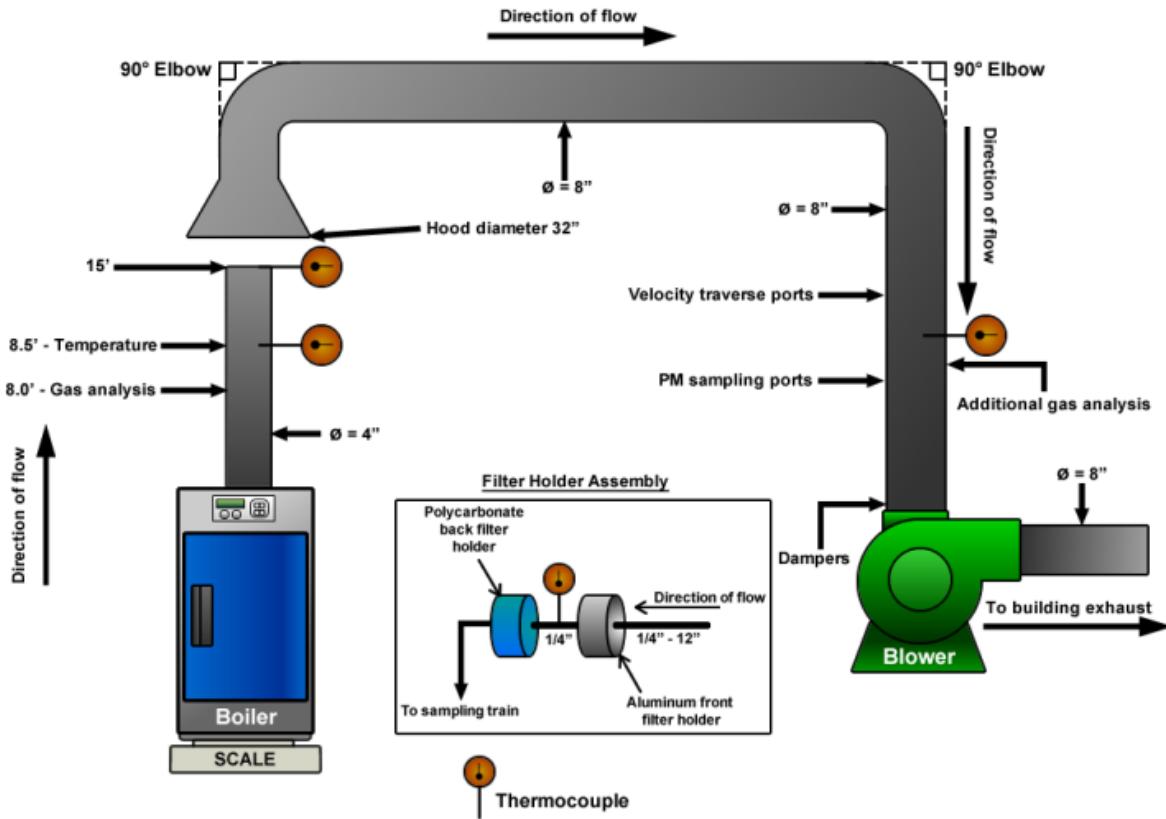
The weigh scale upon which the boiler sits has a rated capacity of 6,000 lbs. and a resolution of 0.2 lbs. Annual calibration to NIST-traceable standards is done by a commercial contractor as part of a BNL-wide scale calibration program. Figure 3 provides a photo of the test boiler and one of the storage tanks tested.



**Figure 3 Photo of 25 kW pellet boiler as tested and 119 gallon storage tank**

#### Dilution Tunnel

The boilers exhaust is connected to a 8" diameter dilution tunnel that collects exhaust gas and mixes it with the room air. The dilution tunnel meets the specifications of ASTM E2515-10 *Standard Test Method for Determination of Particulate Matter Emissions Collected in a Dilution Tunnel*. A pitot tube probe is used to measure dilution tunnel velocity. In the dilution tunnel the gas is cooled and semivolatile organics are condensed to collection on particulate filters downstream. The dilution tunnel also provides nearly constant velocity so that the emission rate of particulates integrated over a transient operating cycle can be determined from average concentration and tunnel flow. Figure 4 illustrates the dilution tunnel arrangement.



**Figure 4 Illustration of the dilution tunnel arrangement**

#### PM Measurements

The particulate emissions were recorded from the dilution tunnel and conducted in compliance with ASTM E2515 -10. The flow in the dilution tunnel is maintained constant throughout the testing and samples are taken then drawn through a filter. In this project both plain 47 mm glass fiber and 47 mm Teflon coated glass fiber filters (Pallflex Emfab TX 40) were used. Filters were conditioned prior to testing in a desiccator and weighted twice over a two day period on a gravimetric balance prior to sampling. Post-test, filters were weighed regularly until weight stabilized (less than 0.2 mg in weight change was determined within a 6 hour period). This mass was then used in the final determination of particulate emissions. Samples were extracted from the center of the dilution tunnel at room temperature with a preset sampling rate. This rate was typically set to 0.2 cubic feet per minute (cfm) which is in the specified range of 0.1 to 0.25 cfm as per ASTM 2515. Particulates were captured in two identical dual-filter EPA method 5 sampling trains which were operated simultaneously. The sampling trains were comprised of two filters in series, each 47 millimeters in diameter which is in accordance to the filter holder assembly conditions put in forth by ASTM E2515.

To remove any previous particulate matter emissions on the probes an acetone rinse was used. Gloves and tweezers were used in all the loading and measuring of any filters and problems to eliminate excess weights from skin contact. Leak tests were also conducted on the sampling

system prior to ignition of the boiler since leaks would decrease the amount of dilution tunnel gas passing through the filters.

Some of the sampling was done integrated over an entire test period. In other tests, sampling was done during discrete phases of operating, for example startup, steady firing, and burnout. When phase sampling was done, train front filters only were changed between phases and this procedure was accomplished typically in less than one minute. Back filters were not changed because the mass collected was negligible and changing these filters would have slowed the filter change process. Any mass collected on the back filter was apportioned to the mass collected on the front filters.

After sampling was completed the mass of the particulate matter on the filters was combined with any additional matter collected on the sampling probes and measured after desiccating the filters and probes over a 24 hour period. Leak checks were also conducted at the end of the test and leakage rates were no more than the acceptable 0.01 cfm however leak tests were not done between sampling periods in order to minimize sampling time lost while changing filters.

One of the two sampling systems used for particulate emission rate measurements was a manual system (Apex Instruments Model 511) and, in this case, flow rate and cumulative volume sampled was recorded at 10 minute intervals. The second sampling system was an automatic unit (Apex Instruments Model XC-5000) which automatically adjusted flow rate to the target value and recorded all parameters at a time interval of 5 seconds. Both samplers used a type K thermocouple for temperature analysis which had an associated error of 2.2° or 0.75%. The automatic sampler and manual sampler had flow rate measurement errors of  $3.53 \times 10^{-5}$  and  $1.25 \times 10^{-3}$  cubic feet and  $\Delta H$  measurement errors of 0.005 and 0.005, respectively.

For some of the testing done with this unit, particulate emissions in the dilution tunnel were measured using a real-time particulate concentration monitor. The unit used was the Wöhler SM500 which is currently used for field in-stack particulate concentration measurements in Germany. This is a Tapered Element Oscillating Monitor (TEOM) – type measurement device and provided, in this project, the opportunity to study particulate emissions during start and stop operation of the pellet boiler.

### Flue Gas Analysis

Flue gas samples for analysis were taken from the dilution tunnel and directly from the stack, as seen in Figure 4. For sampling from the dilution tunnel, water vapor (7.2 °C dew point) was removed using a thermoelectric cooler/drier with a backup anhydrous calcium sulfate column and a diaphragm sampling pump. Gas analysis in the dilution tunnel included oxygen and carbon monoxide. Analysis of samples from the flue gas included oxygen, carbon monoxide, hydrocarbons, and carbon dioxide and were sampled at 8.0 ft. from the top of the scale. Each gas analyzer was calibrated prior to each test with both nitrogen and the specified calibration

gas. All calibration gases were certification grade from Matheson Tri-Gas Co. and provide an accuracy of 2%.

Carbon monoxide was measured in the dilution tunnel using a Rosemount Analytical model 880 NDIR Carbon Monoxide analyzer. Oxygen was measured in both the dilution tunnel and the hot stack via a Beckman model 755 paramagnetic Oxygen Analyzer. Both oxygen analyzers have a set of four ranges: 10%, 25%, 50% and 100%. Carbon monoxide, carbon dioxide, and hydrocarbons were measured directly in the stack using an infrared analyzer (California Analytics, Model ZRE).

For cooling water flow control and logging of flue gas composition, cooling water flow, boiler scale mass, dilution tunnel velocity, and cooling water inlet and outlet temperatures, a laboratory data acquisition (DAQ) system was used with Visual Basic programming. The signals from all analyzers were logged at a five second intervals. Each gas analyzer had a resolution of 0.1%. The programming allowed for a target heat output rate and cooling water flow was continuously adjusted to achieve the target output. The target load could be constant over the test or a profile could be used with variable target load. To create the target load profile a separate text file was created and loaded into the DAQ program. In testing under this project up to 24 load “steps” were used in some tests, although programs with a much higher number of load steps could be used.

Type K thermocouples were also logged at a five second interval for all temperature measurements which included: stack temperature (8.5 ft. from stove base), top of stack (15 ft.), dilution tunnel, ambient air (laboratory), and in-between the front and back filters in each PM sample probe. The thermocouples were purchased from Omega and have an associated error of 2.2° or 0.75%. Thermocouples were logged on a separate computer via Pico Logger software. Velocity in the dilution tunnel was measured with a Pitot tube and digital pressure gauge made by the Pressure Conservatory. A precision Baratron pressure transducer was used to measure a voltage proportional to the pitot tube  $\Delta P$  and recorded on the lab DAQ system.

### Test Fuel

The fuel used for all tests was wood pellets with an 80% hardwood and 20% softwood composition. The average moisture content of the pellets was 3.77% on a dry basis with 0.67% ash content. The high heat value of the pellets was 8261 Btu/lb. An analysis of the test fuel was done by a commercial test lab and the results are included as Appendix I to this report.

### Test Load Conditions

In this study, two different types of load patterns were used for testing. One was the four steady loads used in certification testing for wood hydronic heaters under EPA methods 28 WHH and 28 WHH PTS [6]. These load categories are listed in Table 3, below.

Table 3. Burn Rate Categories Based on EPA Methods 28 WHH and 28 WHH PTS

| Category I | Category II | Category III | Category IV       |
|------------|-------------|--------------|-------------------|
| <15%       | 16-24%      | 25-50%       | Maximum burn rate |

#### *Cat IV*

The purpose of a Category IV test is to run the boiler at 100% output for a maximum burn rate in order to verify the manufacturers' rated output as well as determining the unit's efficiency and PM emissions. For a category IV test external storage is not necessary since the boiler is operated at full load. In the case of a Category IV test the boiler will be running between 90-100% of full output so no cycling will occur.

#### *Cat I*

The purpose of a Category I test is to run the boiler at burn rate to achieve 15% or lower of the manufacturers rated output. This test is done in order to measure the PM emissions at the low-load levels which is when cycling is often most likely to occur. Category I testing was conducted with and without storage. Without storage the boiler control is set so that the burner fires up until the boiler temperature reaches 85 °C and then starts again when boiler temperature gets down to 60 °C. When storage is implemented the boiler is controlled by the tank temperatures and two different control setting approaches were used in this project. In the first, the control was set so that the burner fires on cooling when the top tank temperature decreases to 68 °C and then stops when the tank bottom sensor rises up to 72 °C. A control change was made in consultation with the manufacturer in order to further decrease the cycling of the boiler by increasing the temperature range of the tank control. With this control change the burner fires on cooling when the top tank temperature reaches 63 °C and then stops when the bottom temperature sensor rises up to 74 °C. This decision about the temperature control settings is quite important as it affect the overall performance. These control settings must be those that the manufacturer will include in the installation and operating instructions and must be the standard conditions under which the unit is sold. The manufacturer, after reviewing the preliminary results felt that the settings on the boilers control as-shipped to BNL were incorrect.

Another factor which can affect the cycling pattern is the temperature change of the water from either the boiler or the tank across the heat exchanger. Too high a flow can destratify the tank, reducing the effective thermal capacity. Again based on discussions with the manufacturer, a decision was made to target a temperature change of 20 °F across this heat exchanger in all tests. This was adjusted using a simple throttling valve in the flow to the heat exchanger (See Figure 1). In some tests this was difficult to achieve because of the strong change in either boiler or storage tank temperature over a profile or cycle. In this case the 20 °F was set with the highest temperature during the typical cycle. At lower temperatures the temperature change across the

heat exchanger would be somewhat lower. Attempting to continuously change the flow to the heat exchanger to adjust this parameter was found to lead to an unstable response of the control loop which functioned to achieve the target output load.

### ***Cat II & III***

In EPA Method 28 WHH the Category II and III tests are optional. The test organization has the option to apply the results of the Category I test, considered to be the more challenging, to the Category II and III cases for the determination of the annual averages of efficiency and emissions. For this reason, testing under these categories was not done under this project.

### ***Emulated Loads***

The second type of load pattern studied involved a much more varied set of patterns intended to emulate expected real field use. To develop these profiles a building heat load analysis program (Energy 10) was used to determine heat loss from a 2500 ft<sup>2</sup> model home located in Albany, N.Y. This software produces the hourly heat demand for 8760 hours of the year. Standard code construction was assumed as well as night temperature setback to 65 °F. Added to the heat load profile was a domestic hot water demand profile for each day. From the energy demand profiles generated in this way, the hourly heat demand profiles seen a typical for each of a January, March, and April day were selected. These profiles are illustrated in Figure 5, below. All of the profiles show a very strong increase in the heat demand in the early morning hours. This is the response of the system from the night setback. The peak heat load is 66,000 Btu/hr and this is set as much by the heat delivery capacity of the baseboard system as by the heat load on the structure. For the January profile, the peak load is higher; approaching 70,000 Btu/hr and this is due to the combination of heat load and domestic hot water load on the selected day. All of the days show a low heat demand in the afternoon as the solar gain reduces the demand on the heating system. In all cases the heat demand becomes very low in the evening as the night setback control becomes activated.

In the BNL lab, using this Visual Basic DAQ program, these profiles were then imposed automatically on the boiler system. This process required a full 24 hours of testing and most of the overnight part of this was done unattended. The concerns with this included PM filter blockage which could require filter changes and the potential need to re-fill the pellet hopper on the scale. Under conditions where this was a concern night operating staff at BNL was trained to perform the necessary operations. For most conditions the profile schedule could be planned so that most of the overnight period involved very low loads and manual operations were not required.

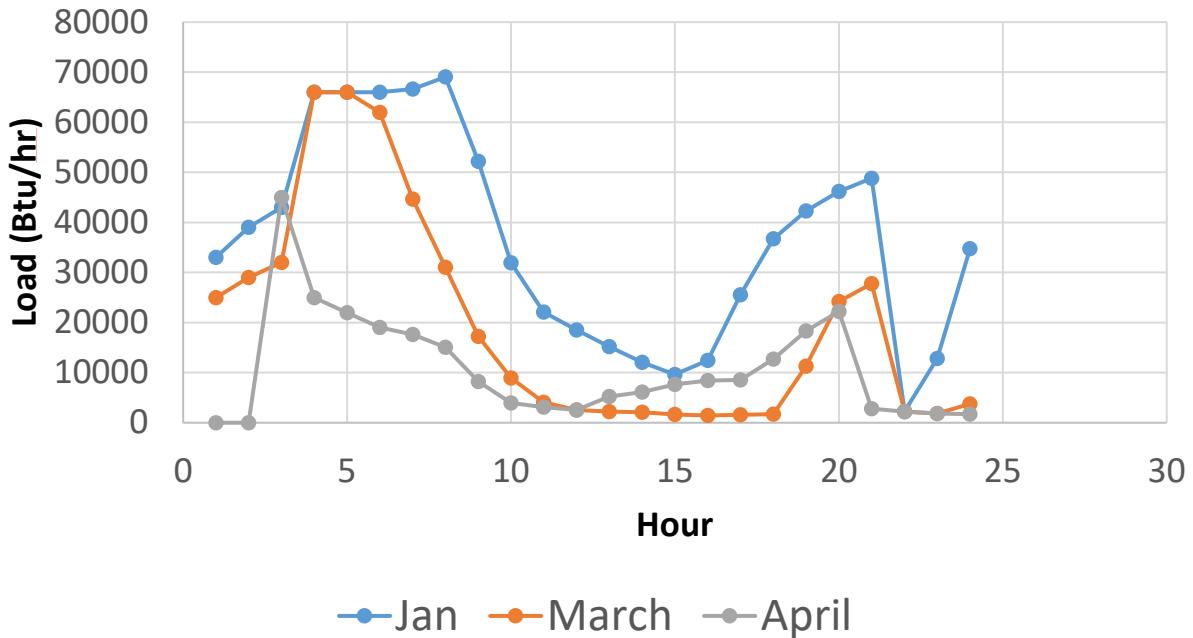


Figure 5 Typical field load profiles for 2500 ft<sup>2</sup> ranch home in Albany, New York.

#### *Tank Idle Loss*

When storage is added to a hydronic heating system lowered efficiency due to tank heat loss comes into question. Tank heat loss testing was conducted in order to determine how the overall efficiency of the system is affected by external storage. Details and results are provided in Appendix II to this report.

## Results

In this section, detailed results of all tests, including both fixed load “Category” tests and the 24 hour emulated load “Profile” tests are presented. Table 4, below provides a summary of all tests conducted to facilitate navigation through all of these tests.

Table 4 Summary of All Test Conditions Included in this Report

| Test Number | Category or Profile | Thermal Storage | Test Date        |
|-------------|---------------------|-----------------|------------------|
| 1           | Category IV         | No              | 8/6/15           |
| 2           | Category IV         | No              | 10/13/15         |
| 3           | Category I          | No              | 8/31/15          |
| 4           | Category I          | No              | 9/21/15          |
| 5           | Category I          | 119 gal         | 8/28/15          |
| 6           | Category I          | 119 gal         | 9/23/15          |
| 7           | Category I          | 119 gal         | 10/23/15         |
| 8           | Category I          | 119 gal         | 11/18/15         |
| 9           | Category I          | 210 gal         | 11/4/16          |
| 10          | Profile April       | No              | 6/6-7/16         |
| 11          | Profile January     | No              | 5/13 and 5/16/16 |
| 12          | Profile March       | No              | 4/28-29/16       |
| 13          | Profile April       | 119 gal         | 5/25-26/16       |
| 14          | Profile January     | 119 gal         | 5/9-10/16        |
| 15          | Profile March       | 119 gal         | 2/1-2/16         |
| 16          | Profile April       | 210 gal         | 11/10-11/16      |

## Category Test Results

### Results of Test 1 – Category IV, No Thermal Storage

#### *Summary of conditions for test*

|                               |                |
|-------------------------------|----------------|
| Test Date                     | August 6, 2015 |
| Test Condition                | Cat IV         |
| Storage                       | N/A            |
| ΔT control change across tank | N/A            |

#### *Discussion of Test Condition*

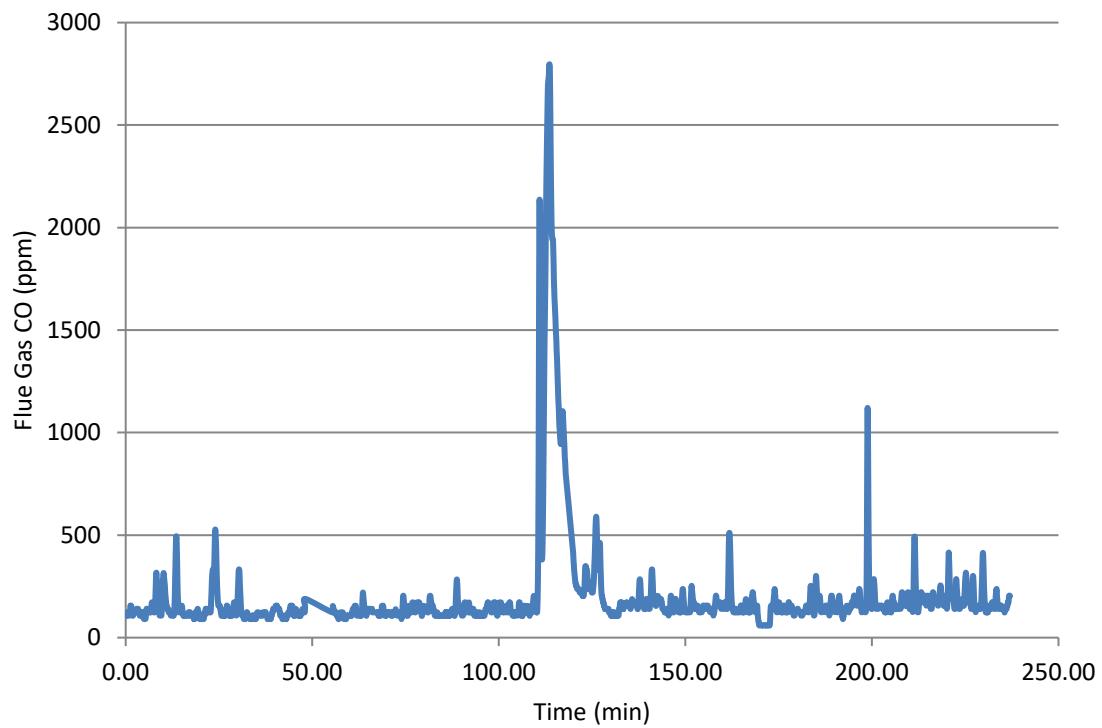
On August 6<sup>th</sup> 2015, a Category IV test (full output) was conducted. The purpose of this test was to run the boiler at 100% output for a maximum burn rate. External storage and cycling are not applicable for this test as it is running at full output. The average output during the combined testing period was 77,155 BTU/hr.

#### *Discussion of Test Results*

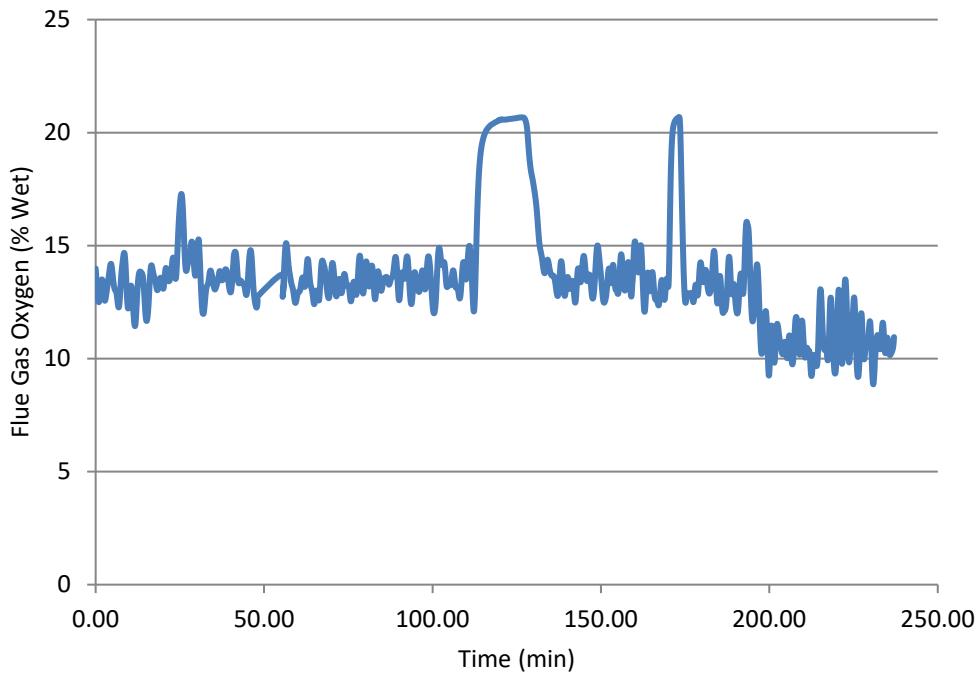
Particulate sampling in the dilution tunnel was conducted from 13:12:40-17:12:02 for a 239.4 minute period. The total fuel consumed during this test was 44.2 lbs. At 15:03:36 the boiler automatically shut down to perform a self-cleaning and it resumed to full output again at 15:20:02. From the figures provided it can be seen that the first interval of the testing (pre-cleaning) ended at 111 minutes into the run and the second interval of testing (post-cleaning) started at 127.4 minutes into the run. The cleaning period lasted for 16.4 minutes. During the cleaning period there was a large spike in flue gas CO and HC. The combined input/output efficiency during the testing interval was 80.0%. The overall particulate emission factor for the entire test period was 0.15 lb/MMBtu which includes the PM collected during the cleaning period as sampling was not stopped.

#### *Emissions overview*

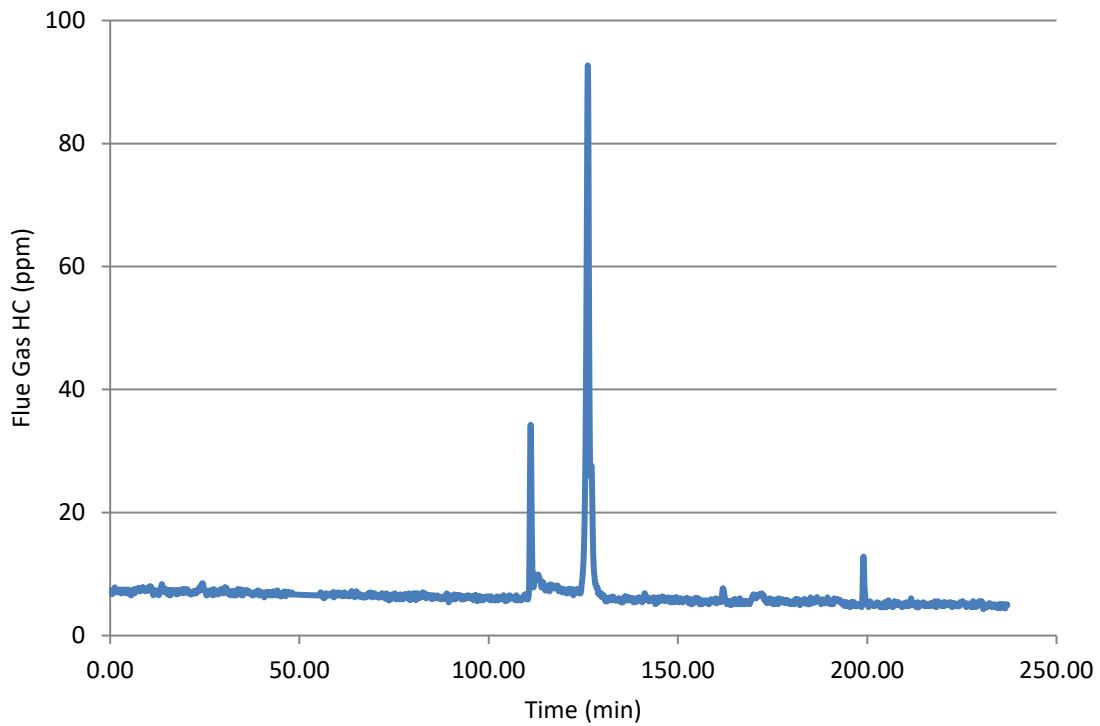
|                  |                        |
|------------------|------------------------|
| PM Concentration | 8.38 mg/m <sup>3</sup> |
| Emission Rate    | 5.16 g/hr              |
| Emission Index   | 1.03 g/kg fuel         |
| Emission Output  | 0.15 lb/MMBtu          |
| Avg. Stack CO    | 203 ppm                |



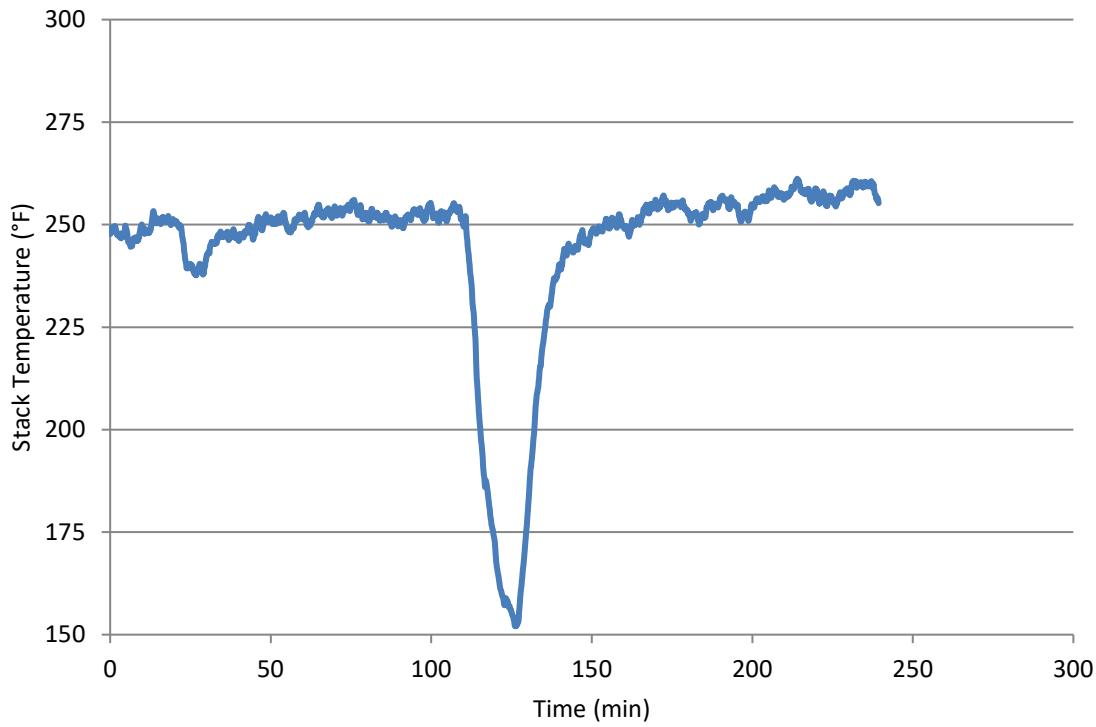
**Figure 6 Flue CO, Test 1, Cat IV, no storage**



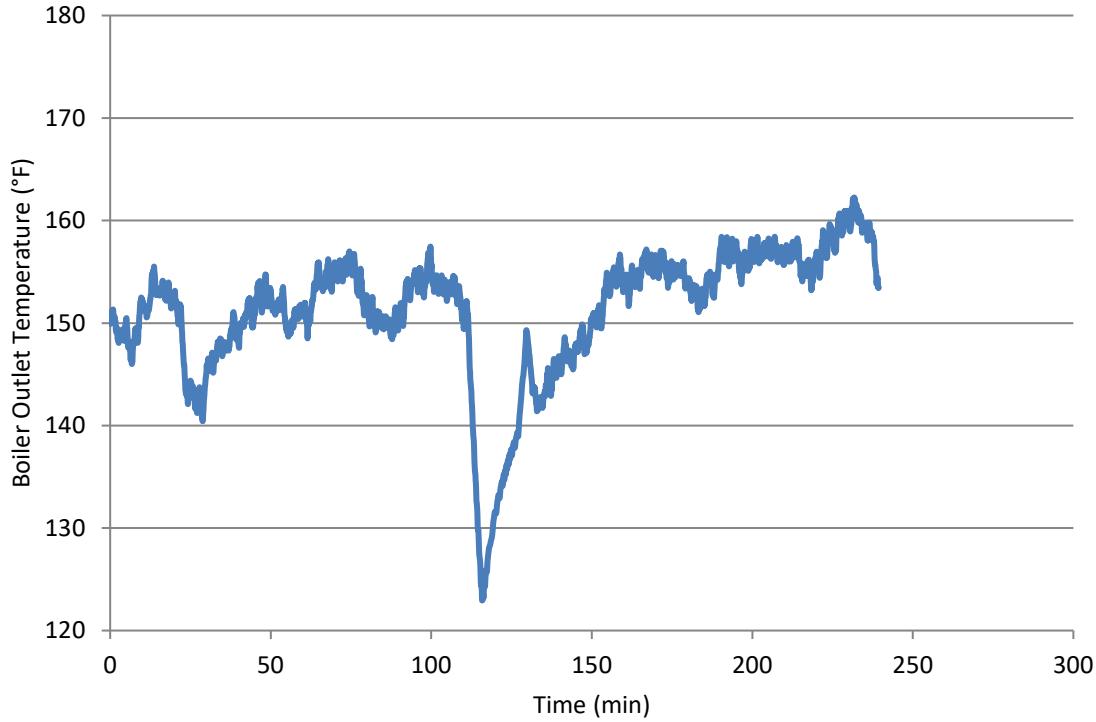
**Figure 7 Flue O<sub>2</sub>, Test 1, Cat IV, no storage**



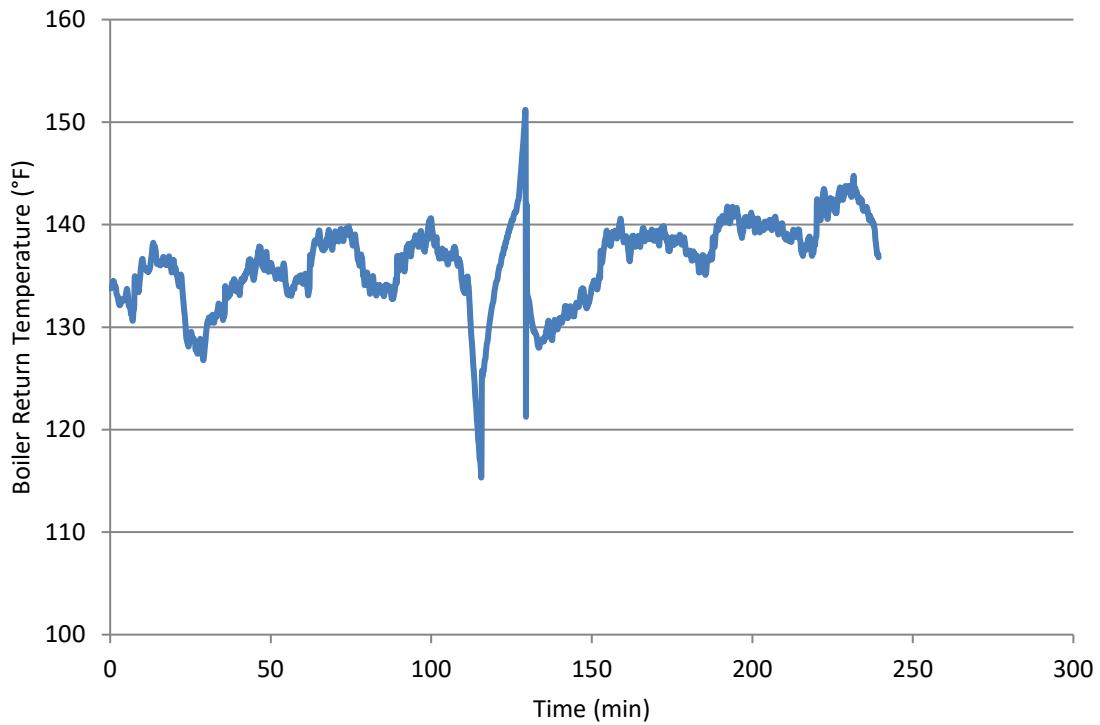
**Figure 8 Flue HC, Test 1, Cat IV, no storage**



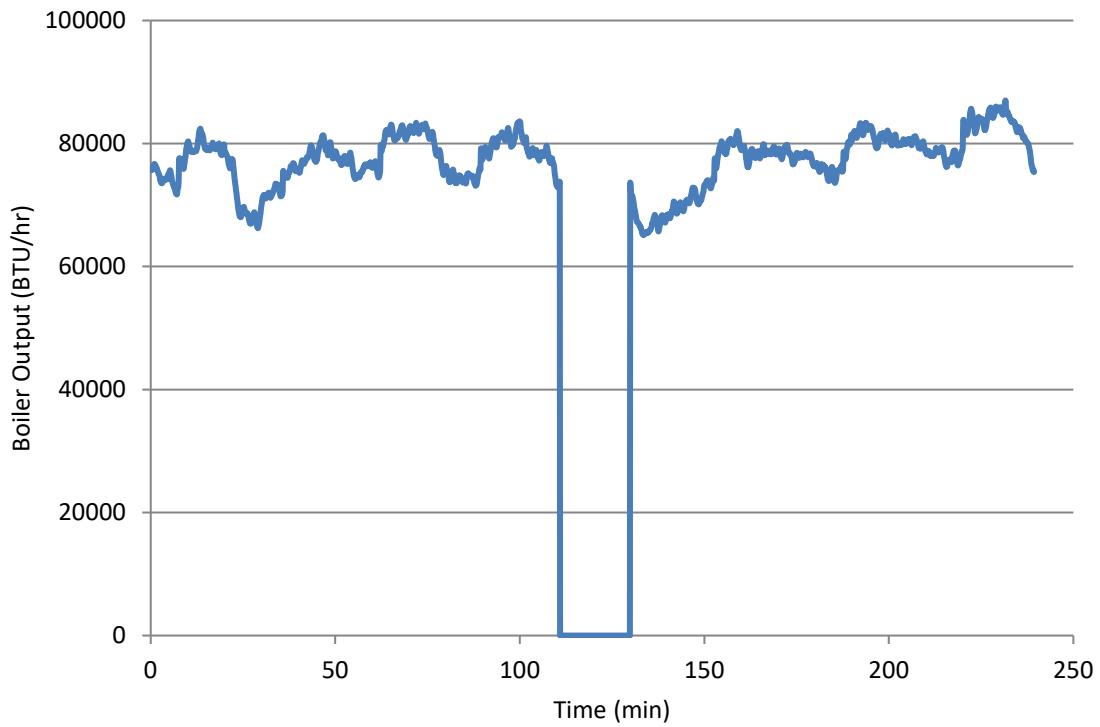
**Figure 9 Stack temperature, Test 1, Cat IV, no storage**



**Figure 10 Boiler outlet temperature, Test 1, Cat IV, no storage**



**Figure 11 Boiler return temperature, Test 1, Cat IV, no storage**



**Figure 12 Boiler output, Test 1, Cat IV, no storage**

## Results of Test 2 – Category IV, No Thermal Storage

### *Summary of conditions for test*

|                               |                  |
|-------------------------------|------------------|
| Test Date                     | October 13, 2015 |
| Test Condition                | Cat IV           |
| Storage                       | N/A              |
| ΔT control change across tank | N/A              |

### *Discussion of Test Condition*

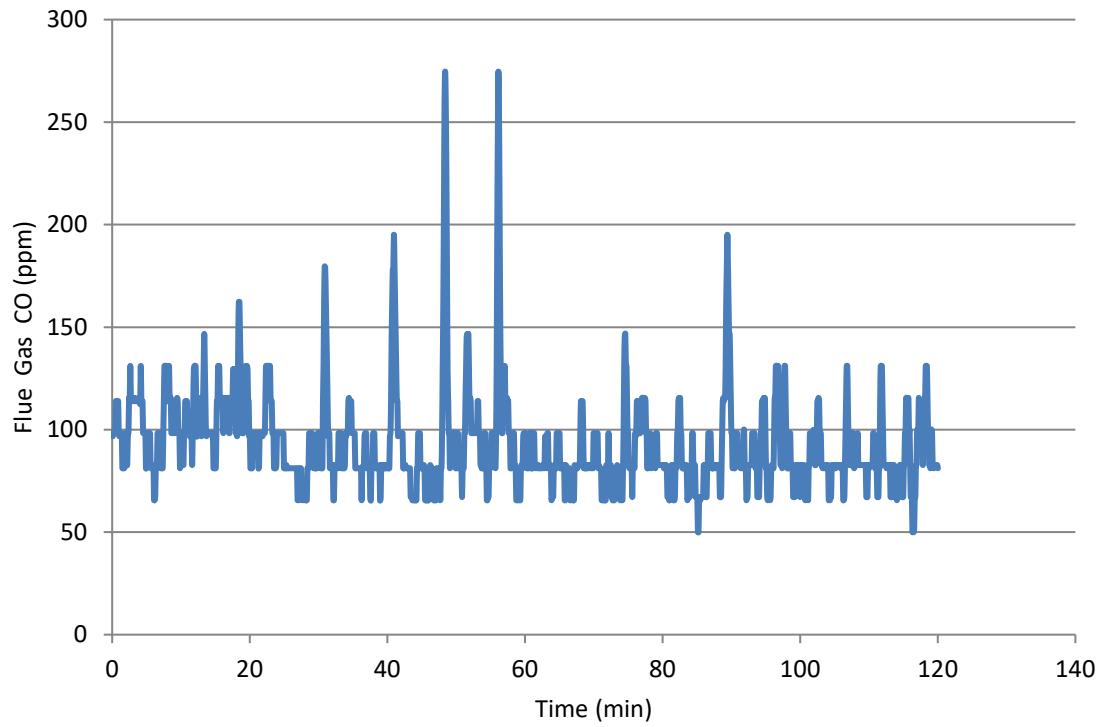
On October 13<sup>th</sup> 2015 a Category IV test was conducted (full output). The purpose of this test was to run the boiler at 100% output for a maximum burn rate. External storage and cycling are not applicable for this test since we are running at full output. The average output during the testing period was 73,109 BTU/hr.

### *Discussion of Test Results*

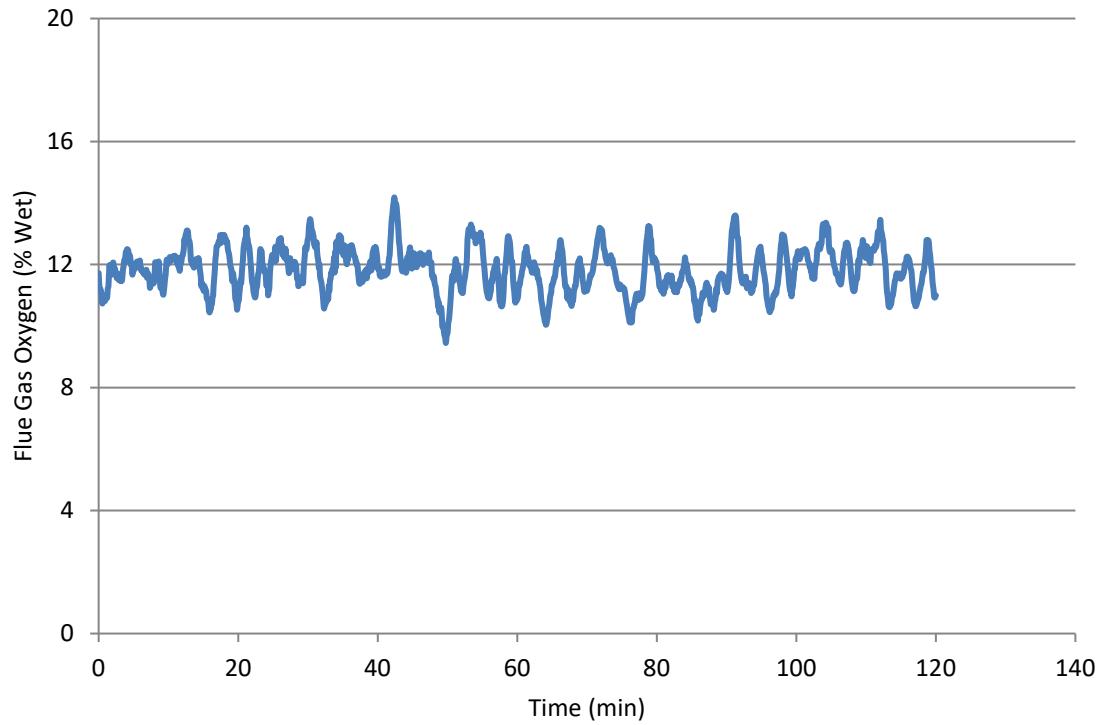
Following a warmup period, particulate sampling in the dilution tunnel was conducted over a two hour interval starting at 12:18:10 and ending at 14:18:10. The total fuel consumed during this test was 22.0 lbs. The input/output efficiency for the testing period was 80.7%. The overall particulate emission factor for this test was 0.13 lb/MMBtu.

### *Emissions overview*

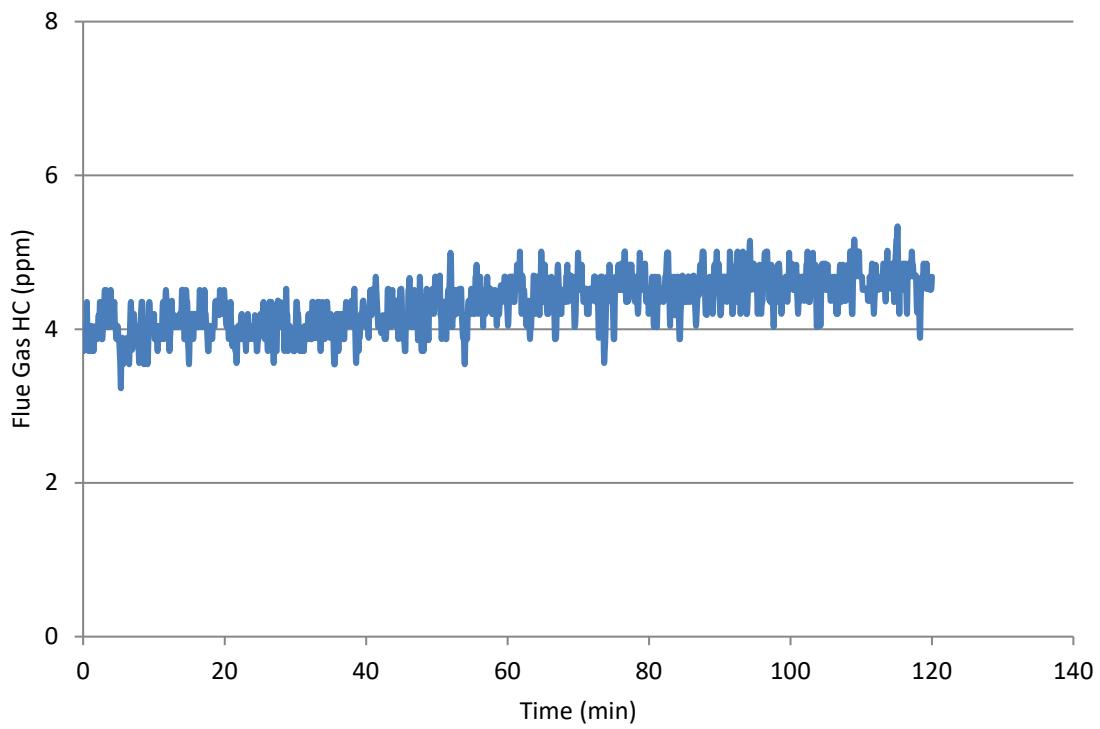
|                  |                        |
|------------------|------------------------|
| PM Concentration | 6.97 mg/m <sup>3</sup> |
| Emission Rate    | 4.42 g/hr              |
| Emission Index   | 0.88 g/kg fuel         |
| Emission Output  | 0.13 lb/MMBtu          |
| Avg. Stack CO    | 93 ppm                 |



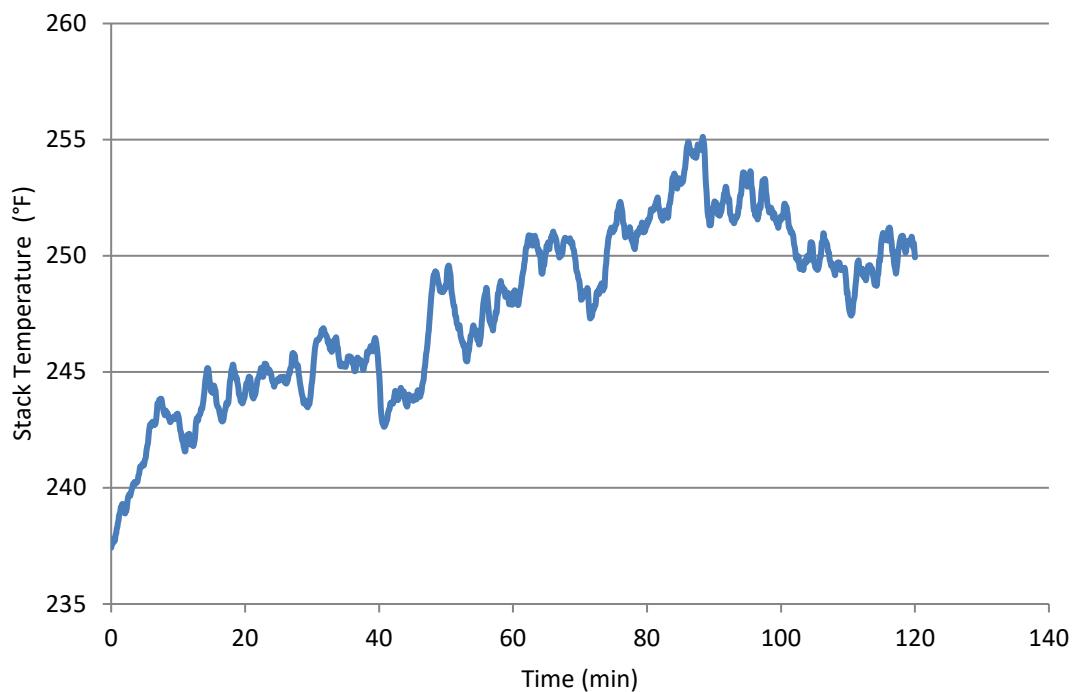
**Figure 13 Flue CO, Test 2, Cat IV, no storage**



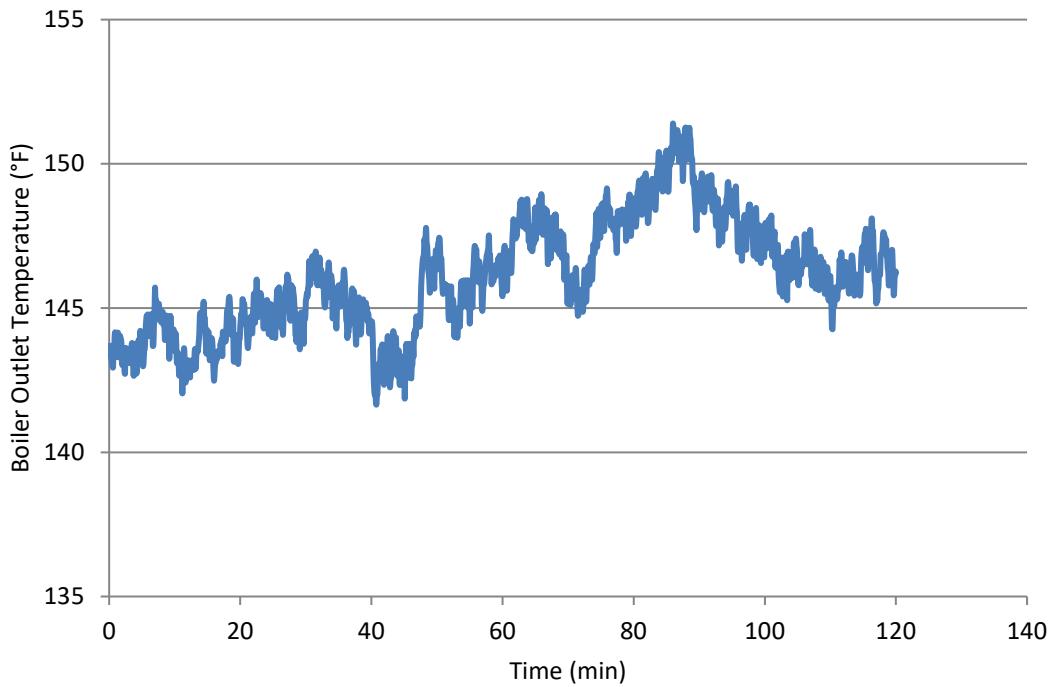
**Figure 14 Flue O<sub>2</sub>, Test 2, Cat IV, no storage**



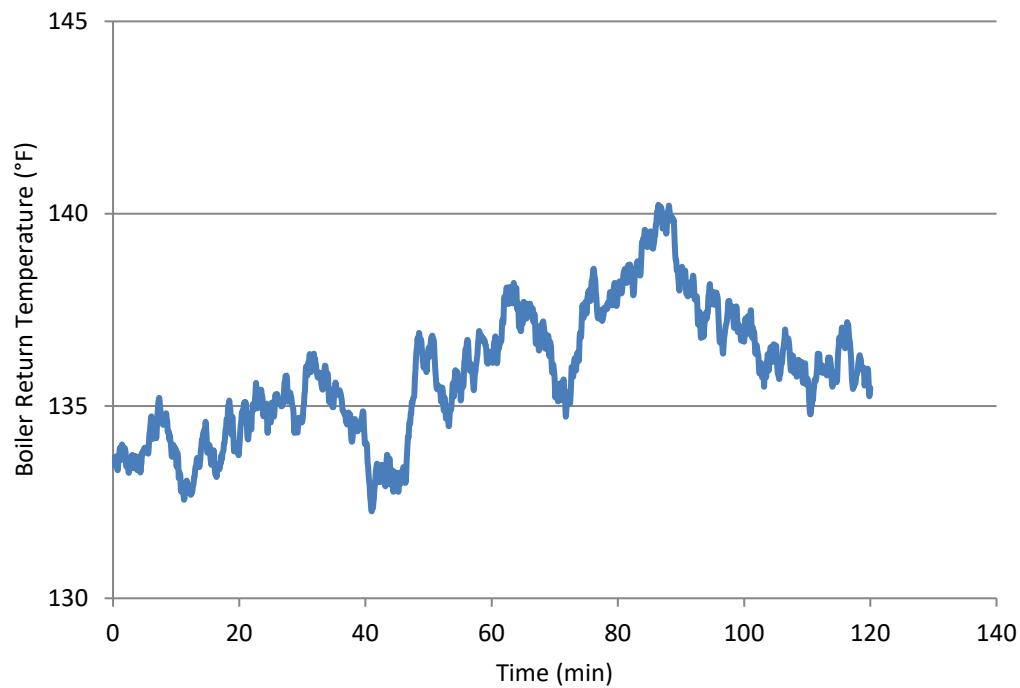
**Figure 15 Flue HC, Test 2, Cat IV, no storage**



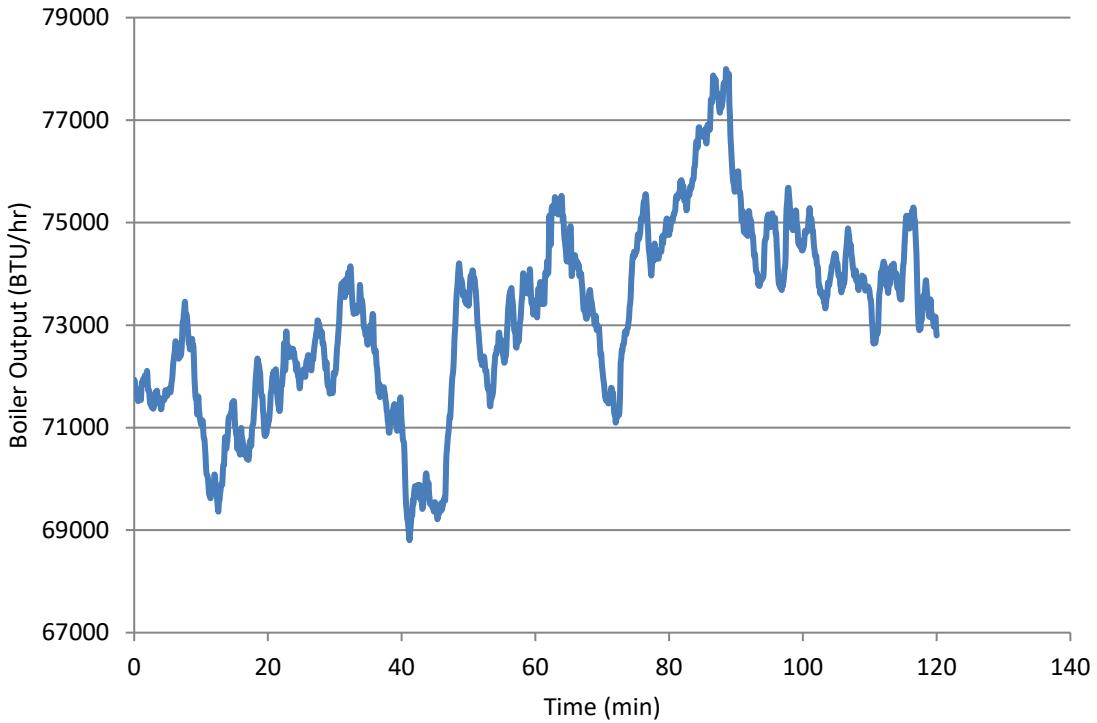
**Figure 16 Stack temperature, Test 2, Cat IV, no storage**



**Figure 17 Boiler outlet temperature, Test 2, Cat IV, no storage**



**Figure 18 Boiler return temperature, Test 2, Cat IV, no storage**



**Figure 19 Boiler output, Test 2, Cat IV, no storage**

Results of Test 3- Category I, No Thermal Storage

*Summary of conditions for test*

|                                       |                 |
|---------------------------------------|-----------------|
| Test Date                             | August 31, 2015 |
| Test Condition                        | Cat I           |
| Storage                               | No              |
| $\Delta T$ control change across tank | N/A             |

#### *Discussion of Test Condition*

On August 31<sup>st</sup> 2015 a Category I test (15%) was conducted without storage. The purpose of this test is to run the boiler at less than or equal to 15% of the manufacturers nominal output in order to determine the efficiency and PM emissions at the low load level. The average output of the boiler for this test period was 10,157 BTU/hr.

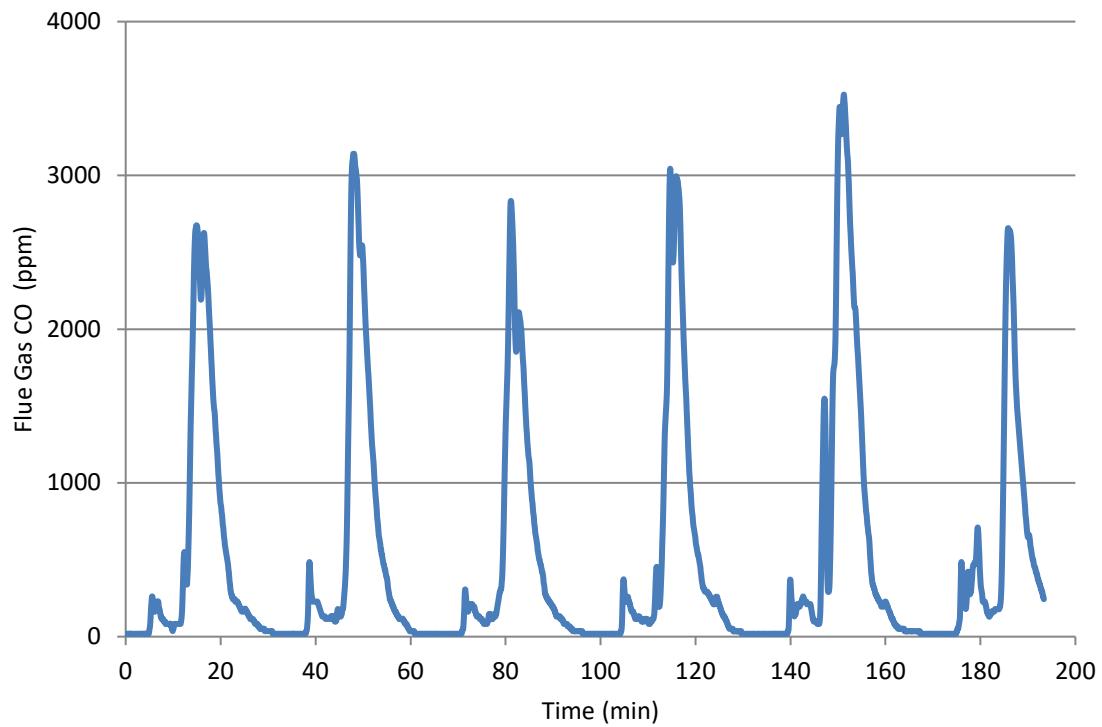
#### *Discussion of Test Results*

Particulate sampling in the dilution tunnel was conducted from 13:06:22-16:14:45 for a 193.38 minute test period. The total fuel consumed during this test was 7.4 lbs. From the figures

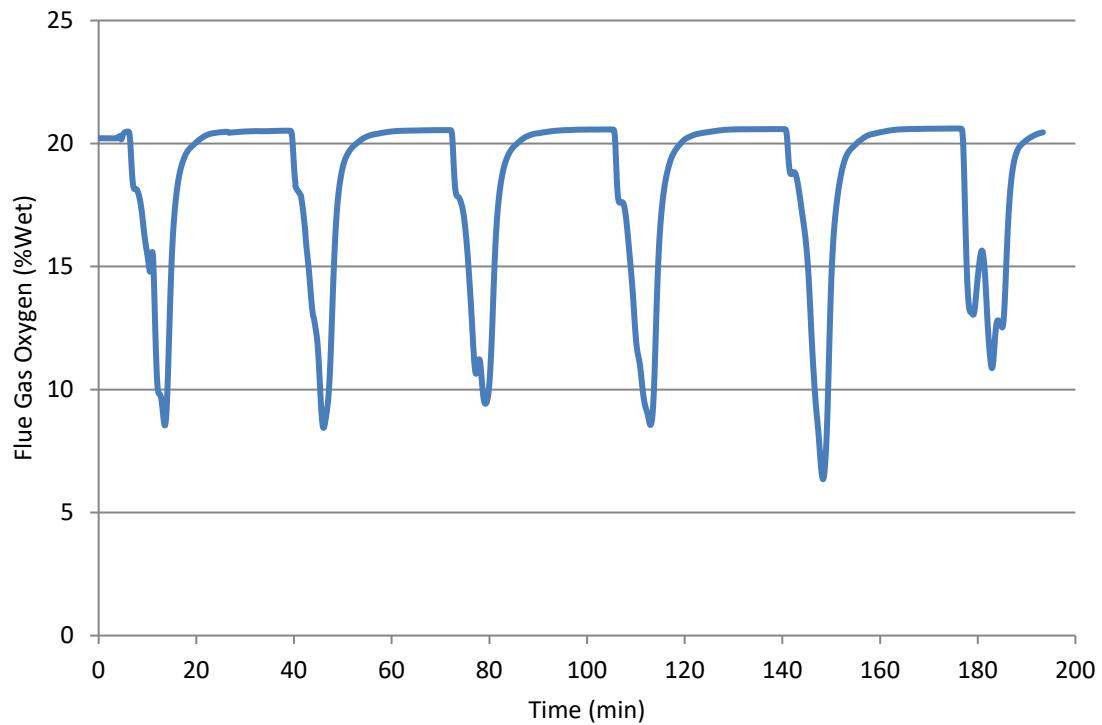
provided it can be seen that the boiler cycled approximately six times. Each cycle lasted approximately 30 minutes consisting of a 10 minute heat up and a 20 minute draw down. Figure 8 shows an overlay of the stack CO, O<sub>2</sub>% and HC of the cycle from 100-130 minutes of testing. The input/output efficiency of the boiler for test period was 56.5%. The overall particulate emission factor for the entire test period was 0.40 lb/MMBtu.

#### *Emissions overview*

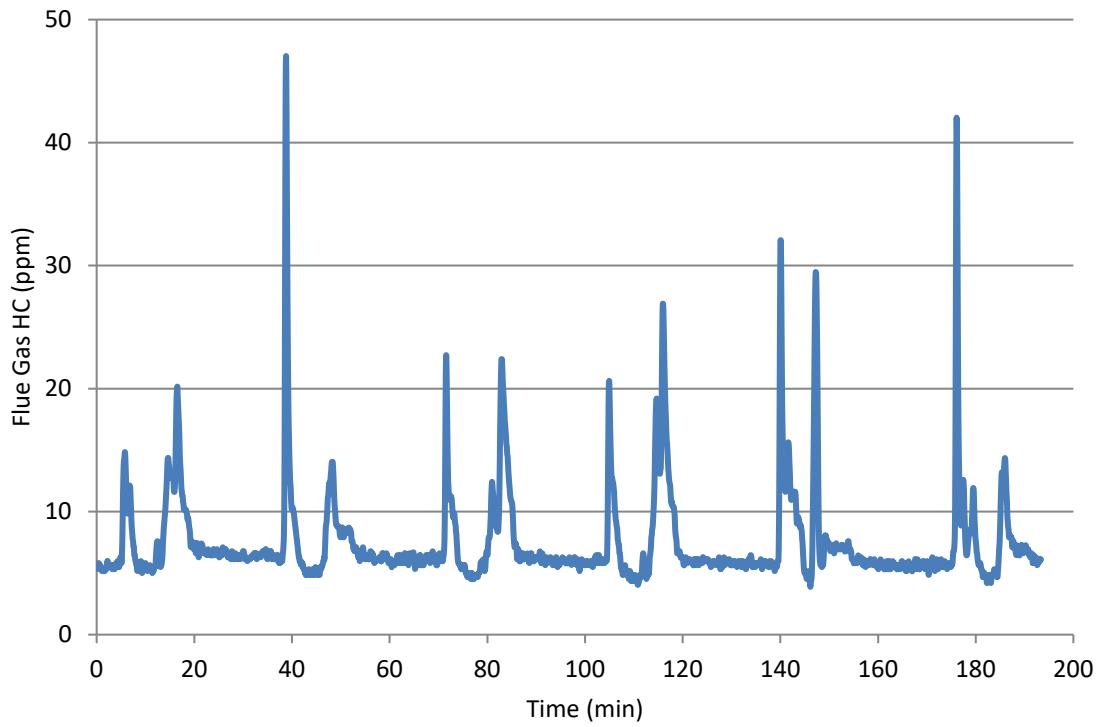
|                  |                        |
|------------------|------------------------|
| PM Concentration | 3.17 mg/m <sup>3</sup> |
| Emission Rate    | 1.97 g/hr              |
| Emission Index   | 1.89 g/kg fuel         |
| Emission Output  | 0.40 lb/MMBtu          |
| Avg. Stack CO    | 525 ppm                |



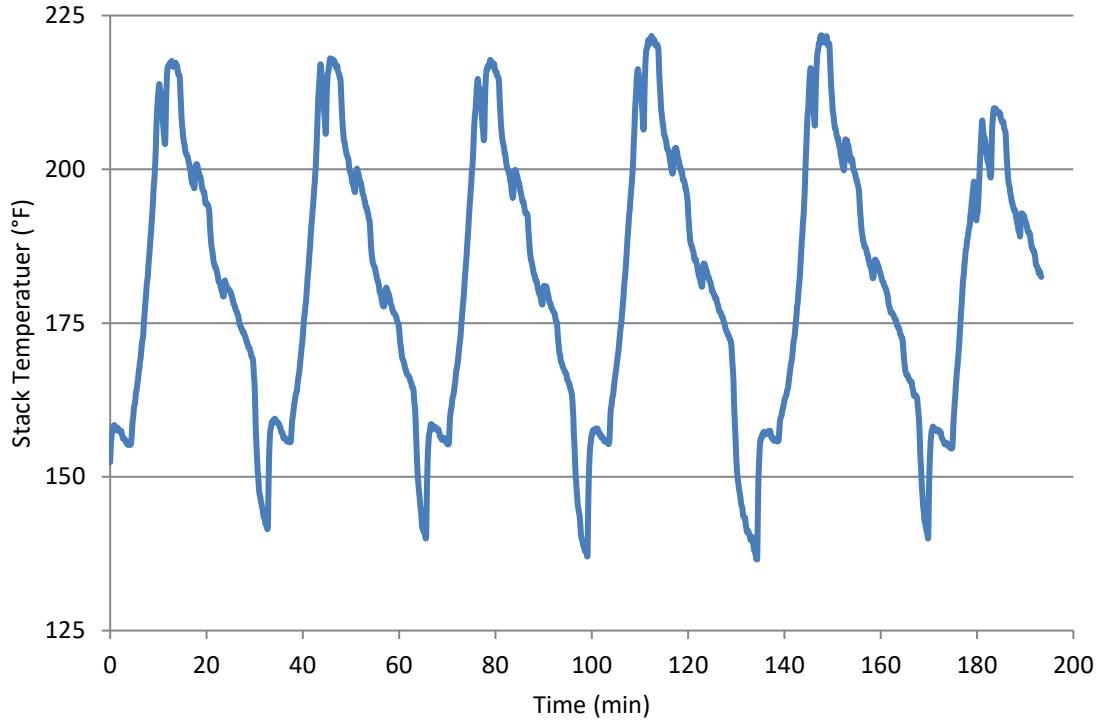
**Figure 20 Flue CO, Test 3, Cat I, no storage**



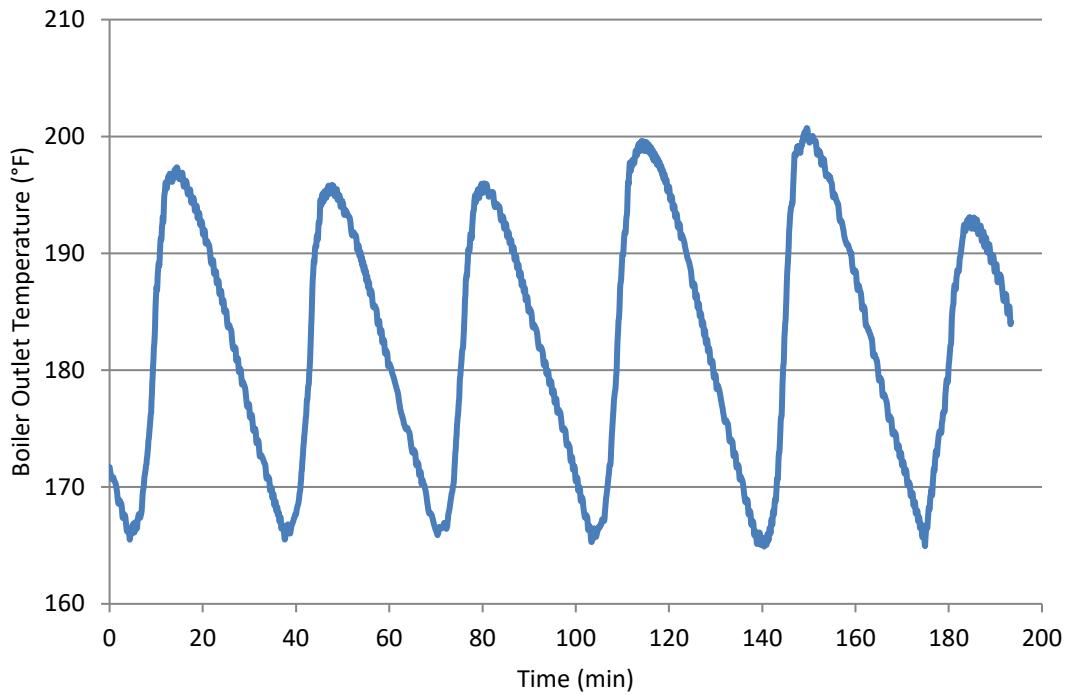
**Figure 21 Flue O<sub>2</sub>, Test 3, Cat I, no storage**



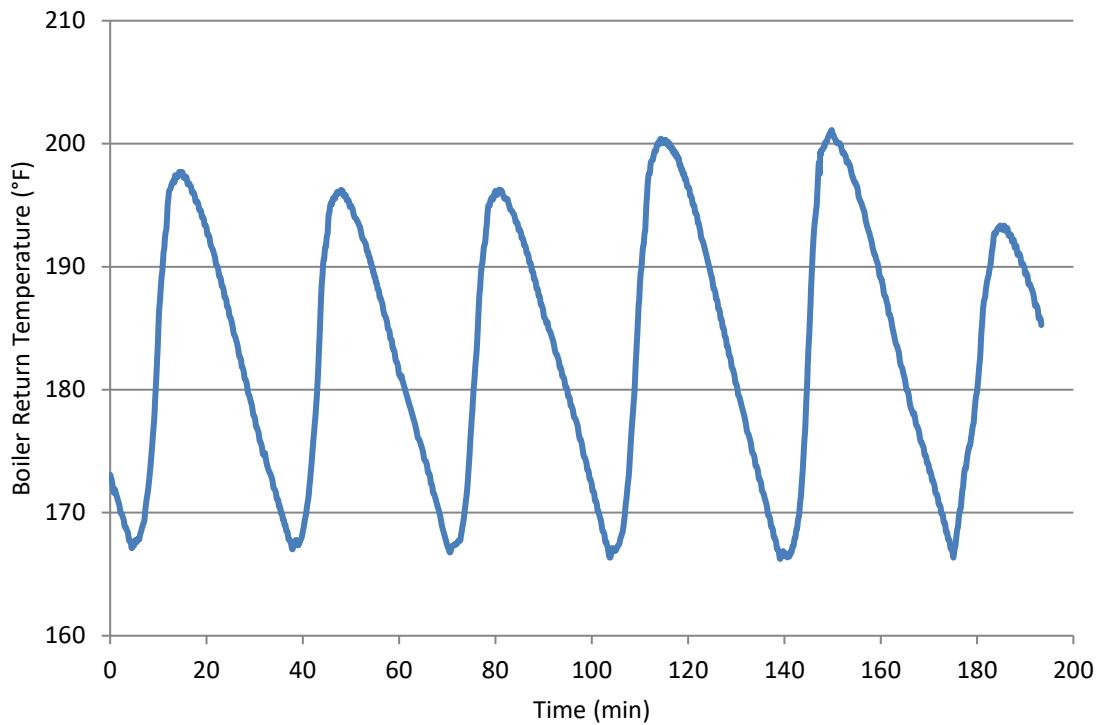
**Figure 22 Flue HC, Test 3, Cat I, no storage**



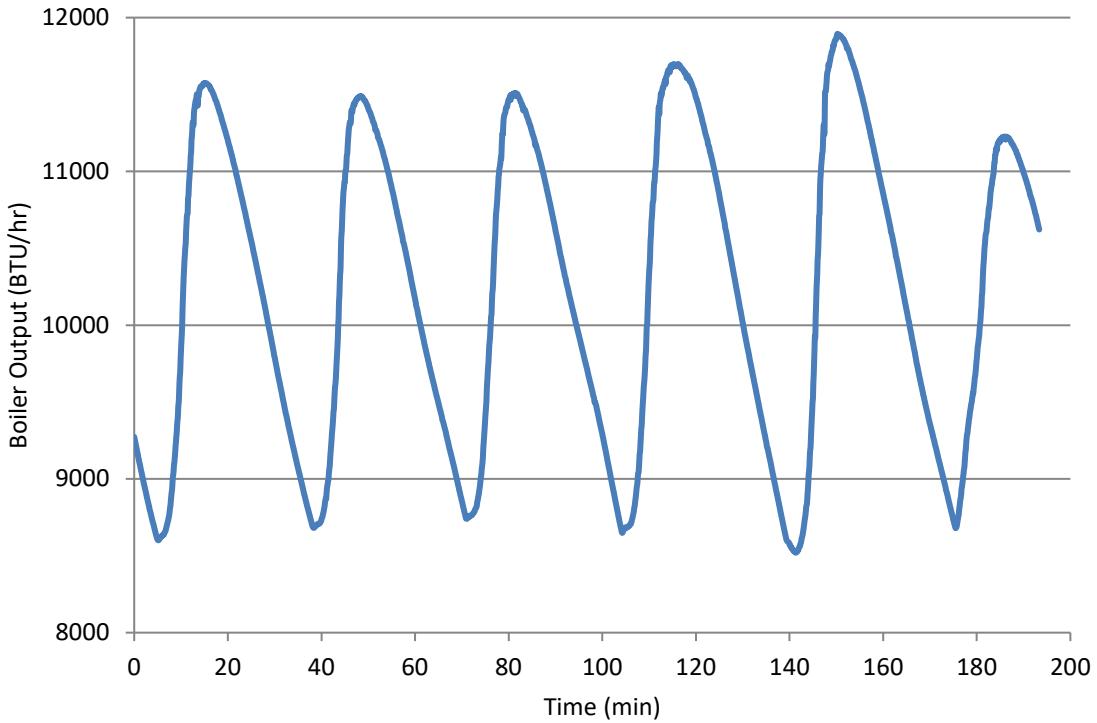
**Figure 23 Stack Temperature, Test 3, Cat I, no storage**



**Figure 24 Boiler outlet temperature, Test 3, Cat I, no storage**



**Figure 25 Boiler return temperature, Test 3, Cat I, no storage**



**Figure 26 Boiler output, Test 3, Cat I, no storage**

#### Results of Test 4 – Category I, No Thermal Storage

*Summary of conditions for test*

|                                       |                    |
|---------------------------------------|--------------------|
| Test Date                             | September 21, 2015 |
| Test Condition                        | Cat I              |
| Storage                               | No                 |
| $\Delta T$ control change across tank | N/A                |

#### *Discussion of Test Condition*

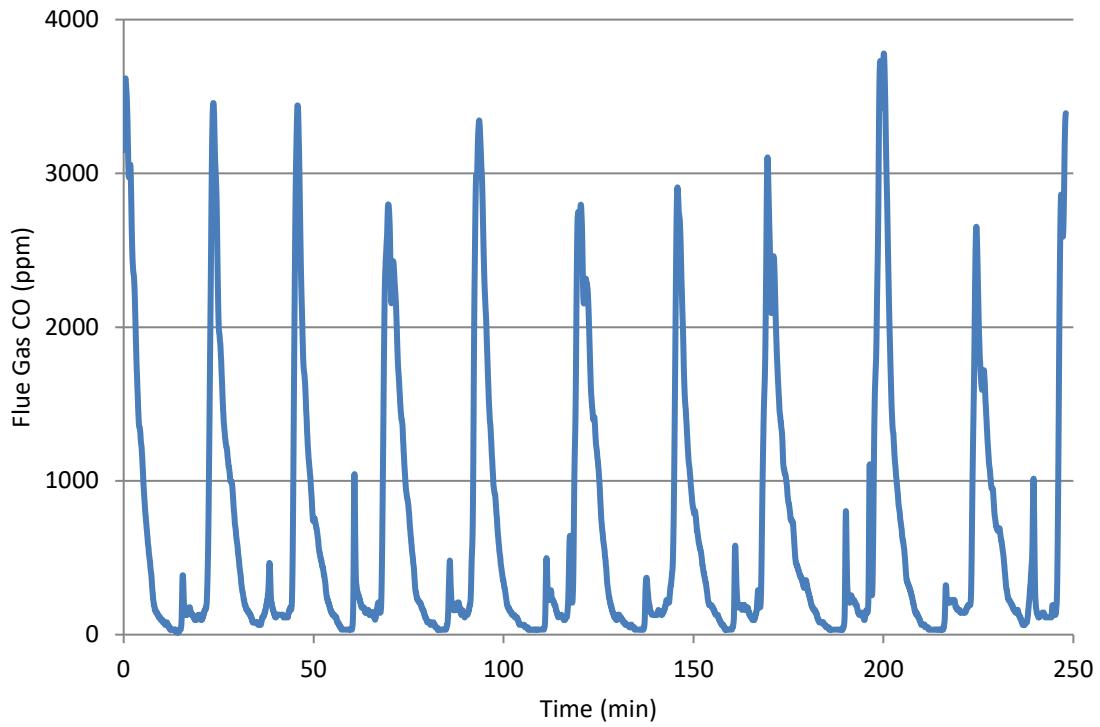
On September 21<sup>st</sup> 2015 a Category I test (15%) was conducted without storage. The purpose of this test is to run the boiler at less than or equal to 15% of the manufacturers nominal output in order to determine the efficiency and PM emissions at the low load level. The average output of the boiler for this test period was 10,828 BTU/hr.

### *Discussion of Test Results*

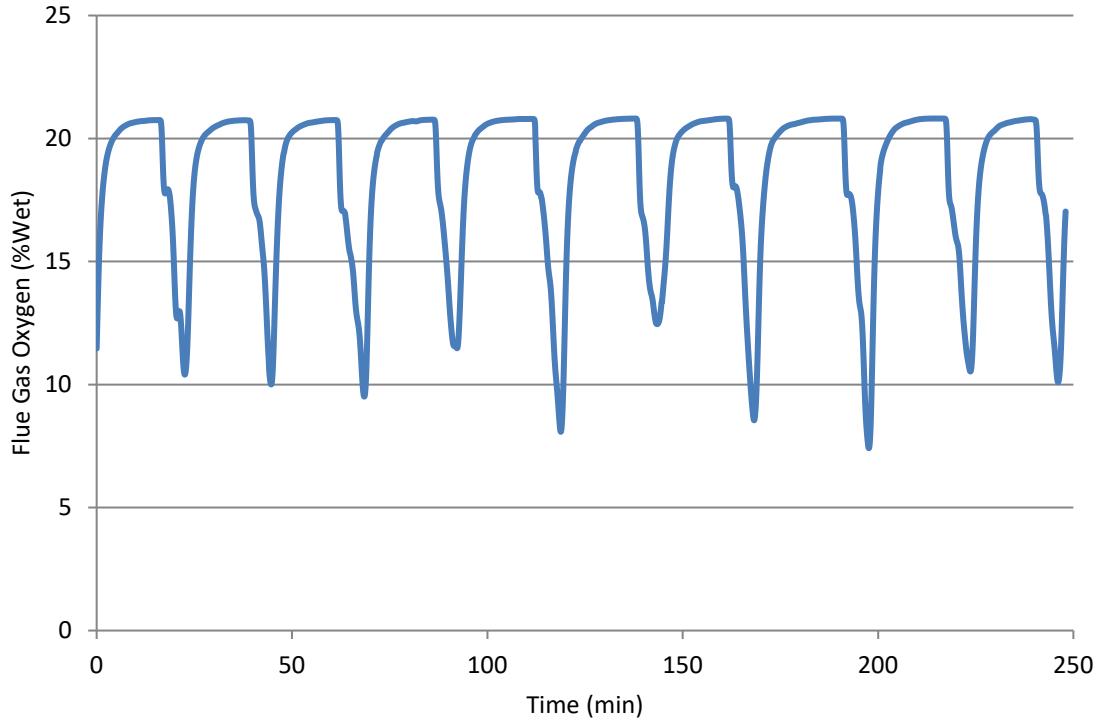
Particulate sampling in the dilution tunnel was conducted from 12:43:27-16:51:25 for a 248 minute test period. The total fuel consumed during this test was 9.6 lbs. From the figures it can be seen that the boiler cycled approximately ten times. Each cycle lasted approximately 25 minutes consisting of an 8 minute heat up and a 17 minute draw down. Figure 8 shows an overlay of the stack CO, O<sub>2</sub>% and HC of the cycle from 105-135 minutes of testing. The input/output efficiency for the test period was 56.2%. The overall particulate emission factor for the entire test period was 0.42 lb/MMBtu.

### *Emissions overview*

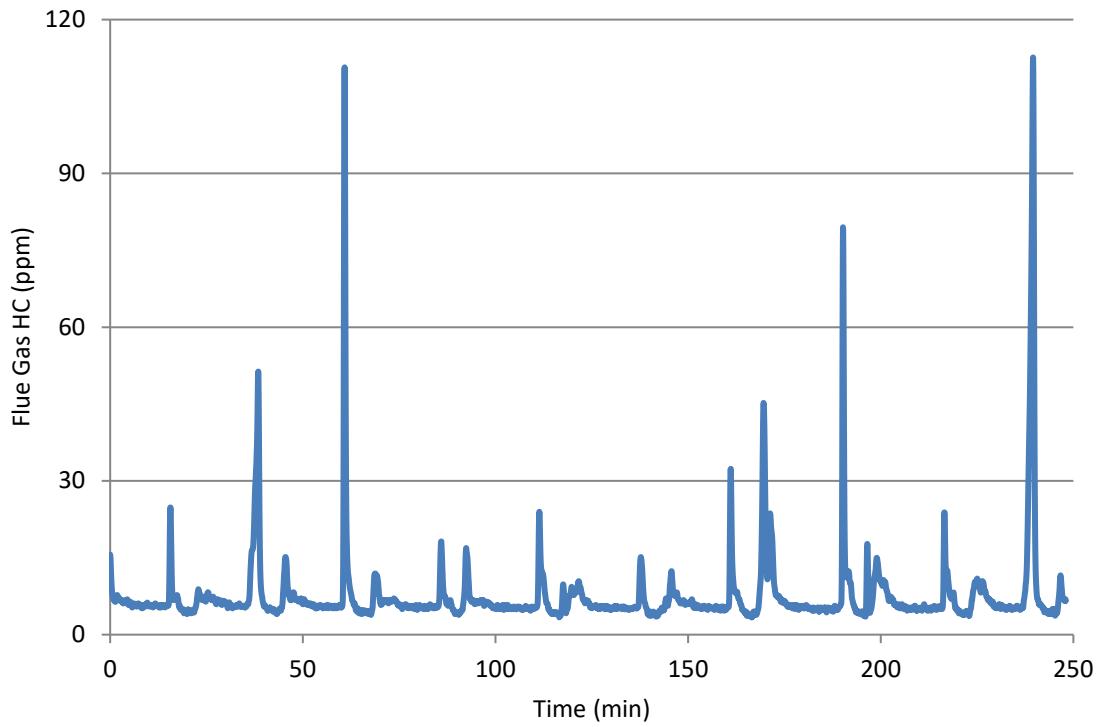
|                  |                        |
|------------------|------------------------|
| PM Concentration | 3.12 mg/m <sup>3</sup> |
| Emission Rate    | 2.10 g/hr              |
| Emission Index   | 1.99 g/kg fuel         |
| Emission Output  | 0.42 lb/MMBtu          |
| Avg. Stack CO    | 657 ppm                |



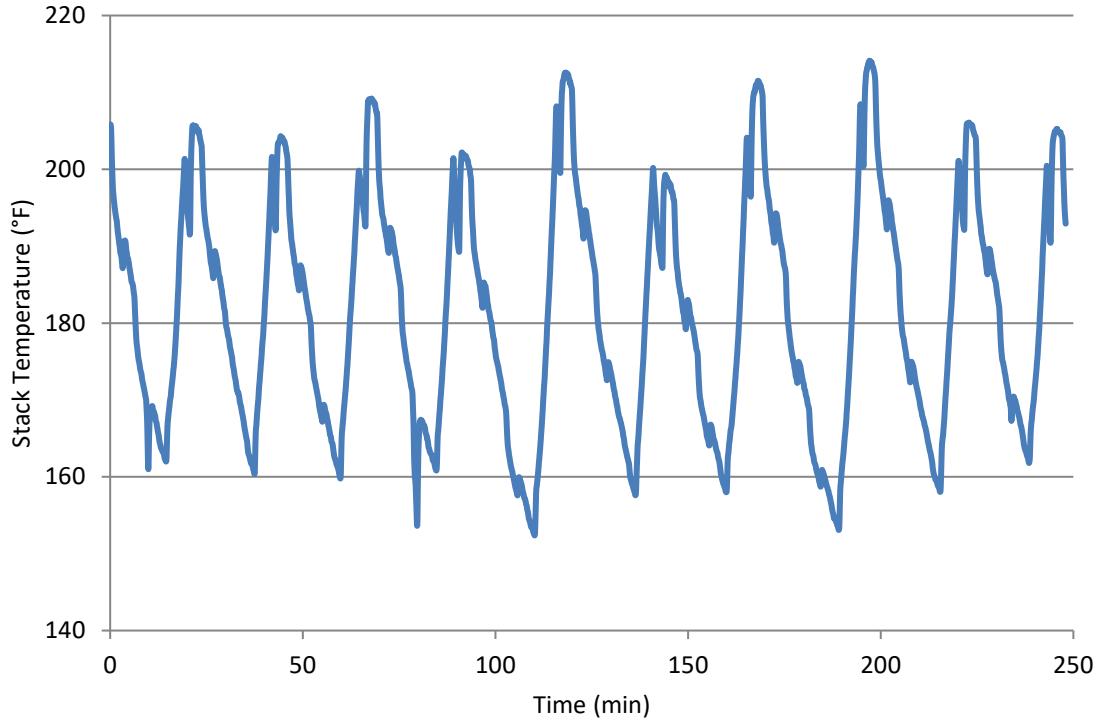
**Figure 27 Flue CO, Test 4, Cat I, no storage**



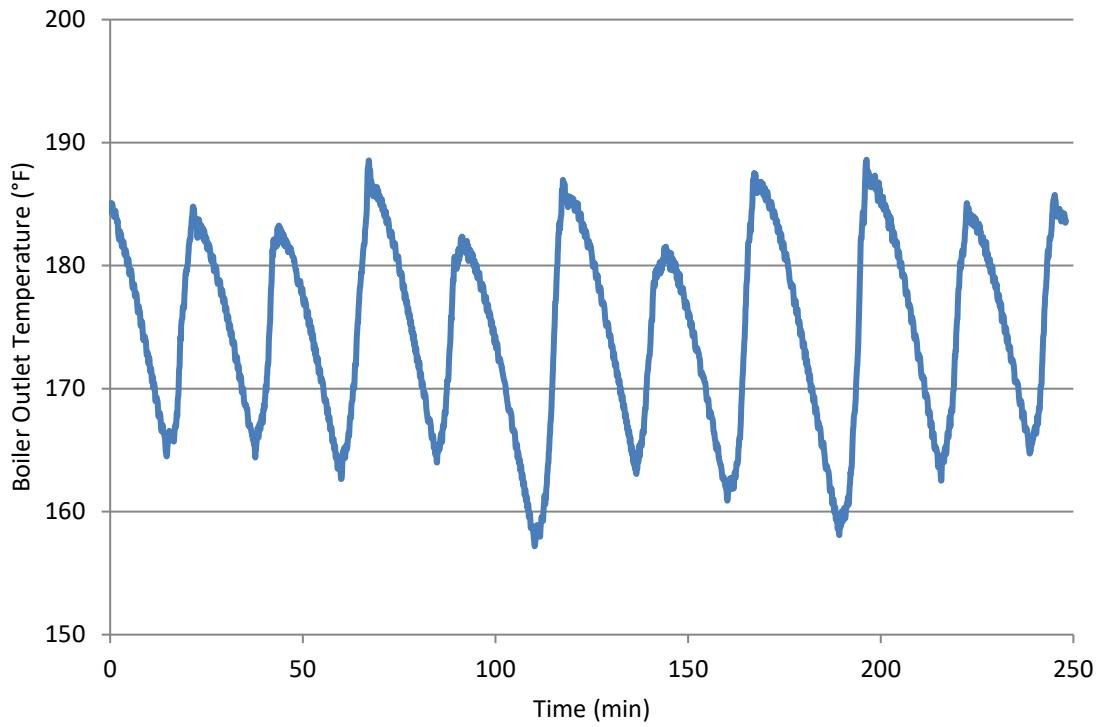
**Figure 28 Flue O<sub>2</sub>, Test 4, Cat I, no storage**



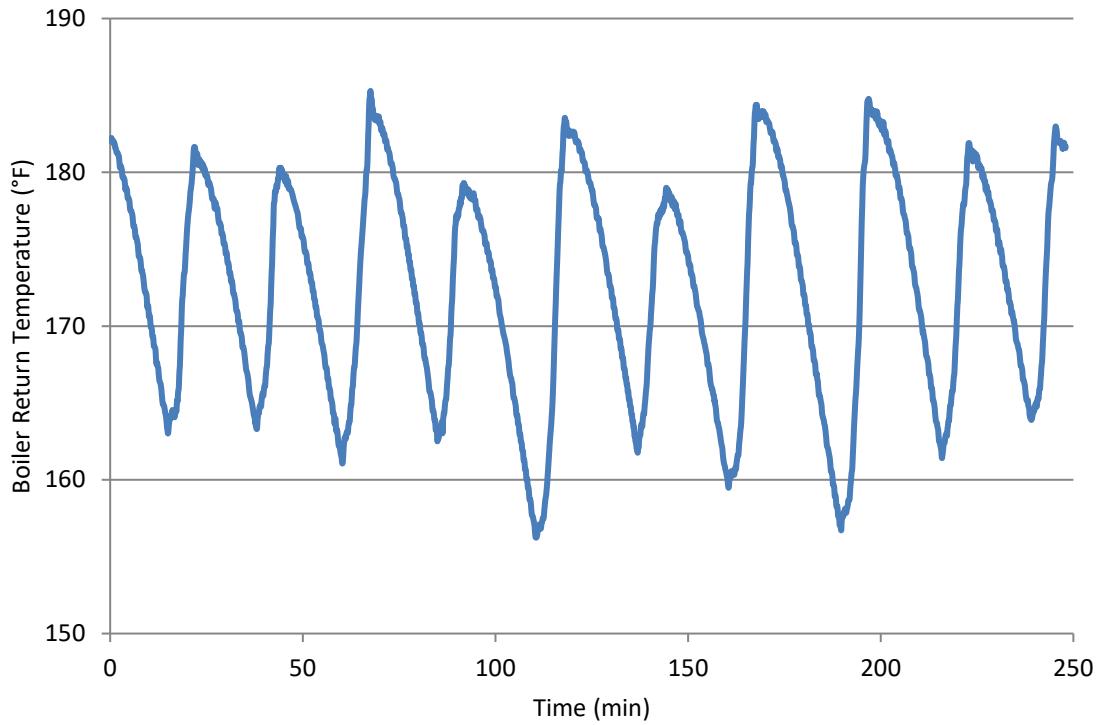
**Figure 29 Flue HC, Test 4, Cat I, no storage**



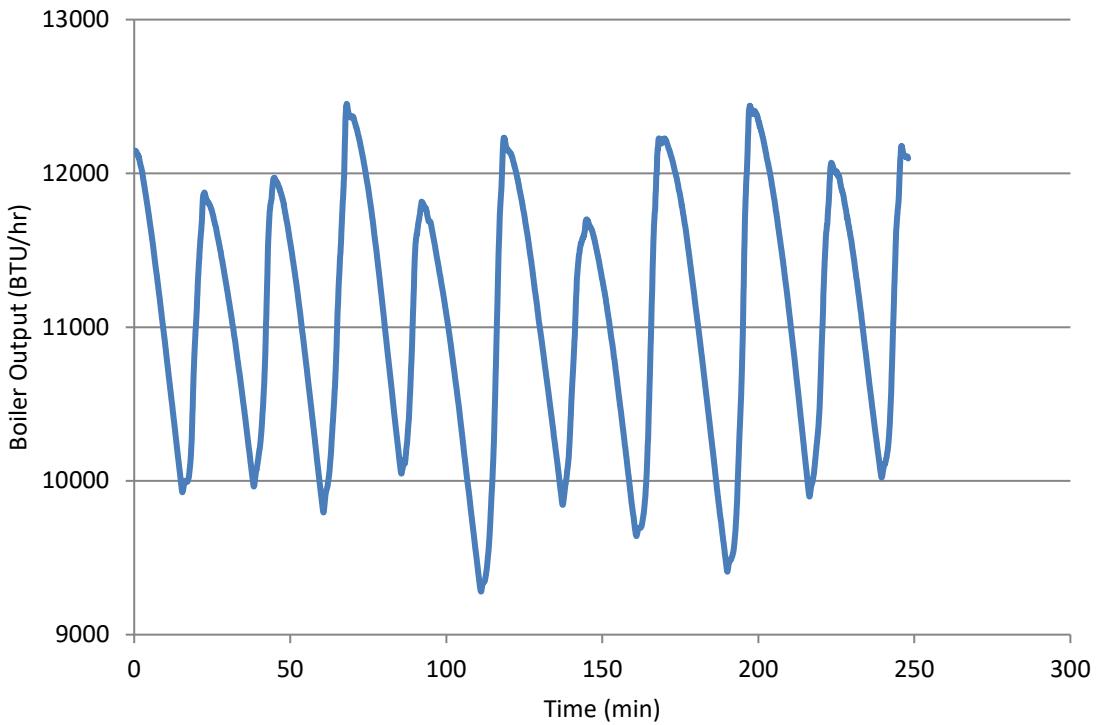
**Figure 30 Stack temperature, Test 4, Cat I, no storage**



**Figure 31 Boiler outlet temperature, Test 4, Cat I, no storage**



**Figure 32 Boiler return temperature, Test 4, Cat I, no storage**



**Figure 33 Boiler output, Test 4, Cat I, no storage**

#### Results of Test 5 – Category I, 119 Gallons of Thermal Storage

*Summary of conditions for test*

|                                       |                 |
|---------------------------------------|-----------------|
| Test Date                             | August 28, 2015 |
| Test Condition                        | Cat I           |
| Storage                               | Yes             |
| $\Delta T$ control change across tank | 7 °F            |

#### *Discussion of Test Condition*

On August 28<sup>th</sup> 2015 a Category I test (15%) was conducted with storage. The purpose of this test is to run the boiler at less than or equal to 15% of the manufacturers nominal output which is 11,475 BTU/hr after taking into account the efficiency of the boiler. From this test the efficiency and PM emissions at the low load level are determined. The temperature control change across the tank was 4 °C. During the heat up period of a cycle the burner runs until the bottom temperature sensor reaches 72 °C and during a cool down period the burner re-fires when the top

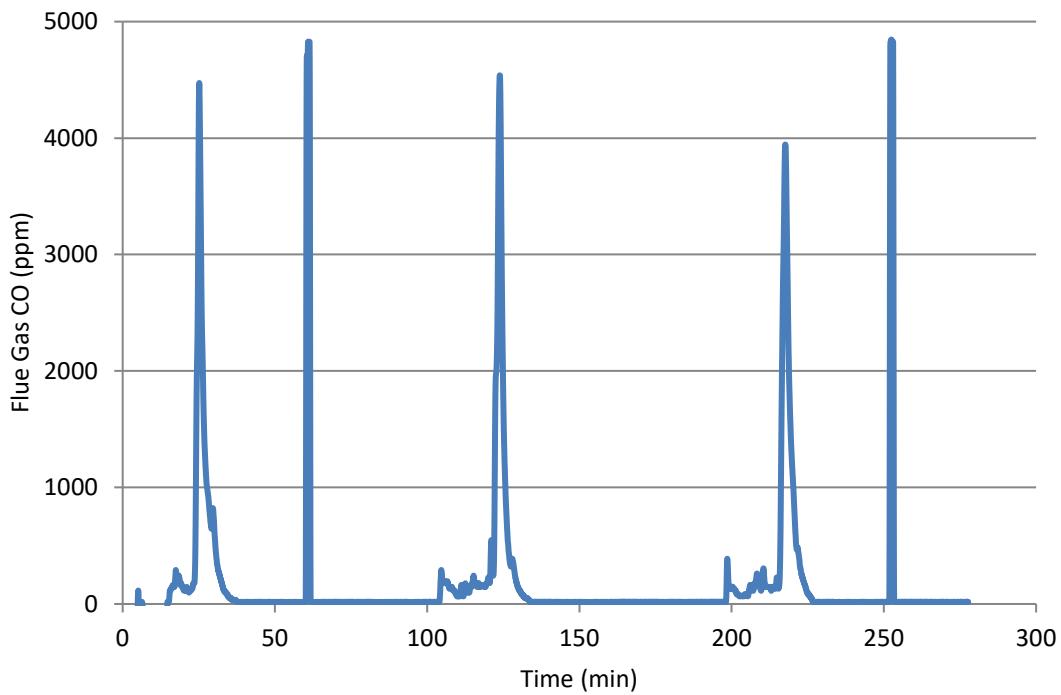
temperature sensor hits 68 °C. The average output of the boiler for the test period was 11,170 BTU/hr.

#### *Discussion of Test Results*

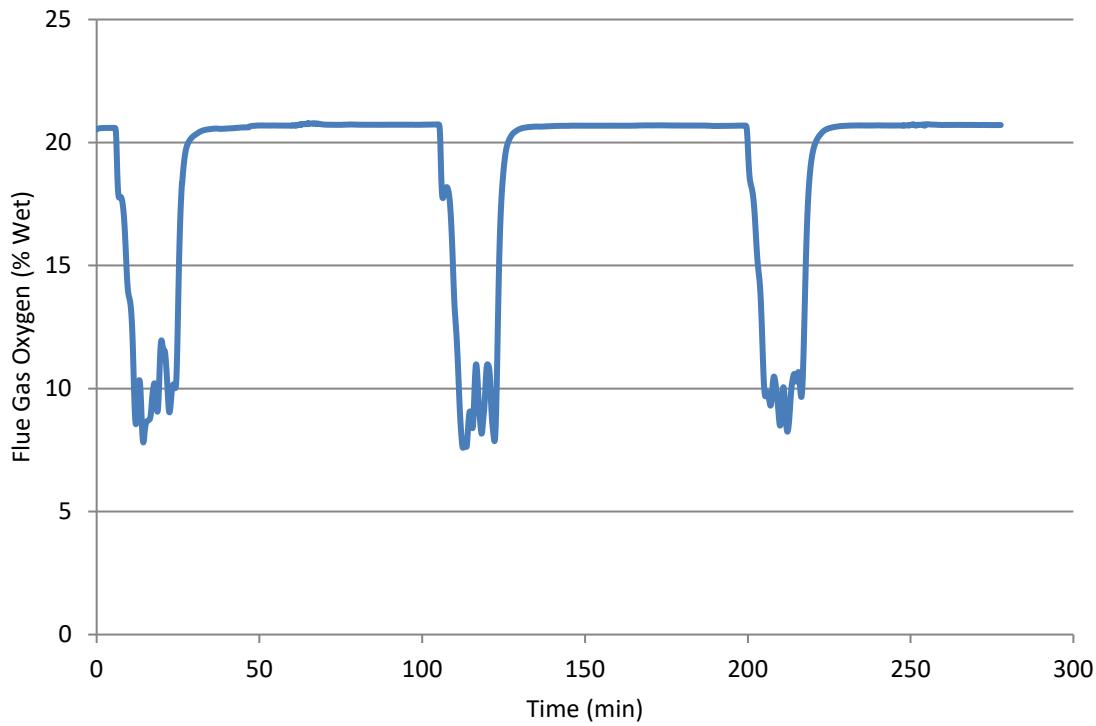
After an initial warmup period, particulate sampling in the dilution tunnel was conducted for 278 minutes from 12:23:40 to 17:01:22. The included figures show that the boiler cycled three times during this test period and 10.8 lbs of fuel was consumed. At the end of each heating cycle when the boiler reached the maximum control temperature the remaining fuel was burnt out and the boiler was subsequently switched into standby mode until it cooled enough to re-fire. Once the boiler temperature was cool enough to re-fire it initially went through the flush, fill, and ignite modes then stabilized once the target output was reached. The input/output efficiency of the testing period was 59.5%. The overall particulate emission factor for the three sampling intervals was 0.16 lb/MMBtu .

#### *Emissions overview*

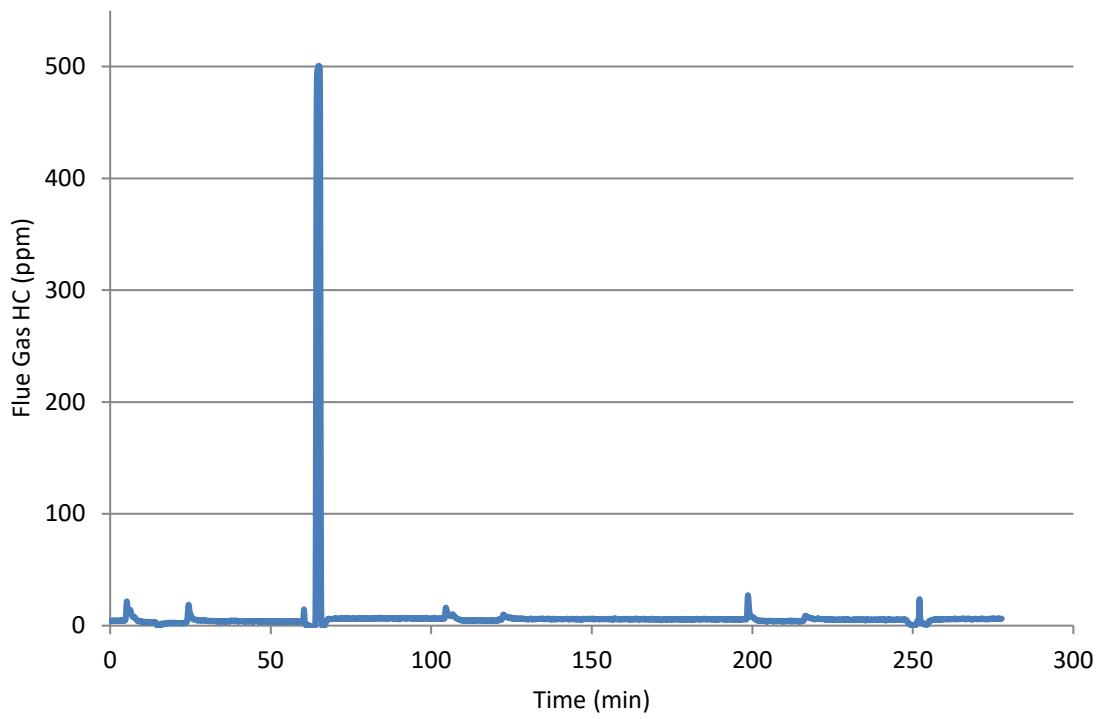
|                  |                        |
|------------------|------------------------|
| PM Concentration | 1.67 mg/m <sup>3</sup> |
| Emission Rate    | 1.11 g/hr              |
| Emission Index   | 1.04 g/kg fuel         |
| Emission Output  | 0.16 lb/MMBtu          |
| Avg. Stack CO    | 195 ppm                |



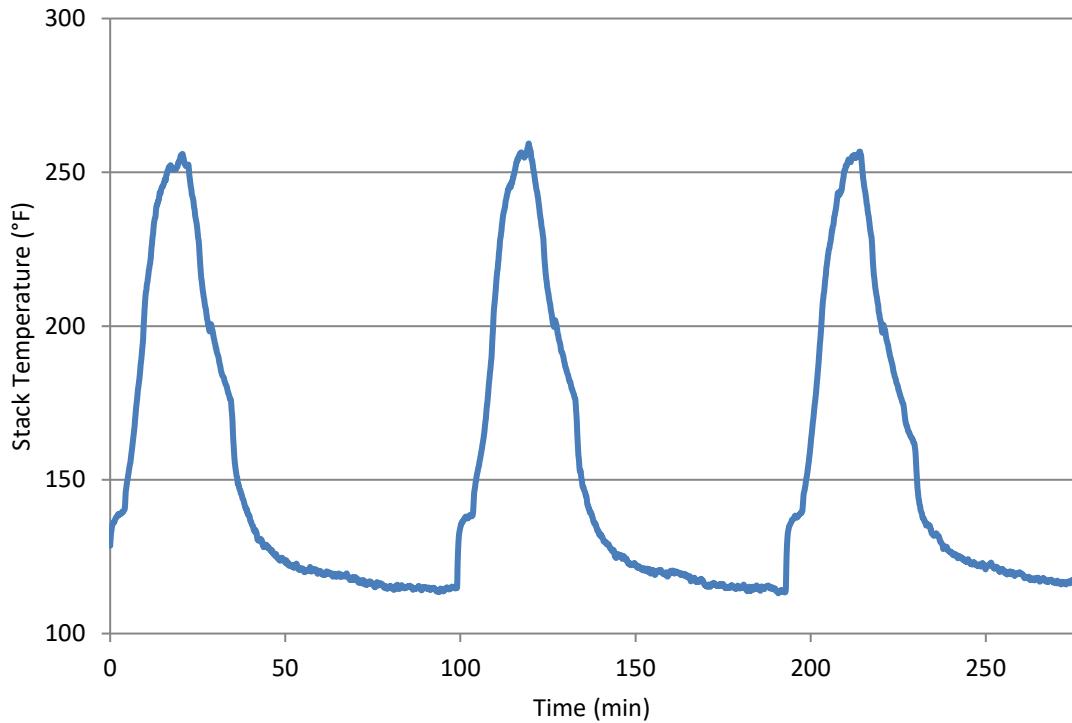
**Figure 34 Flue CO, Test 5, Cat I, 119 gal. storage**



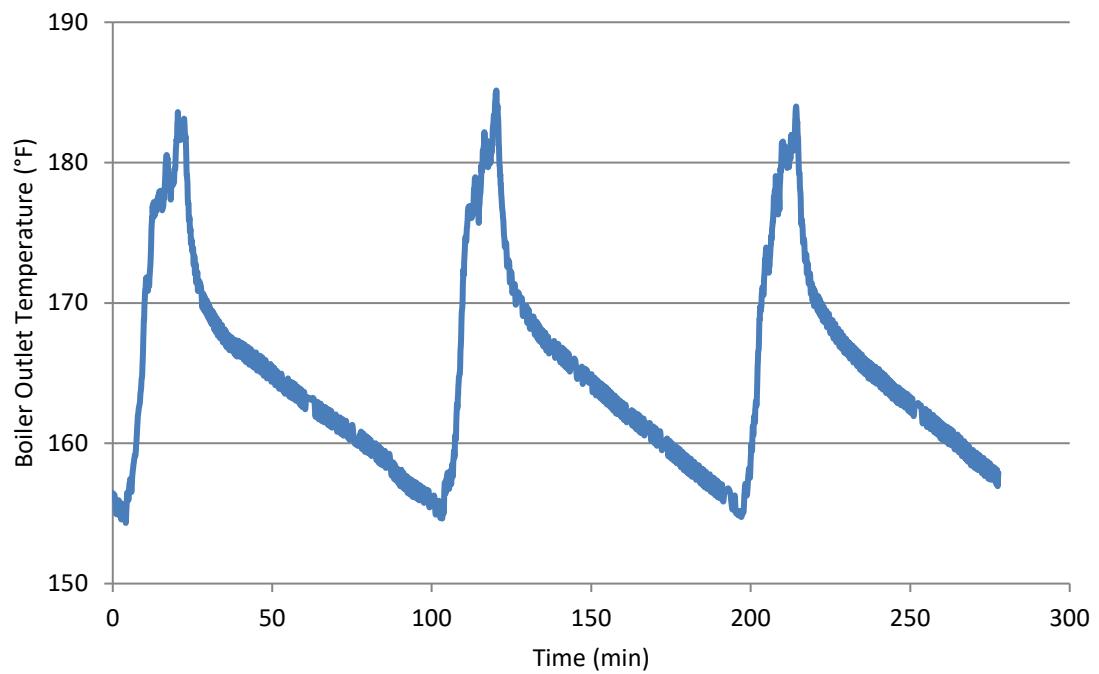
**Figure 35 Flue O<sub>2</sub>, Test 5, Cat I, 119 gal. storage**



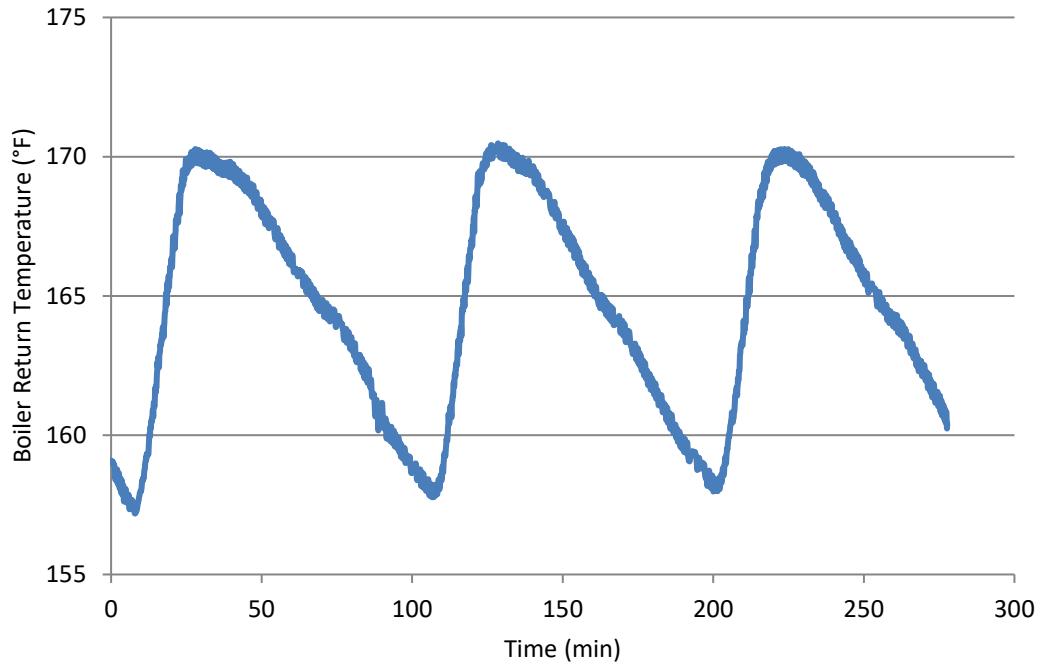
**Figure 36 Flue HC, Test 5, Cat I, 119 gal. storage**



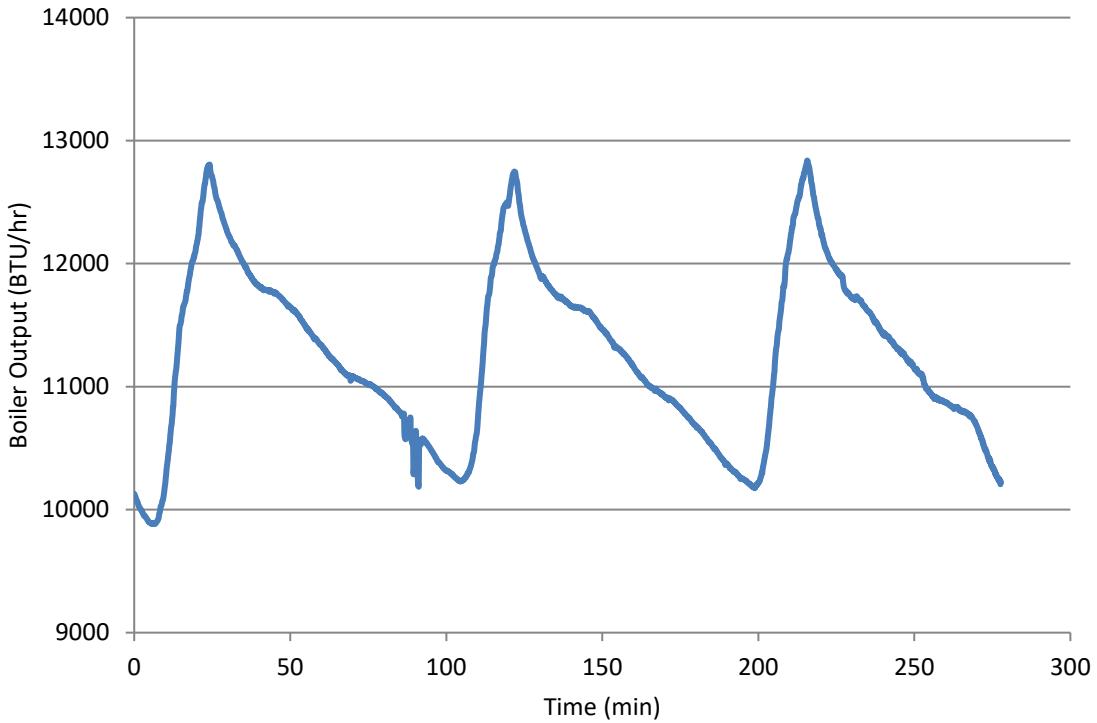
**Figure 37 Stack temperature, Test 5, Cat I, 119 gal. storage**



**Figure 38 Boiler outlet temperature, Test 5, Cat I, 119 gal. storage**



**Figure 39 Boiler return temperature, Test 5, Cat I, 119 gal. storage**



**Figure 40 Boiler output, Test 5, Cat I, 119 gal. storage**

Results of Test 6 – Category I, 119 Gallons of Thermal Storage

*Summary of conditions for test*

|                                       |                    |
|---------------------------------------|--------------------|
| Test Date                             | September 23, 2015 |
| Test Condition                        | Cat I              |
| Storage                               | Yes                |
| $\Delta T$ control change across tank | 7 °F               |

*Discussion of Test Condition*

On September 23<sup>rd</sup> 2015 a Category I test (15%) was conducted with storage. The purpose of this test is to run the boiler at less than or equal to 15% of the manufacturers nominal output which is 11,475 BTU/hr after taking into account the efficiency of the boiler. From this test the efficiency and PM emissions at the low load level are determined. The temperature control change across the tank was 7 °F. During the heat up period of a cycle the burner runs until the bottom temperature sensor reaches 161 °F and during the draw down period the burner re-fires when the

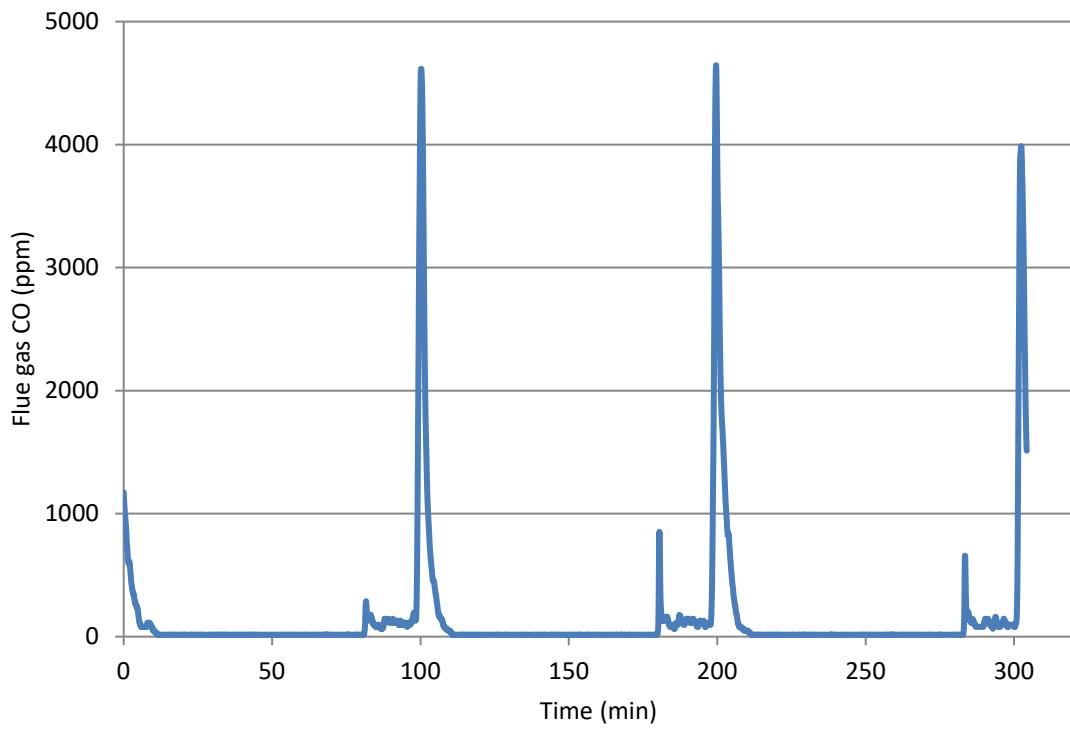
top temperature sensor hits 154 °F. The average output of the boiler for the test period was 9,754 BTU/hr.

#### *Discussion of Test Results*

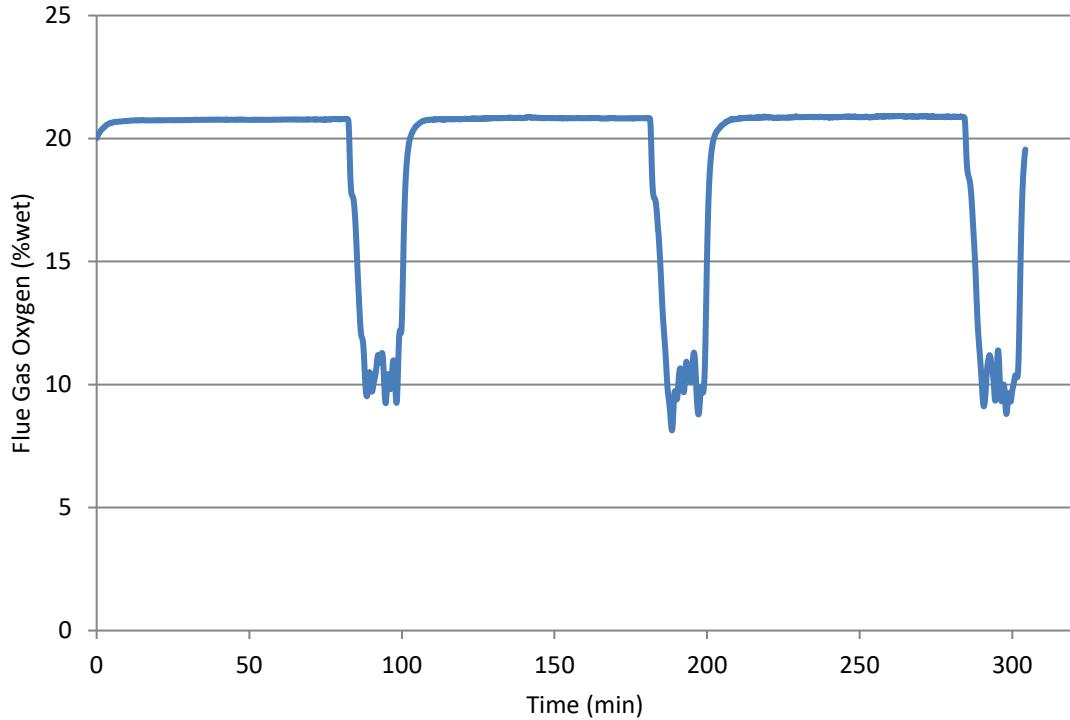
After an initial warmup period, particulate sampling in the dilution tunnel was conducted for 304.28 minutes from 12:52:30 to 17:56:47. The figures included for this test show that the boiler cycled three times during this test period and 9.4 lbs of fuel was consumed. It can also be seen that the draw down time for each cycle is approximately 75 minutes and the heat up is approximately 20 minutes. At the end of each heating cycle when the boiler reached the maximum control temperature the remaining fuel was burnt out and the boiler was subsequently switched into standby mode until it cooled enough to re-fire. Once the boiler temperature was cool enough to re-fire it initially went through the flush, fill, and ignite modes then stabilized once the target output was reached. During the test period the boiler had a 63.5% input/output efficiency. The overall particulate emission factor for the sampling period was 0.34 lb/MMBtu.

#### *Emissions overview*

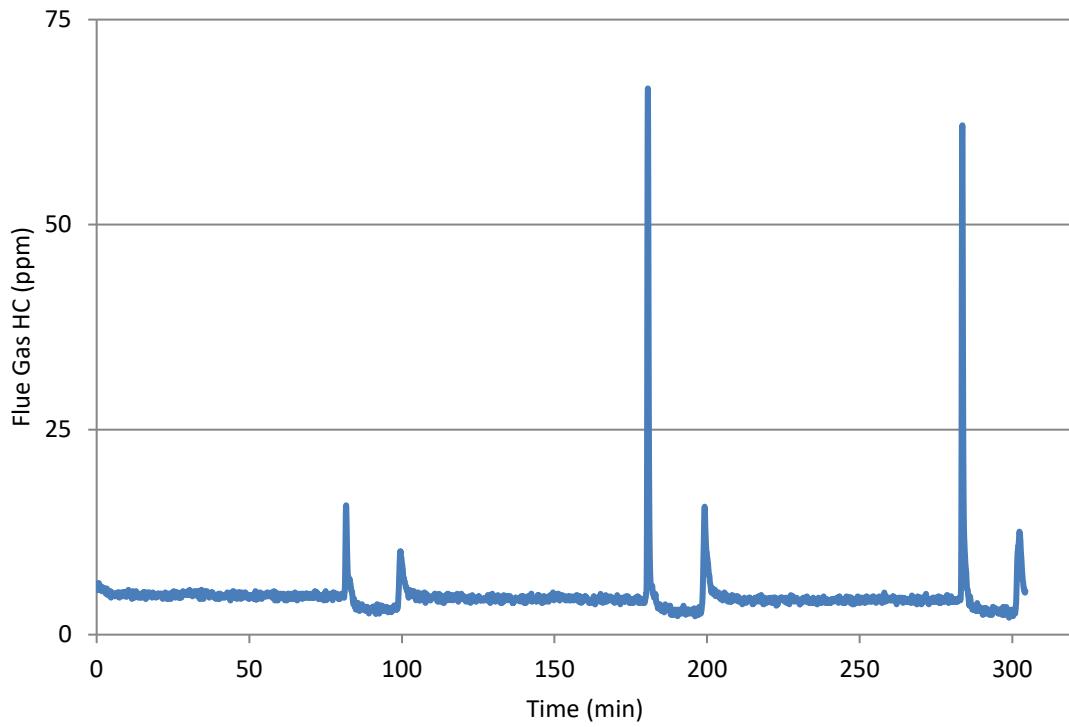
|                  |                        |
|------------------|------------------------|
| PM Concentration | 2.37 mg/m <sup>3</sup> |
| Emission Rate    | 1.50 g/hr              |
| Emission Index   | 1.79 g/kg fuel         |
| Emission Output  | 0.34 lb/MMBtu          |
| Avg. Stack CO    | 156 ppm                |



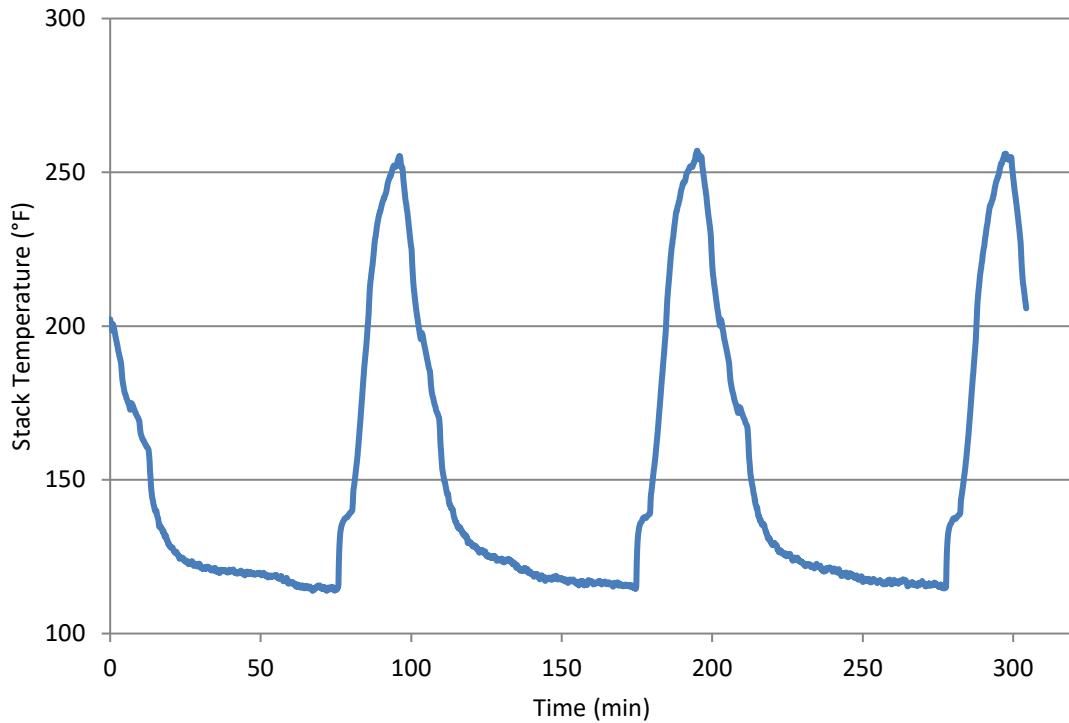
**Figure 41 Flue CO, Test 6, Cat I, 119 gal. storage**



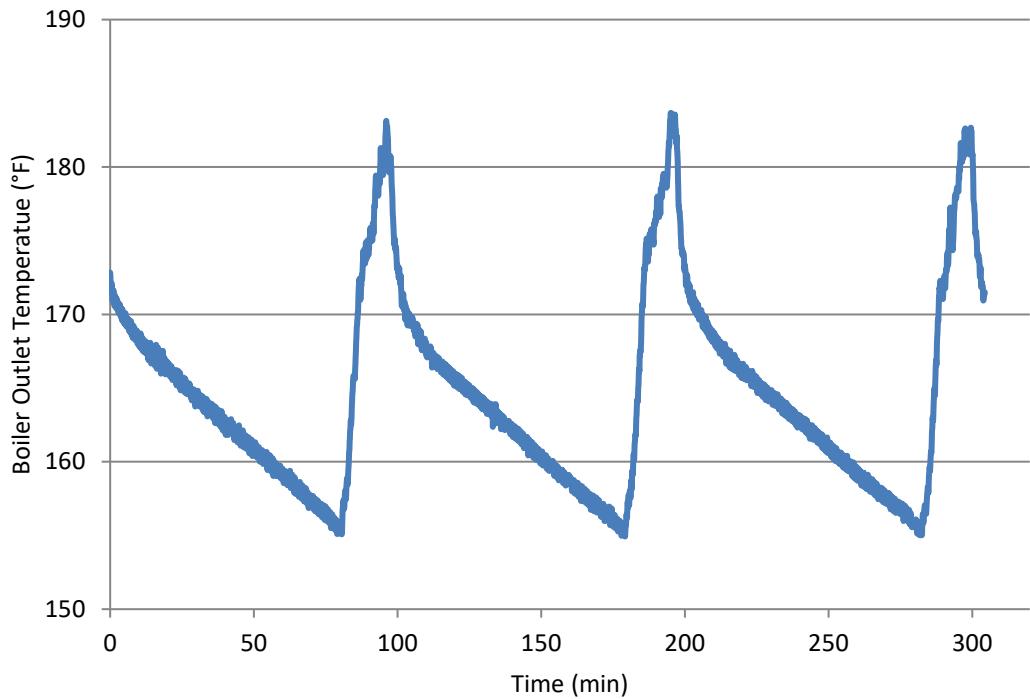
**Figure 42 Flue O<sub>2</sub>, Test 6, Cat I, 119 gal. storage**



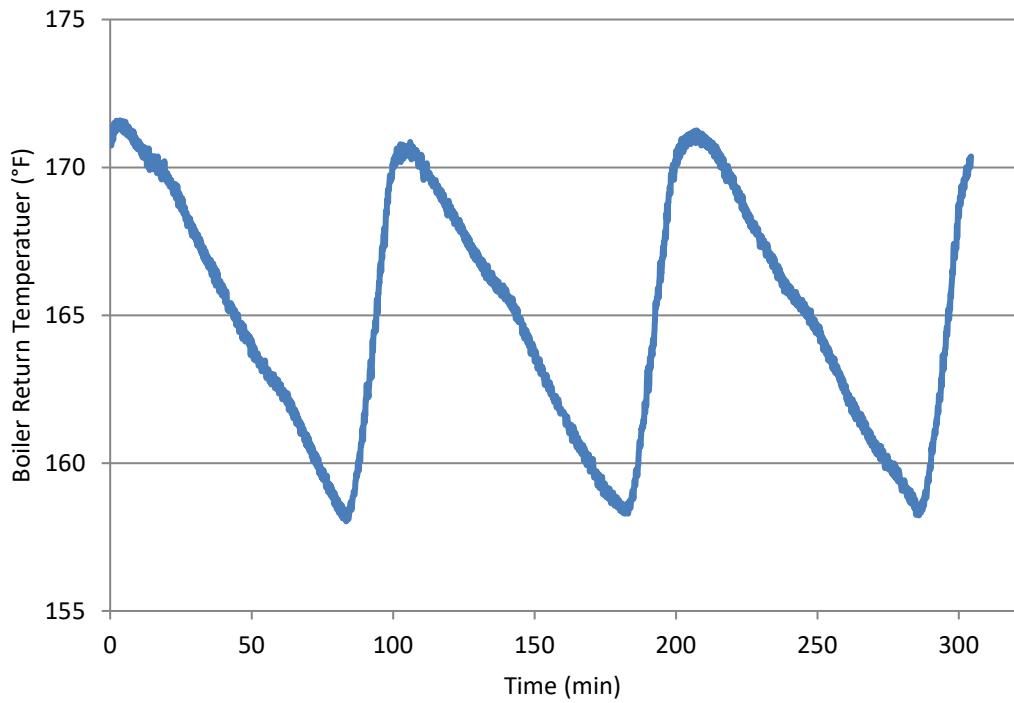
**Figure 43 Flue HC, Test 6, Cat I, 119 gal. storage**



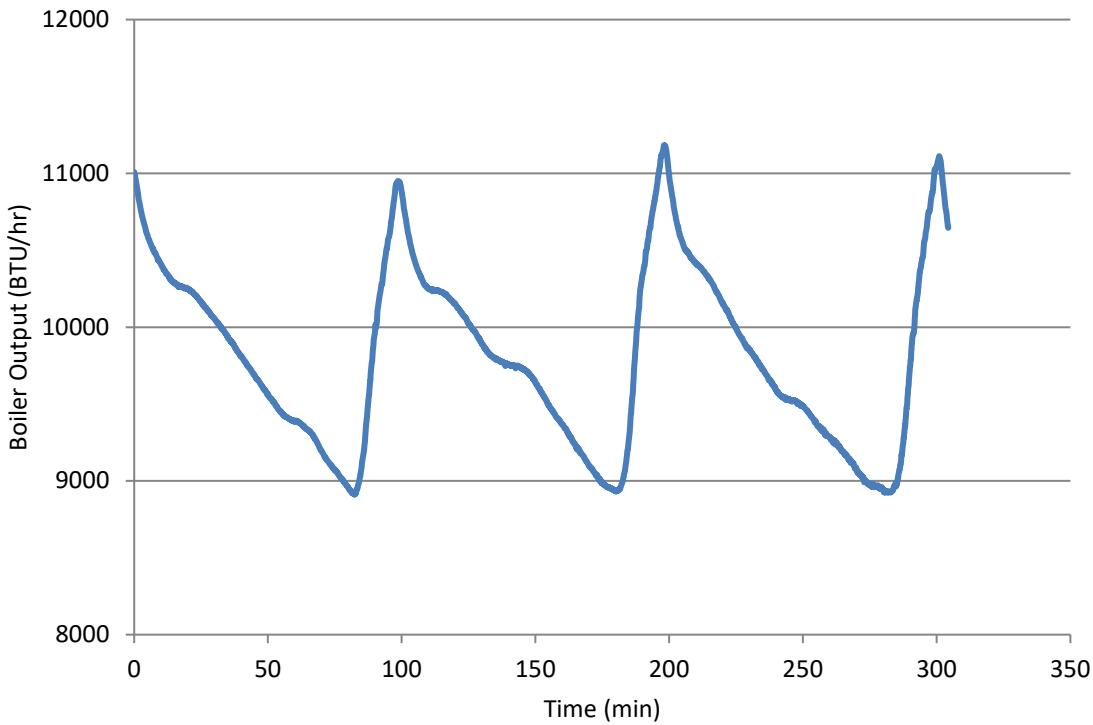
**Figure 44 Stack temperature, Test 6, Cat I, 119 gal. storage**



**Figure 45 Boiler outlet temperature, Test 6, Cat I, 119 gal. storage**



**Figure 46 Boiler return temperature, Test 6, Cat I, 119 gal. storage**



**Figure 47 Boiler output, Test 6, Cat I, 119 gal. storage**

Results of Test 7 – Category I, 119 Gallons of Thermal Storage

*Summary of conditions for test*

|                               |                  |
|-------------------------------|------------------|
| Test Date                     | October 23, 2015 |
| Test Condition                | Cat I            |
| Storage                       | Yes              |
| ΔT control change across tank | 20 °F            |

*Discussion of Test Condition*

On October 23<sup>rd</sup> 2015 a Category I test (15%) was conducted with storage. The purpose of this test is to run the boiler at less than or equal to 15% of the manufacturers nominal output which is 11,475 BTU/hr after taking into account the efficiency of the boiler. From this test the efficiency and PM emissions at the low load level are determined. The temperature control change across the tank was 20 °F to reduce cycling with storage. During the heat up period of a cycle the burner runs until the bottom temperature sensor reaches 165 °F and during a cool down period

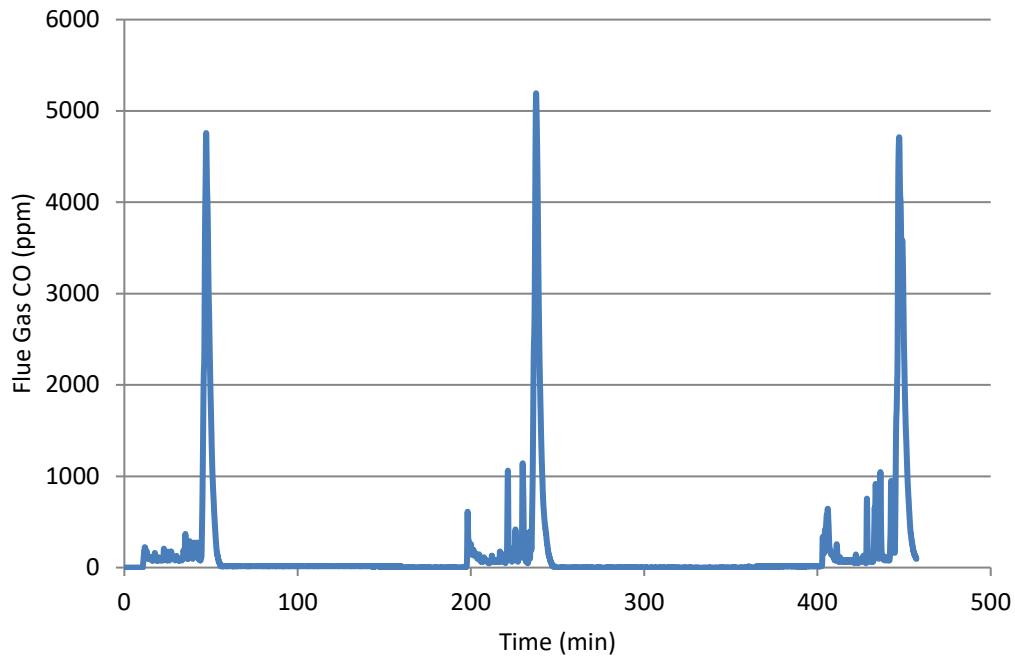
the burner re-fires when the top temperature sensor hits 145 °F. The average output of the boiler for the test periods was 12,104 BTU/hr.

#### *Discussion of Test Results*

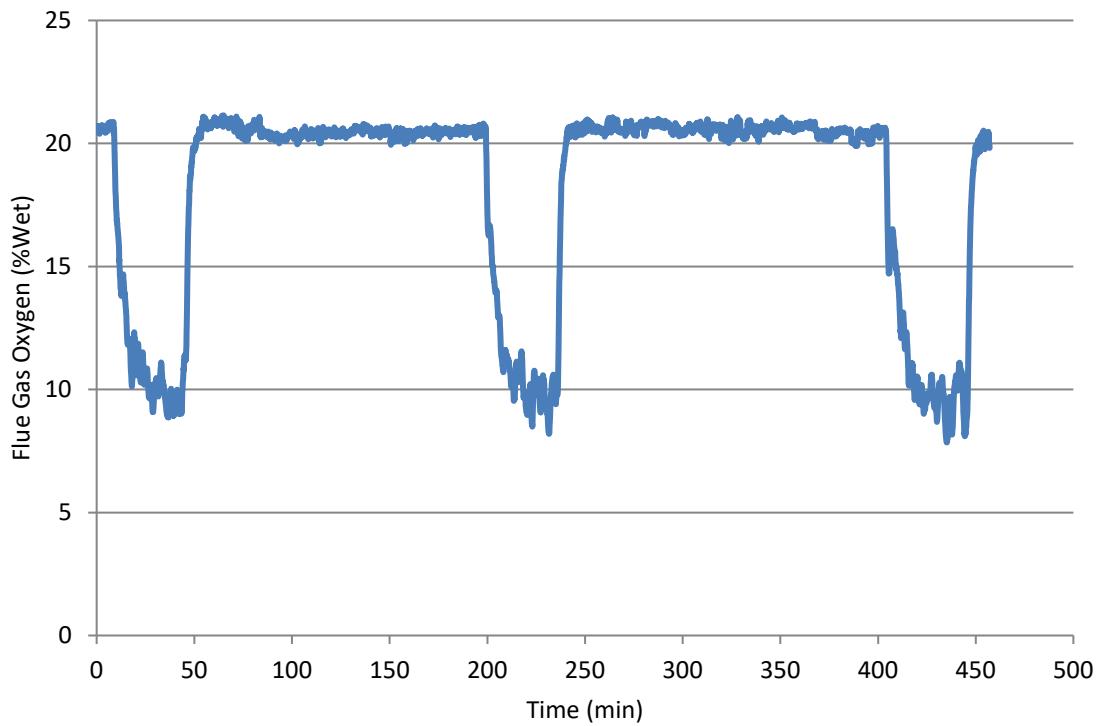
After an initial warmup period, particulate sampling in the dilution tunnel was conducted for three cycles which were from 10:40:10 to 11:46:00, 13:51:00 to 14:53:30, and 17:16:30 to 18:17:15 for a total sampling time of 189.08 minutes. The figures included for this test show that the boiler went through three cycles and the entire test period was 457 minutes during which 22.2 lbs of fuel were consumed. It can also be seen that the cool down time for each cycle is approximately 150 minutes while the burner run time is 30 minutes during heat up. At the end of each heating cycle when the boiler reached the maximum control temperature the remaining fuel was burnt out and the boiler was subsequently switched into standby mode until it cooled enough to re-fire. Once the boiler temperature was cool enough to re-fire it initially went through the flush, fill, and ignite modes then stabilized once the target output was reached. The input/output efficiency during the test period was 68.1%. The overall particulate emission factor for the three sampling intervals was 0.15 lb/MMBtu

#### *Emissions overview*

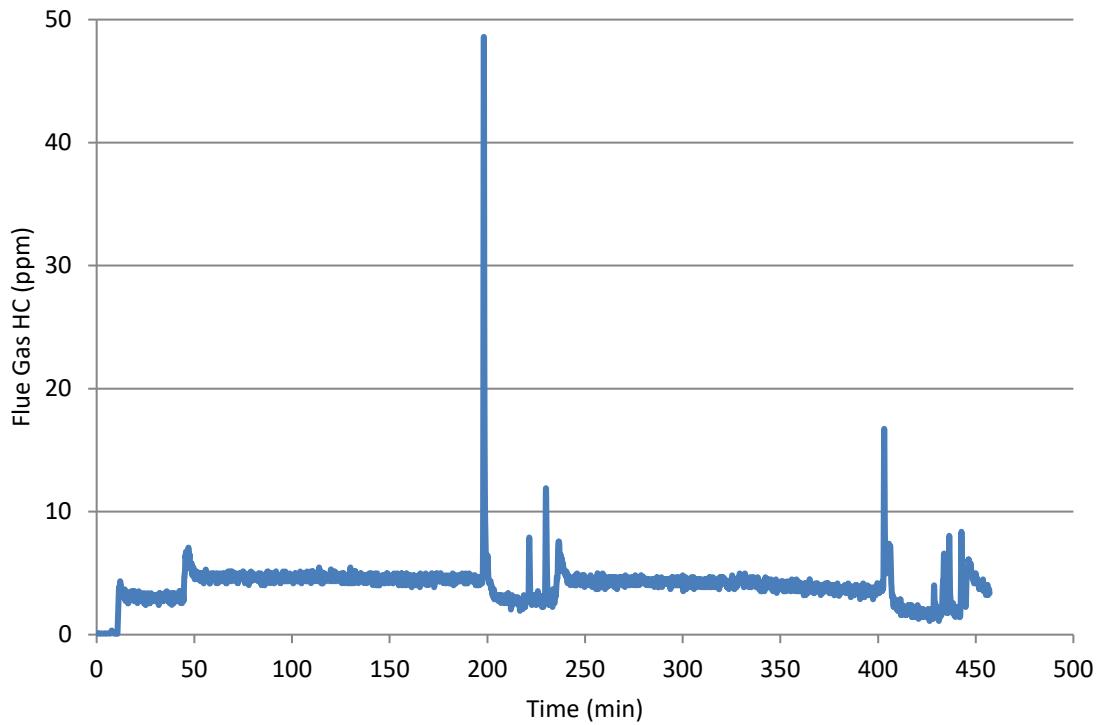
|                  |                        |
|------------------|------------------------|
| PM Concentration | 4.25 mg/m <sup>3</sup> |
| Emission Rate    | 1.15 g/hr              |
| Emission Index   | 0.87 g/kg fuel         |
| Emission Output  | 0.15 lb/MMBtu          |
| Avg. Stack CO    | 423 ppm                |



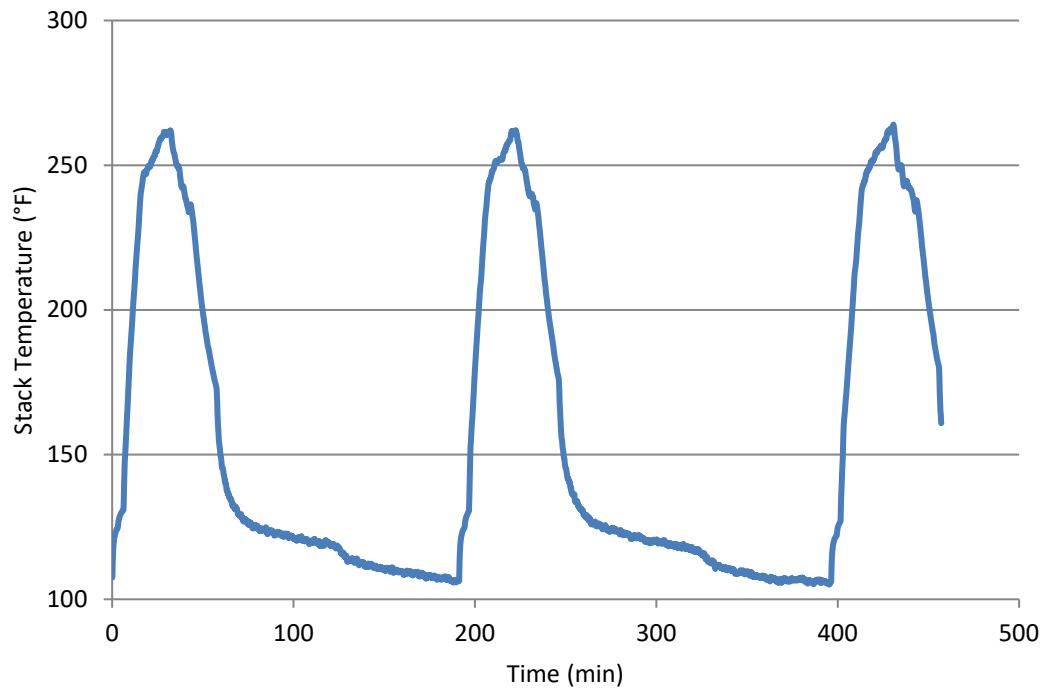
**Figure 48 Flue CO, Test 7, Cat I, 119 gal. storage**



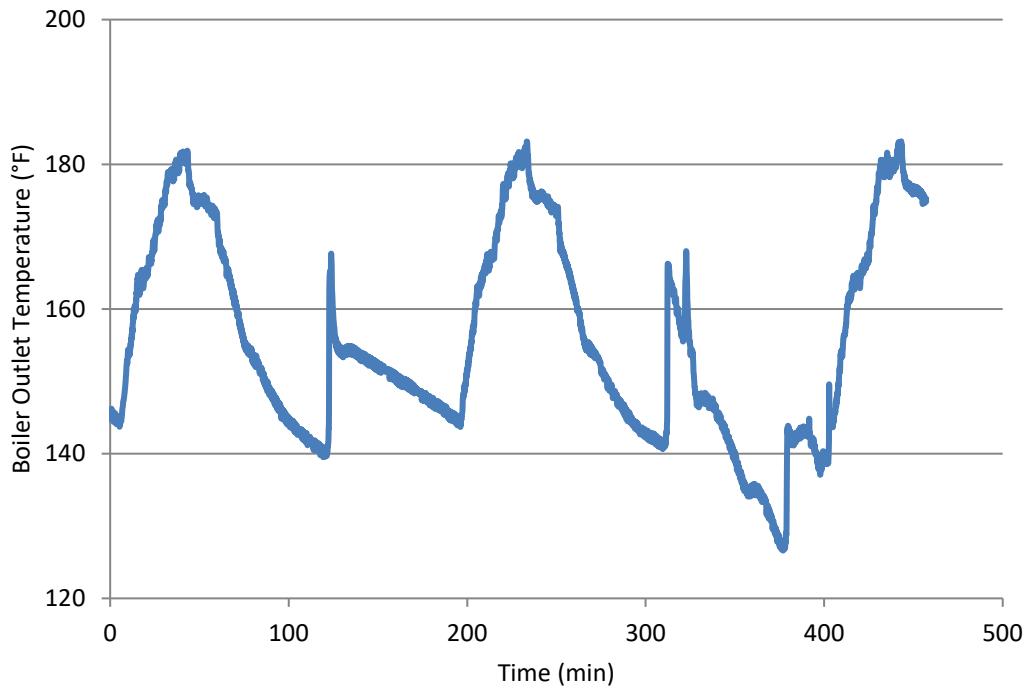
**Figure 49 Flue O<sub>2</sub>, Test 7, Cat I, 119 gal. storage**



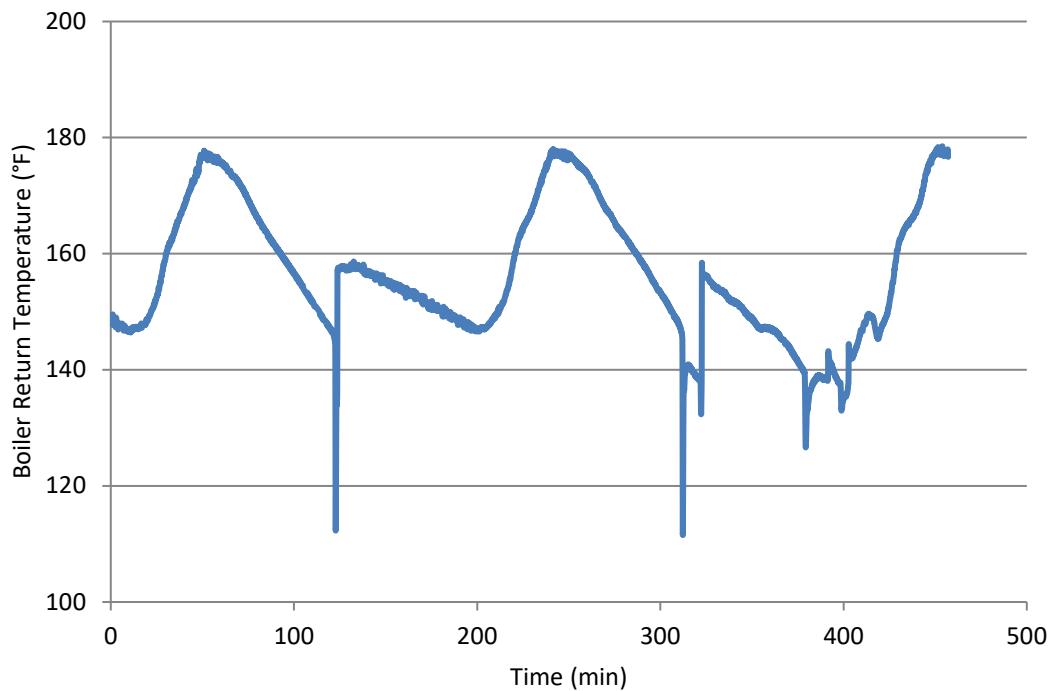
**Figure 50 Flue HC, Test 7, Cat I, 119 gal. storage**



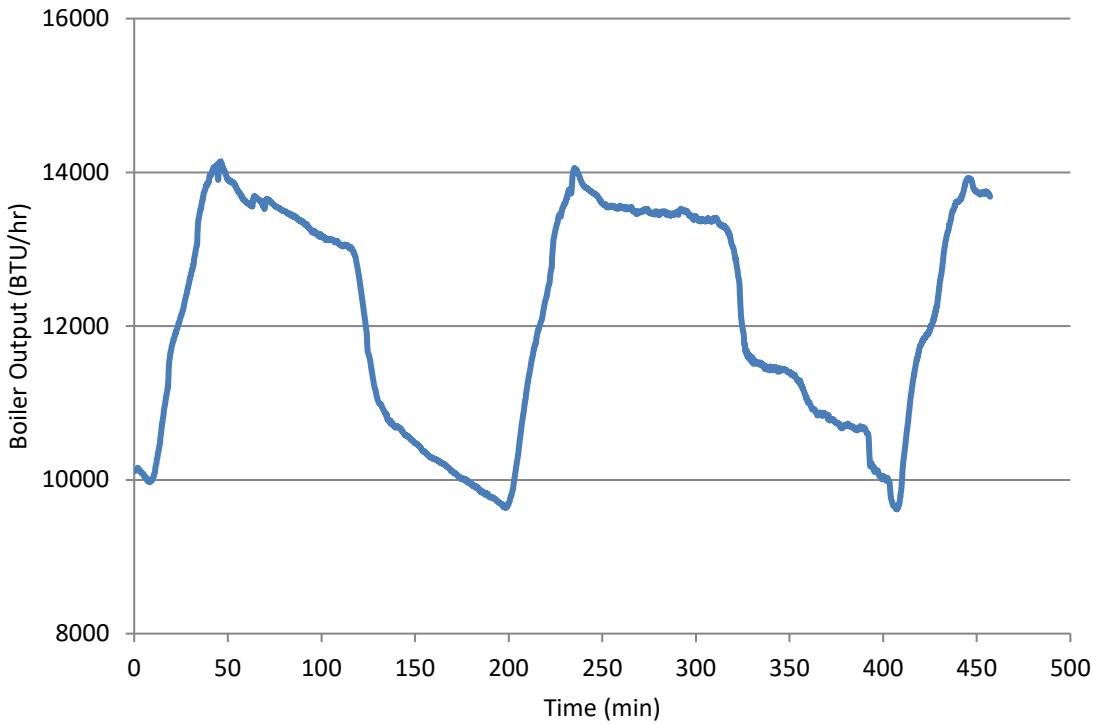
**Figure 51 Stack temperature, Test 7, Cat I, 119 gal. storage**



**Figure 52 Boiler outlet temperature, Test 7, Cat I, 119 gal. storage**



**Figure 53 Boiler return temperature, Test 7, Cat I, 119 gal. storage**



**Figure 54 Boiler output, Test 7, Cat I, 119 gal. storage**

Results of Test 8 – Category I, 119 Gallons of Thermal Storage

*Summary of conditions for test*

|                               |                   |
|-------------------------------|-------------------|
| Test Date                     | November 18, 2015 |
| Test Condition                | Cat I             |
| Storage                       | Yes               |
| ΔT control change across tank | 20 °F             |

#### *Discussion of Test Condition*

On November 18<sup>th</sup> 2015 a Category I test (15%) was conducted with storage. The purpose of this test is to run the boiler at less than or equal to 15% of the manufacturers nominal output which is 11,475 BTU/hr when the efficiency of the boiler is factored in. From this test the overall efficiency and PM emissions can be determined at the low load level. In order to reduce cycling with storage the temperature control change across the tank was 11 °C. During the heat up period of a cycle the burner runs until the bottom temperature sensor reaches 165 °F and during a cool

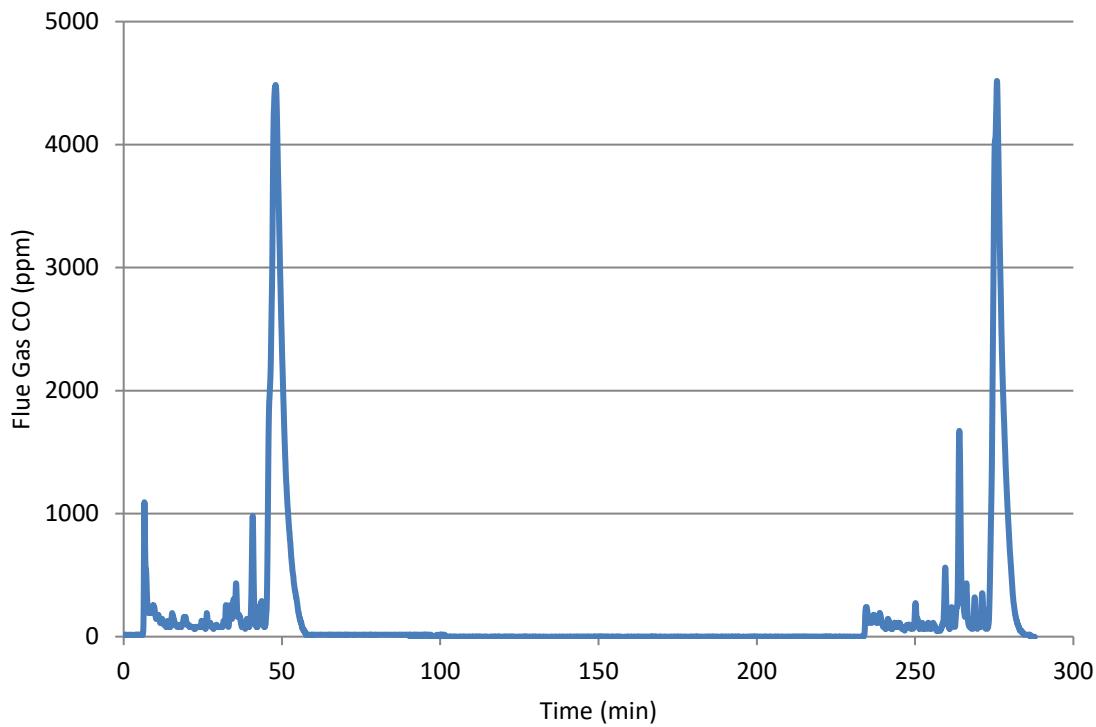
down period the burner re-fires when the top temperature sensor hits 145 °F. The average output of the boiler for the entire test period was 10,956 BTU/hr.

#### *Discussion of Test Results*

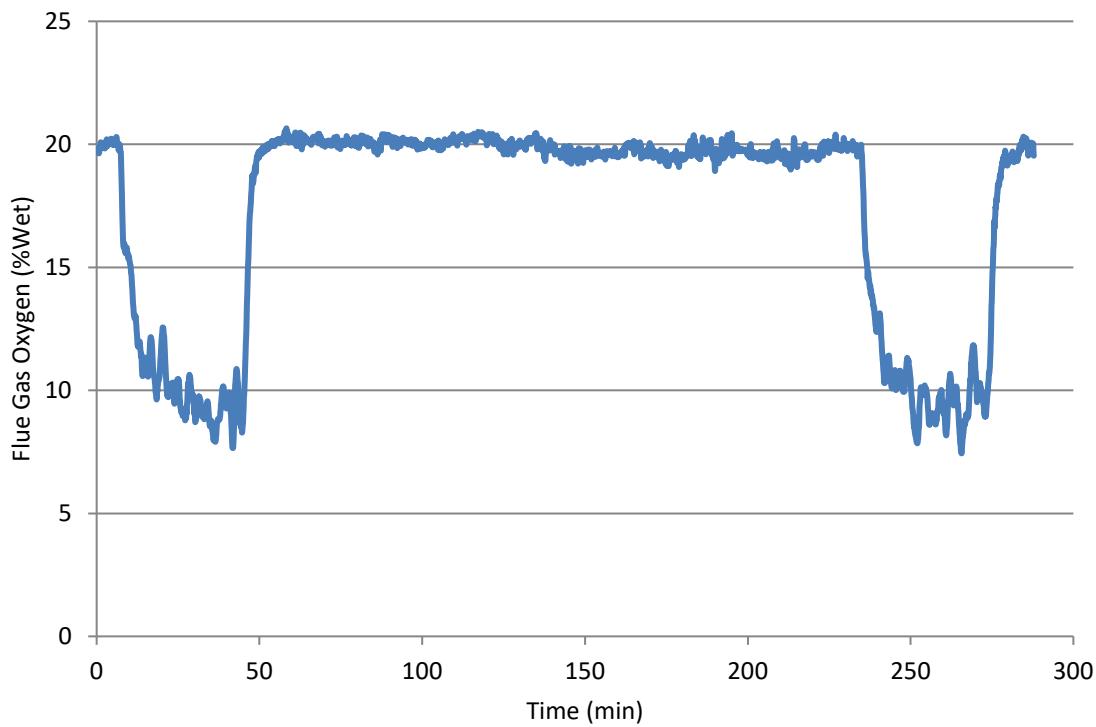
After the initial warm up period the boiler was cooled and particulate sampling in the dilution tunnel was conducted for two separate heating cycles the first being from 12:11:10 to 13:10:04 and the second beginning at 15:57:17 and ending at 16:59:00 for a total sampling time of 120.6 minutes. The figures included for this test show that the boiler went through three cycles and the entire test period was 457.1 minutes during which 22.2 lbs of fuel were consumed. The entire test period was 457 minutes during which 16.0 lbs of fuel was consumed. The included figures for this test show the two cycles the boiler went through and it can be seen that each cycle consisted of approximately a 30 minute heating period and a 200 minute cool down period. Once the boiler reached its maximum control temperature the remaining fuel was burnt out and the boiler switched into standby mode until the tank cooled enough to re-fire. Once the boiler re-fired it initially went through the flush, fill, and “ignite” modes then stabilized once the target output was reached. For the test period the boiler had a 71.3% input/output efficiency. The overall particulate emission factor for the two sampling cycles was 0.13 lb/MMBtu

#### *Emissions overview during sampling periods*

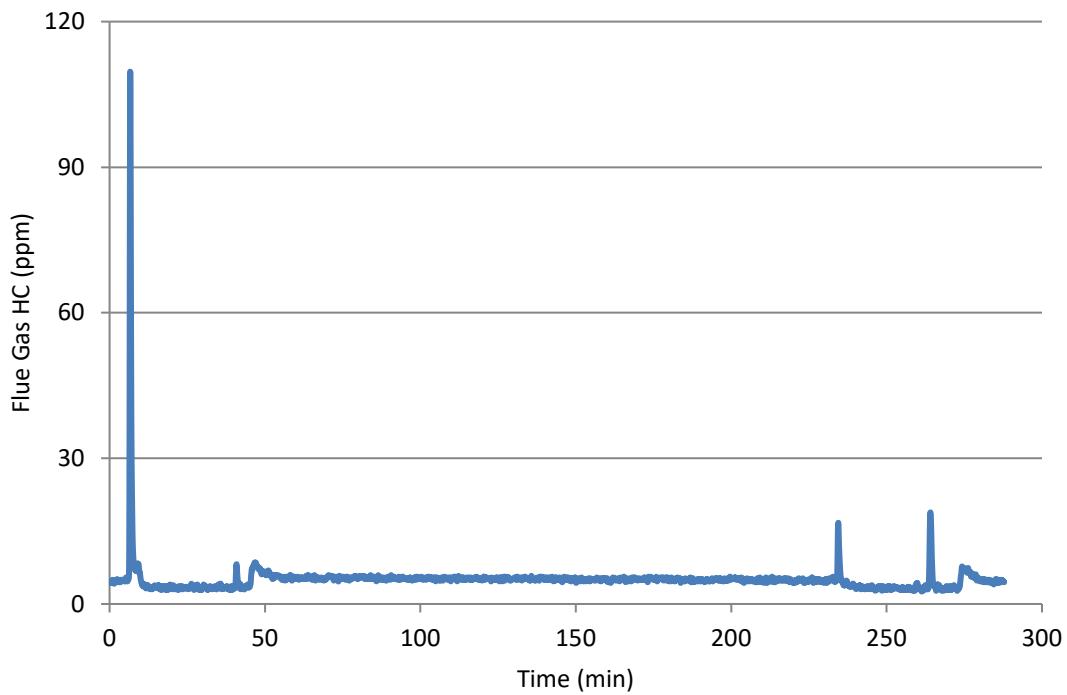
|                  |                        |
|------------------|------------------------|
| PM Concentration | 4.27 mg/m <sup>3</sup> |
| Emission Rate    | 1.16 g/hr              |
| Emission Index   | 0.77 g/kg fuel         |
| Emission Output  | 0.13 lb/MMBtu          |
| Avg. Stack CO    | 395 ppm                |



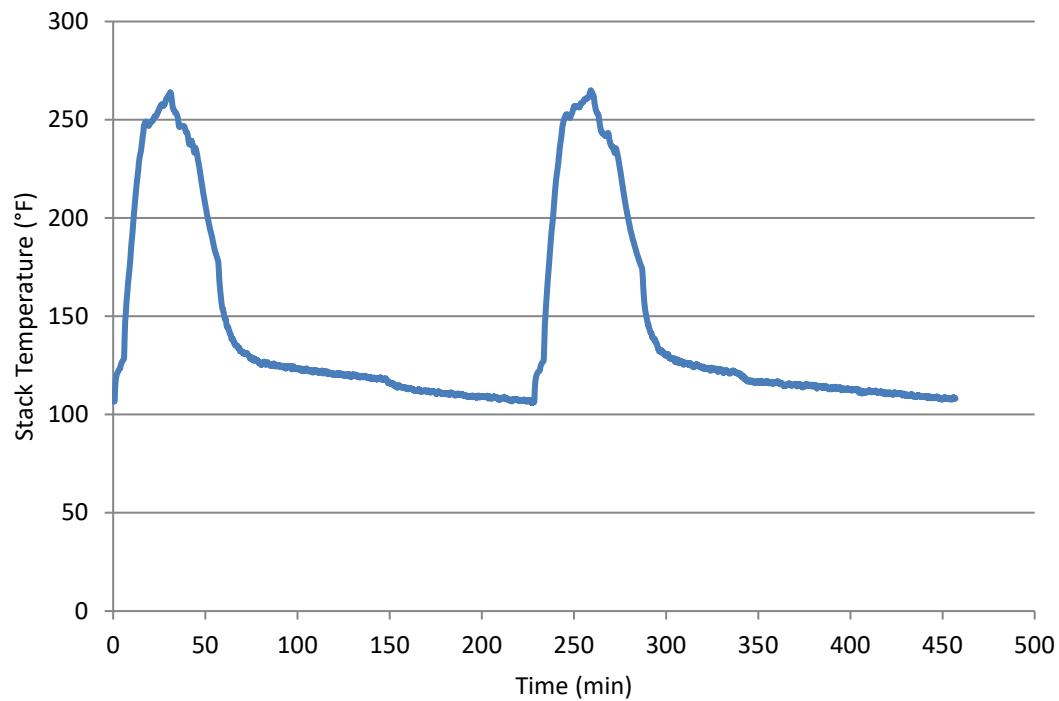
**Figure 55 Flue CO, Test 8, Cat I, 119 gal. storage**



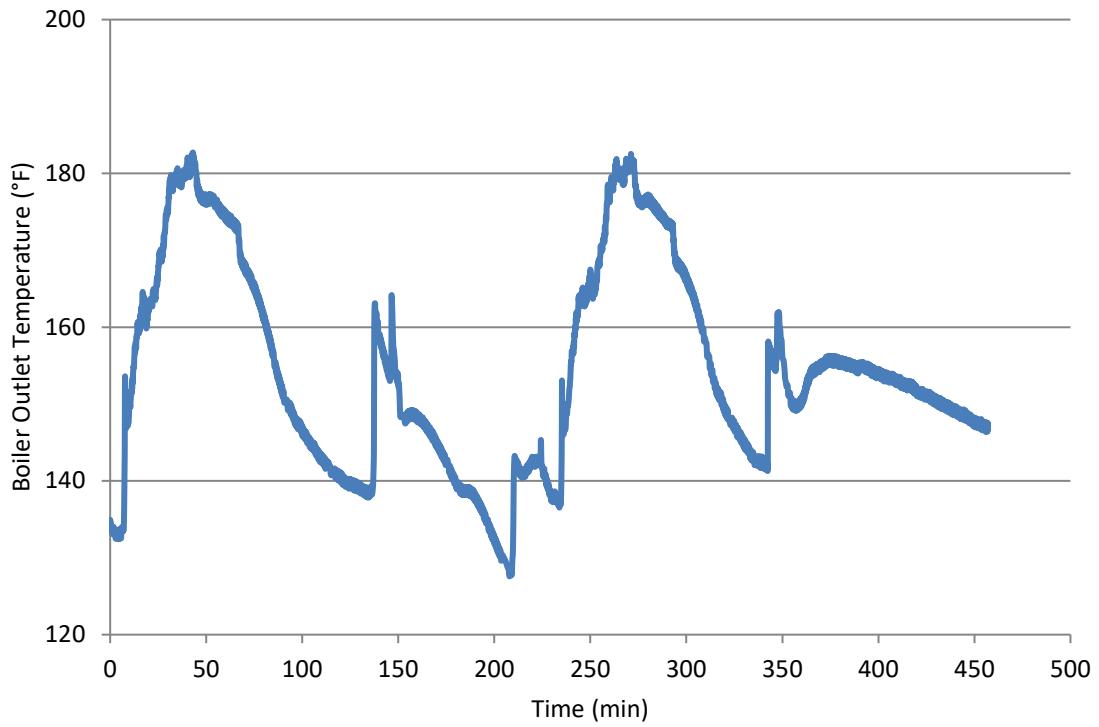
**Figure 56 Flue O<sub>2</sub>, Test 8, Cat I, 119 gal. storage**



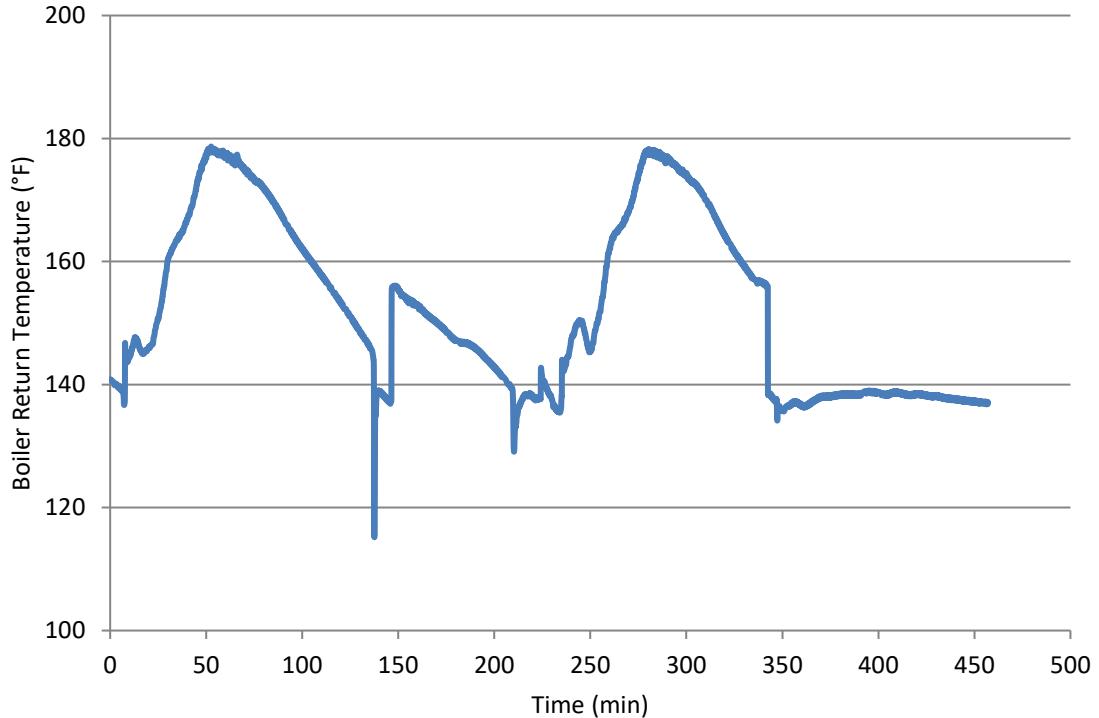
**Figure 57 Flue HC, Test 8, Cat I, 119 gal. storage**



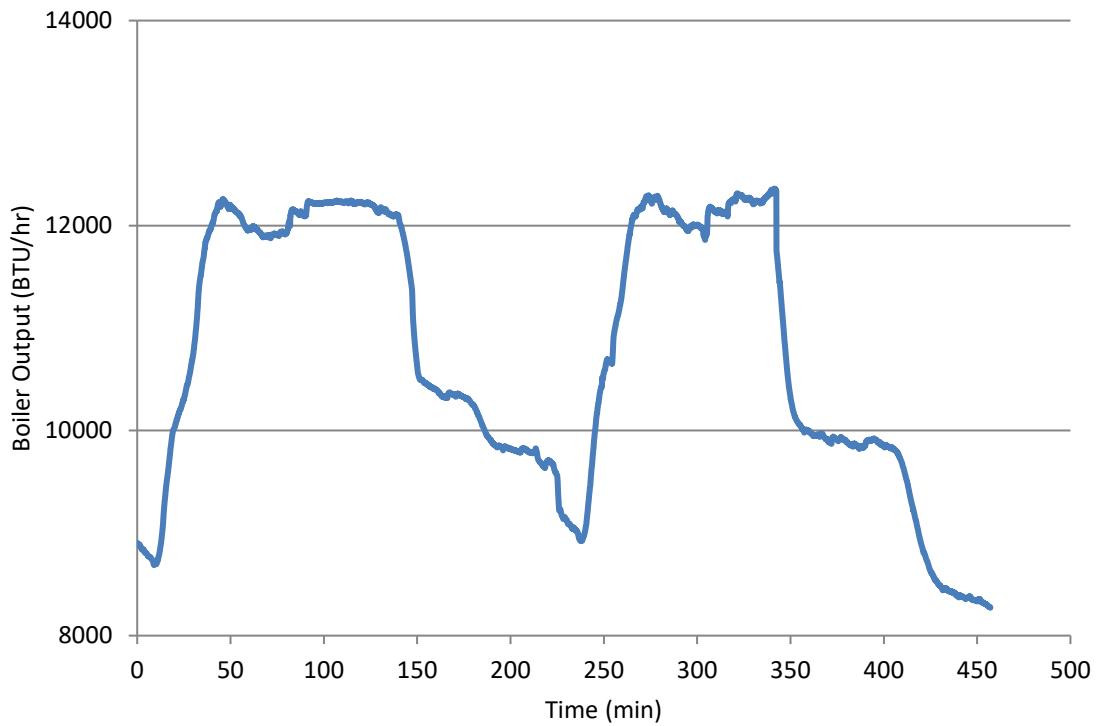
**Figure 58 Stack temperature, Test 8, Cat I, 119 gal. storage**



**Figure 59 Boiler outlet temperature, Test 8, Cat I, 119 gal. storage**



**Figure 60 Boiler return temperature, Test 8, Cat I, 119 gal. storage**



**Figure 61 Boiler output, Test 8, Cat I, 119 gal. storage**

Results of Test 9 – Category I, 210 Gallons of Thermal Storage

*Summary of conditions for test*

|                                       |                  |
|---------------------------------------|------------------|
| Test Date                             | November 4, 2016 |
| Test Condition                        | Cat I            |
| Storage                               | Yes              |
| Storage Capacity                      | 210 gallons      |
| $\Delta T$ control change across tank | 20 °F            |

#### *Discussion of Test Condition*

On November 4<sup>th</sup> 2016 a Category I test (15%) was conducted with storage. The purpose of this test is to run the boiler at less than or equal to 15% of the manufacturers nominal output which is 11,475 BTU/hr when the efficiency of the boiler is factored in. From this test the overall

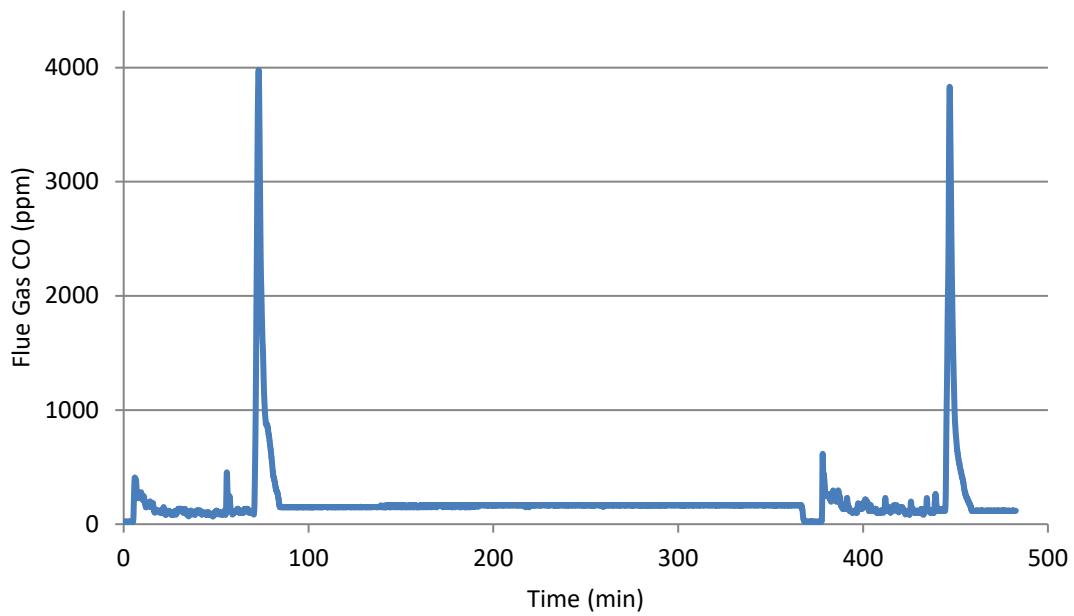
efficiency and PM emissions can be determined at the low load level. The temperature control across the tank was 20 °F. The storage used in this test was a 210 gallon highly insulated steel storage tank. The average output of the boiler for the entire test period was 11,057 BTU/hr.

### *Discussion of Test Results*

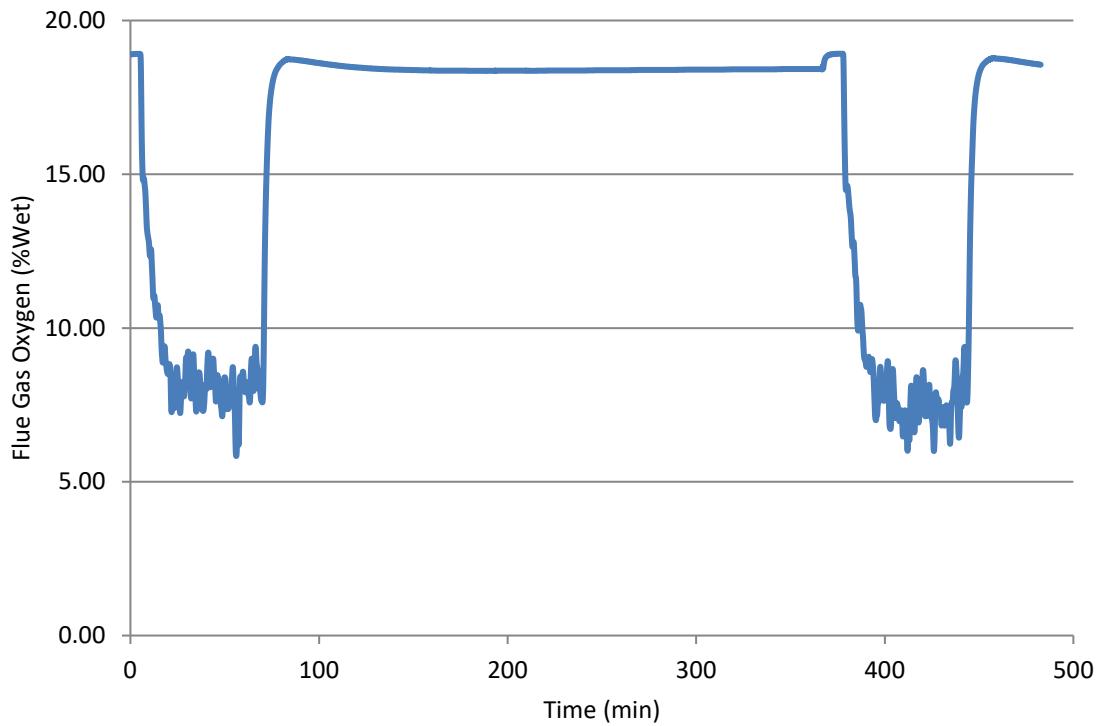
After the initial warm up period the boiler was cooled and particulate sampling in the dilution tunnel was conducted for two separate heating cycles for a total of 167 minutes. The first sampling cycle was from 9:38:00 to 11:00:35 am and the second was from 3:50:35 to 5:14:40. The entire test period lasted 456.67 minutes and 22.33 lbs of fuel was consumed. From the included figures it can be seen that the boiler cycled two times. Each cycle lasted approximately 350 minutes with a 75 minute heat-up and a 275 minute cool down. At the end of each heating period when the temperature sensor reached its limit the boiler burned the remaining fuel and switched into standby mode until the tank cooled enough to re-fire. Once the boiler re-fired it initially went through the flush, fill, and ignite modes then stabilized once the target output was reached. For the test period the boiler had an input/output efficiency of 74.1%. The overall particulate emission factor for the entire sampling period was 0.14 lb/MMBtu.

### *Emissions overview during sampling periods*

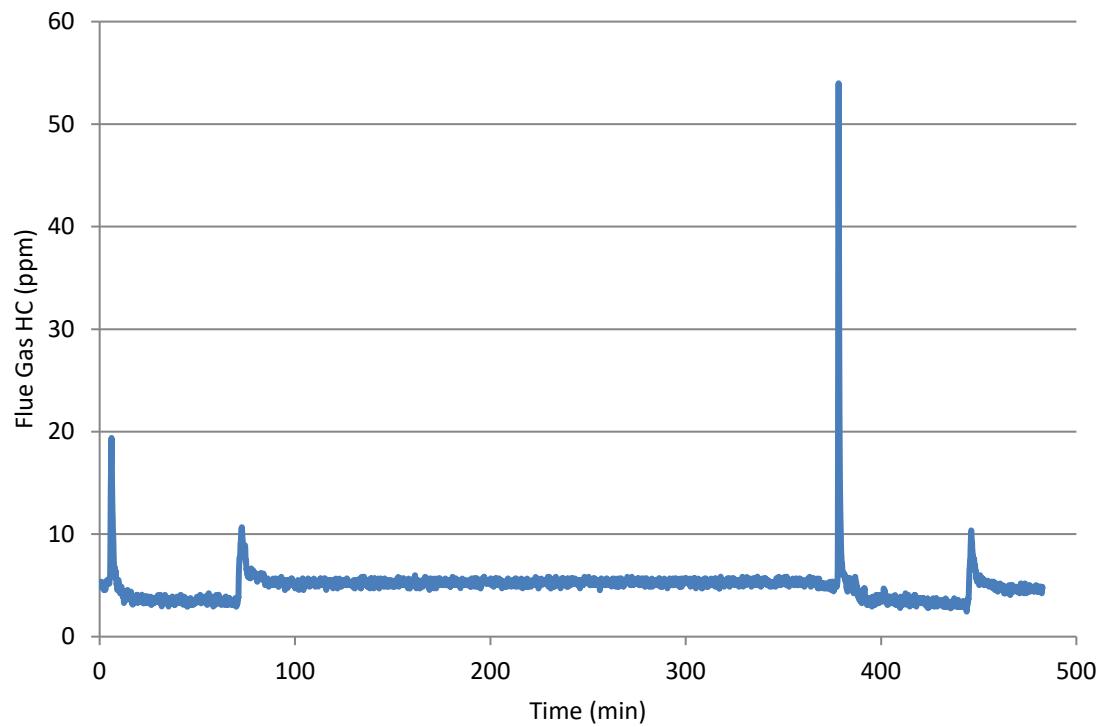
|                  |                        |
|------------------|------------------------|
| PM Concentration | 5.37 mg/m <sup>3</sup> |
| Emission Rate    | 1.21 g/hr              |
| Emission Index   | 0.83 g/kg fuel         |
| Emission Output  | 0.14 lb/MMBtu          |
| Avg. Stack CO    | 289 ppm                |



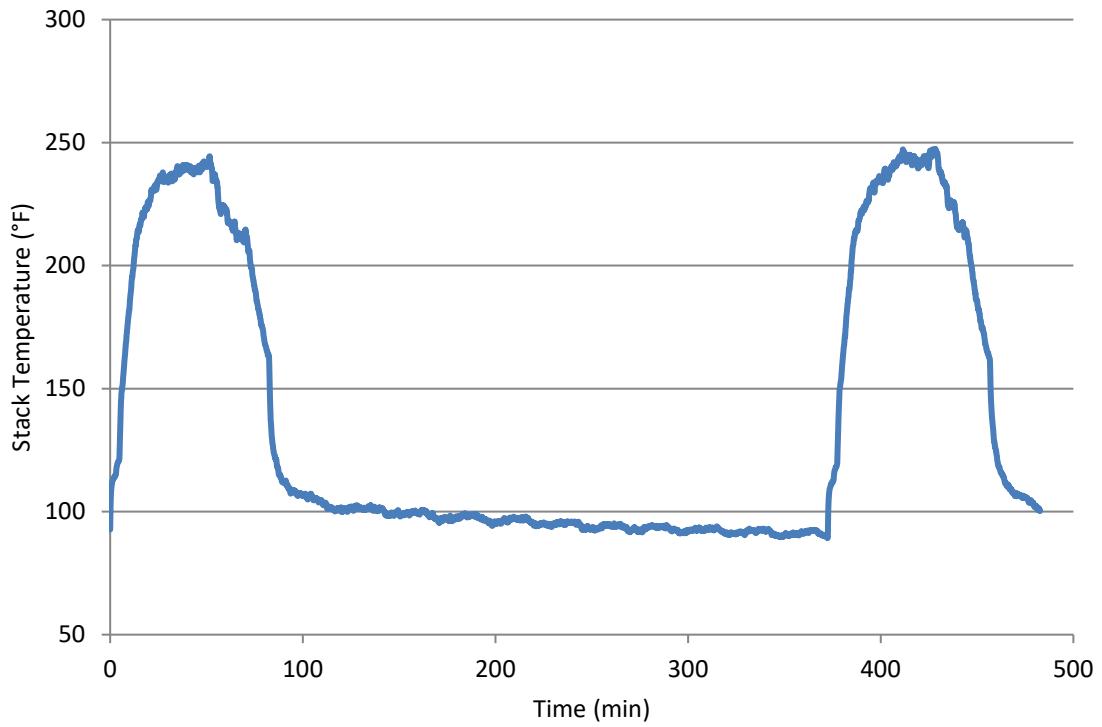
**Figure 62 Flue CO, Test 9, Cat I, 210 gal. storage**



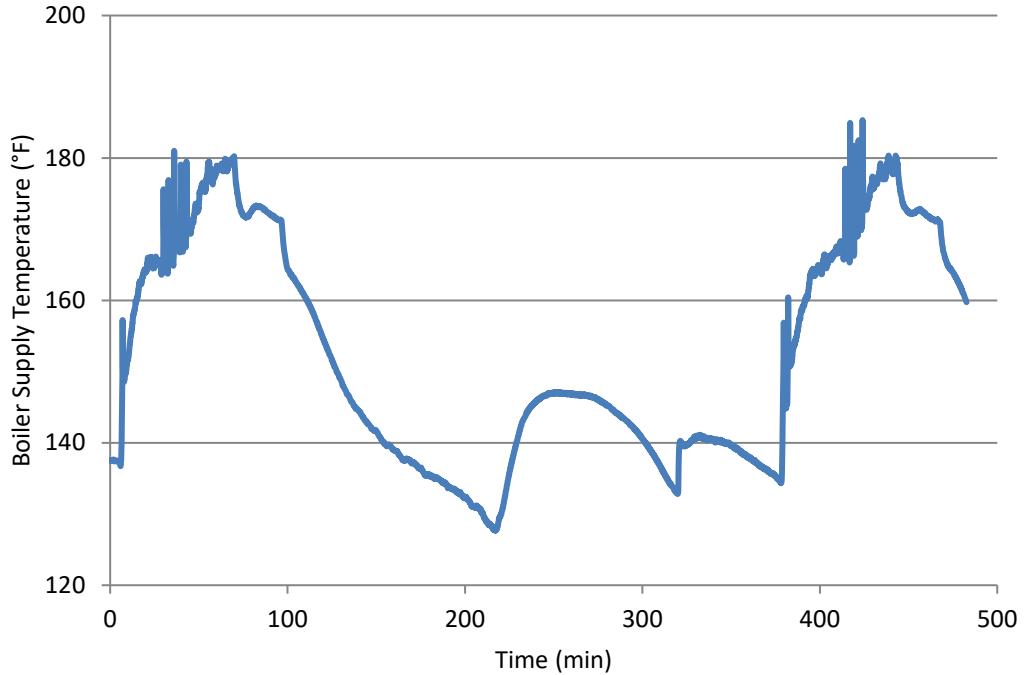
**Figure 63 Flue O<sub>2</sub>, Test 9, Cat I, 210 gal. storage**



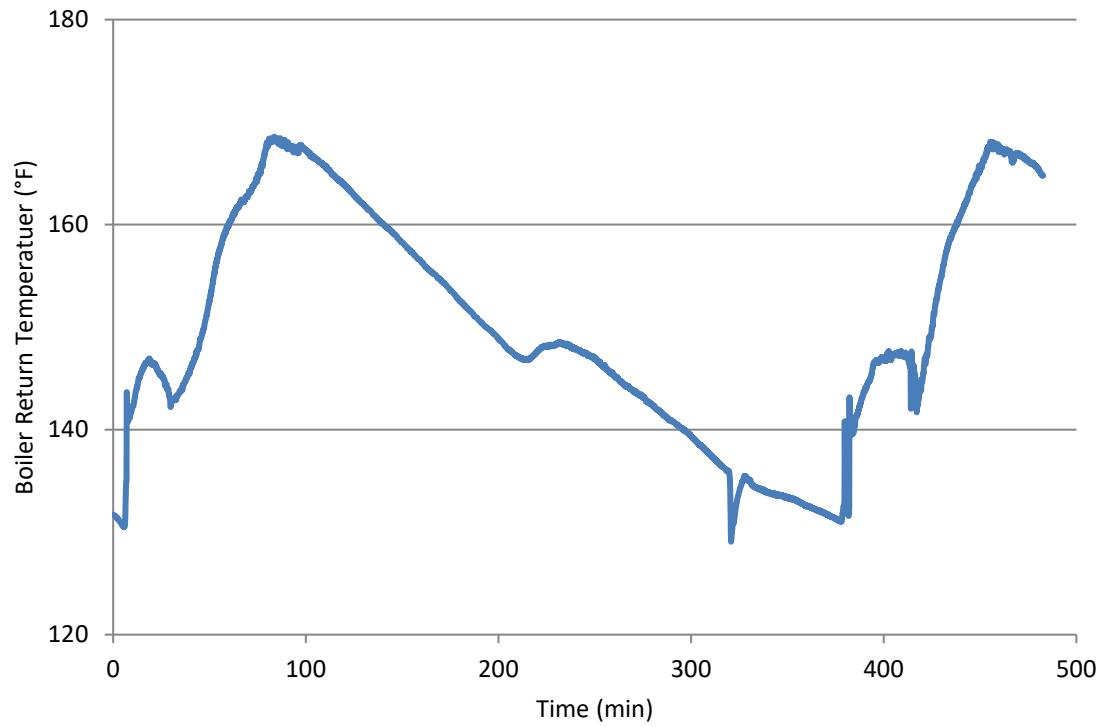
**Figure 64 Flue HC, Test 9, Cat I, 210 gal. storage**



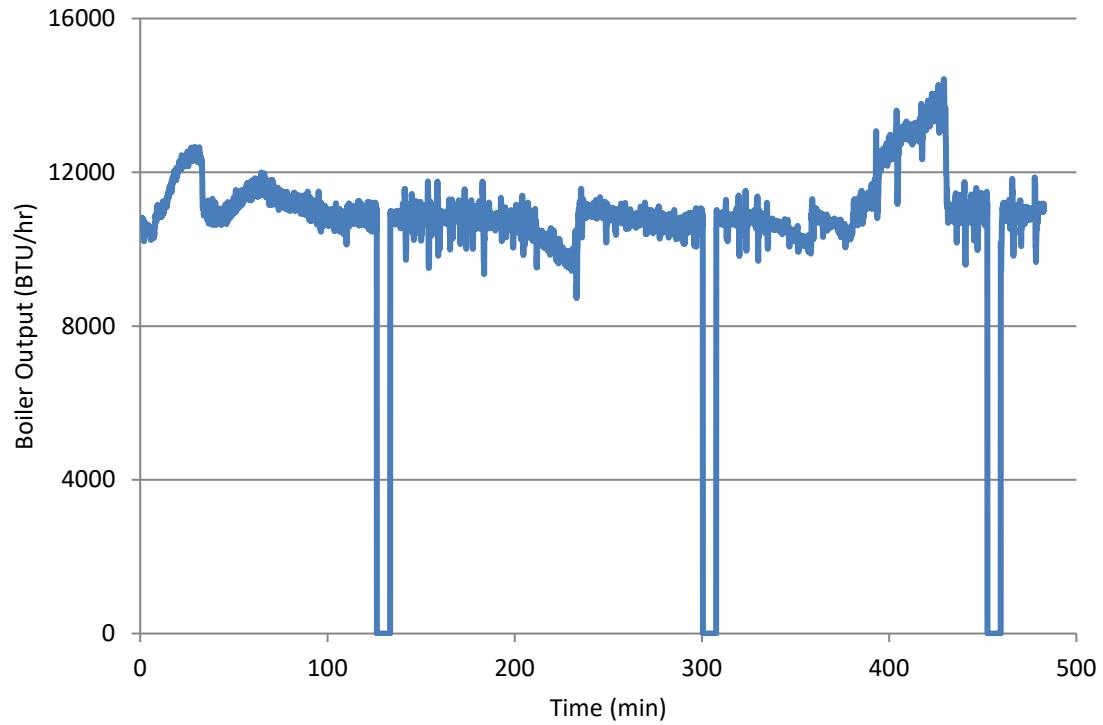
**Figure 65 Stack temperature, Test 9, Cat I, 210 gal. storage**



**Figure 66 Boiler outlet temperature, Test 9, Cat I, 210 gal. storage**



**Figure 67 Boiler return temperature, Test 9, Cat I, 210 gal. storage**



**Figure 68 Boiler output, Test 9, Cat I, 210 gal. storage**

## Emulated Load Test Results

### Results of Test 10 – April Profile, No Storage

#### *Summary of conditions for test*

|                               |                            |
|-------------------------------|----------------------------|
| Test Date                     | June 6 to 7, 2016          |
| Test Condition                | April 24 hour load profile |
| Storage                       | No                         |
| Storage Tank Capacity         | N/A                        |
| ΔT control change across tank | N/A                        |

#### *Discussion of Test Condition*

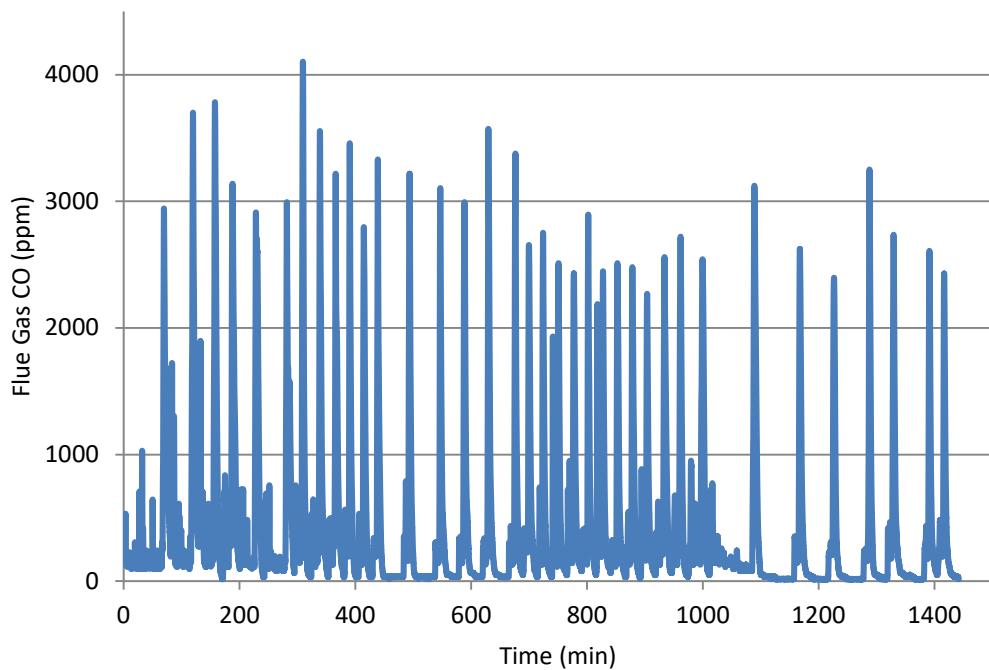
On June 6<sup>th</sup>-7<sup>th</sup> 2015 a 24 hour April load profile test was conducted. The purpose of this test is to determine the emissions and efficiency of the boiler based on actual in home usage. In order to achieve this, a load pattern emulating the boiler output in one hour increments was applied to the boiler's control system. The target load pattern was the output of the boiler for an average April weekday at a simulation home located in Albany, New York. The average output of the boiler during this test was 10,194 BTU/hr.

#### *Discussion of Test Results*

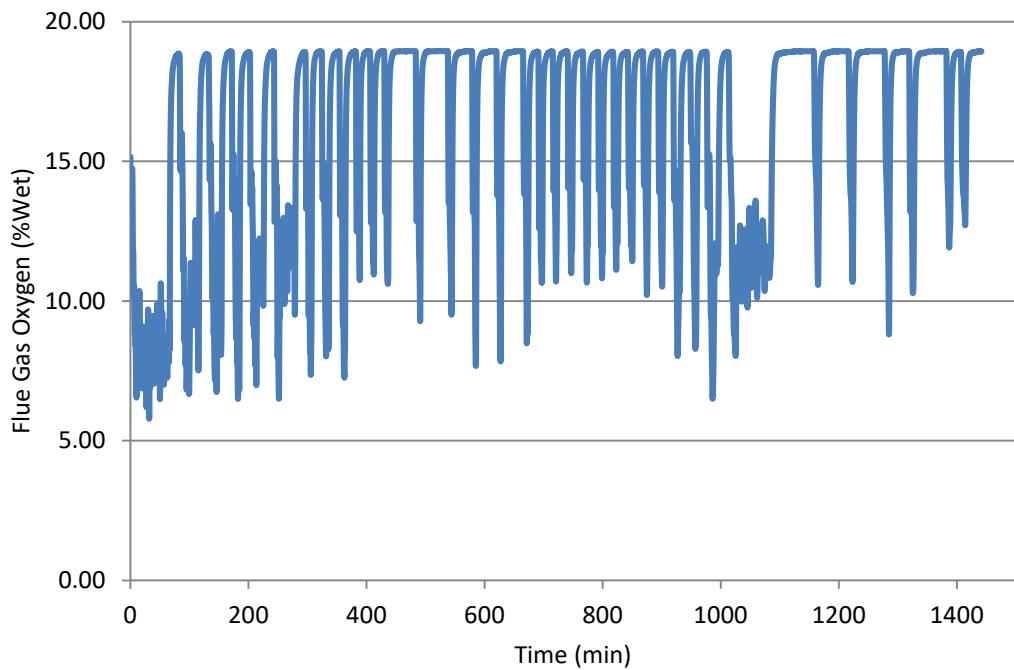
Particulate sampling in the dilution tunnel began at 11:15:00am on June 6<sup>th</sup> and completed at 11:15:00am on June 7<sup>th</sup> for a 24 hour (1440 minute) sampling period. The total fuel consumed during the test was 50.6 lbs. From the included figures, it can be seen that the boiler cycled approximately 36 times during the entire test period. During the test the input/output efficiency of the boiler was 58.7%. The overall particulate emission factor for the entire test period was 0.34 lb/MMBtu.

*Emissions overview during sampling periods*

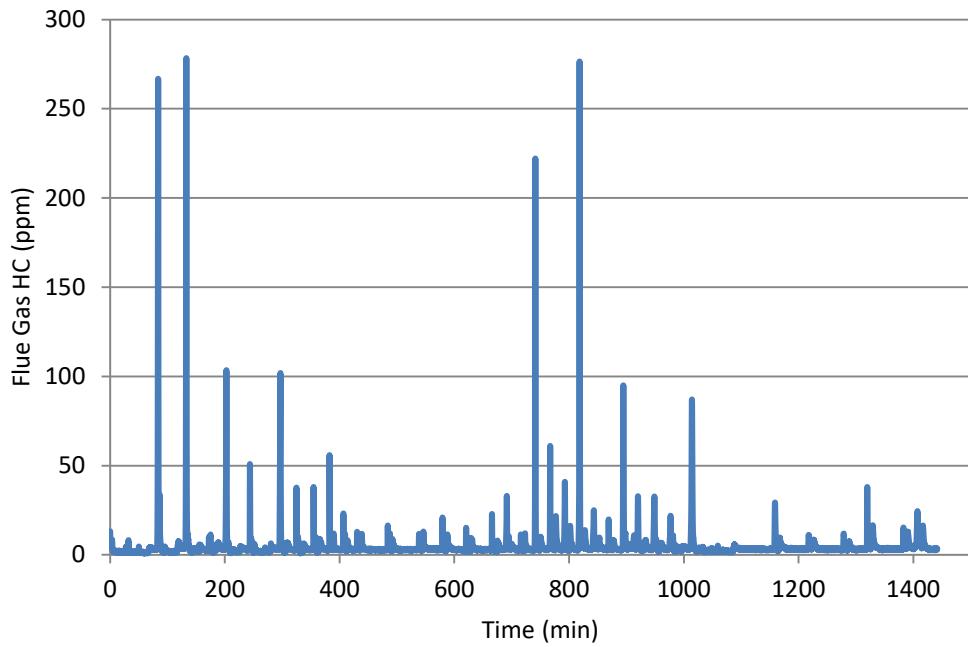
|                  |                        |
|------------------|------------------------|
| PM Concentration | 2.74 mg/m <sup>3</sup> |
| Emission Rate    | 1.68 g/hr              |
| Emission Index   | 1.73 g/kg fuel         |
| Emission Output  | 0.34 lb/MMBtu          |
| Avg. Stack CO    | 420 ppm                |



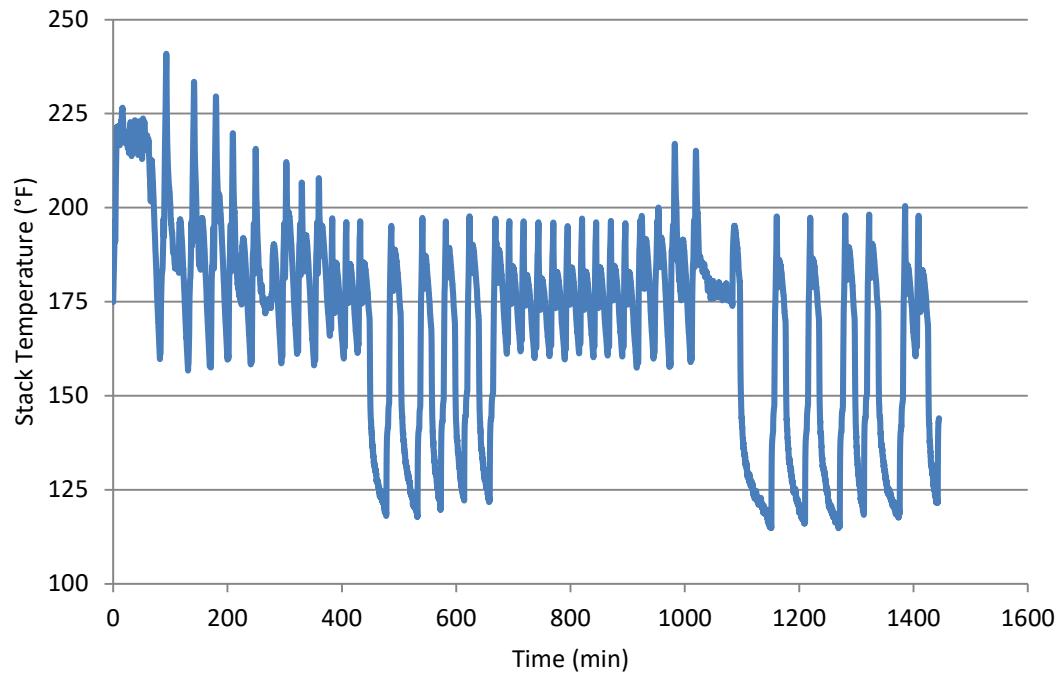
**Figure 69 Flue CO, Test 10, April profile, no storage**



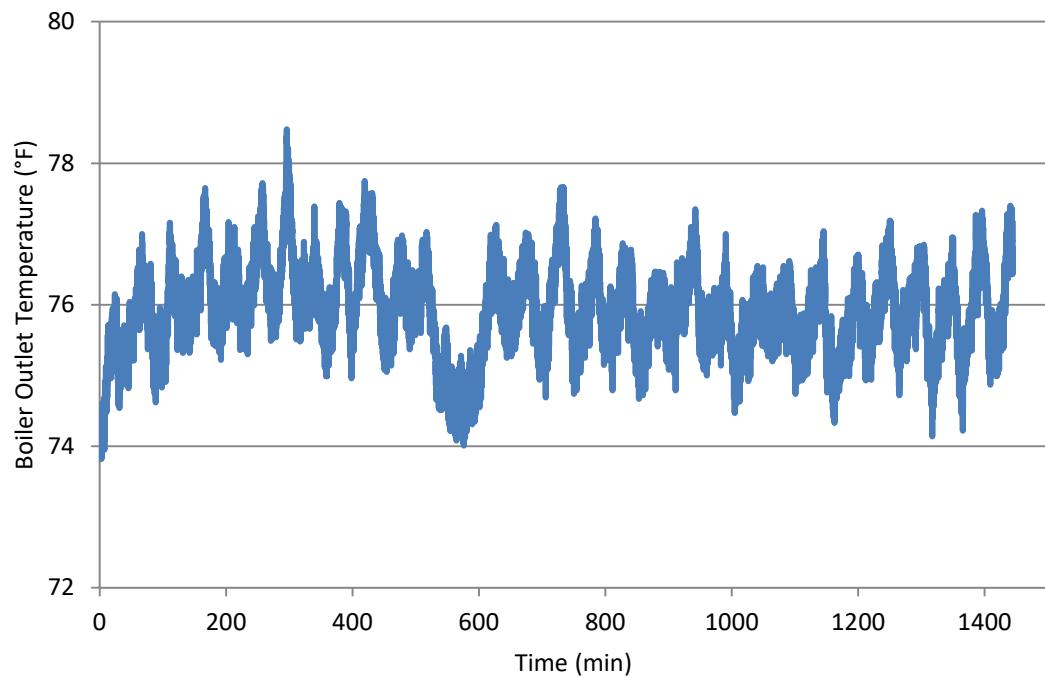
**Figure 70 Flue O<sub>2</sub>, Test 10, April profile, no storage**



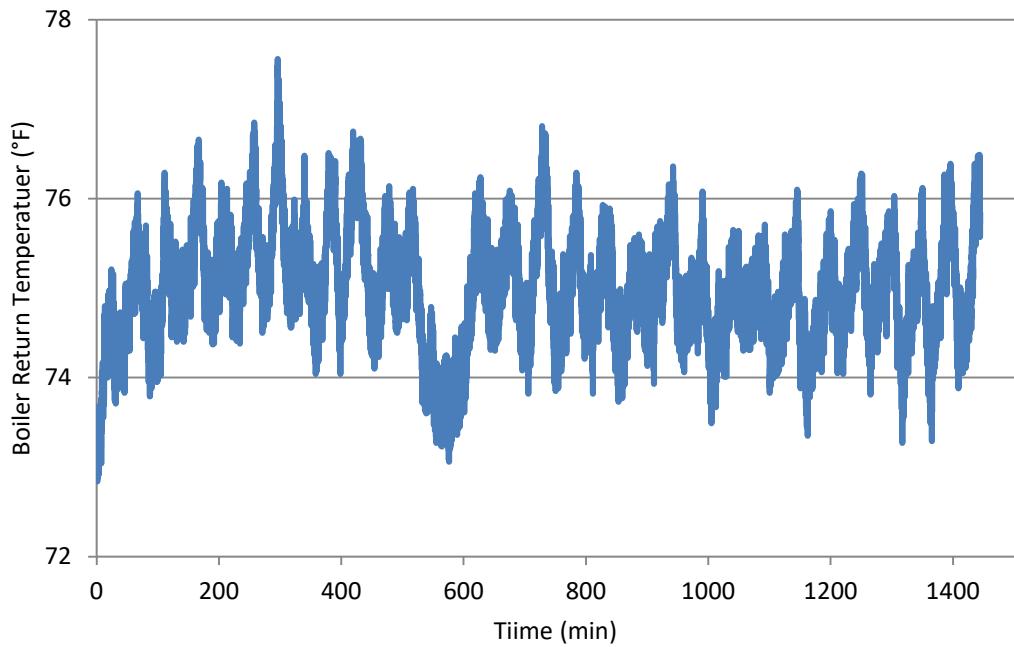
**Figure 71 Flue HC, Test 10, April profile, no storage**



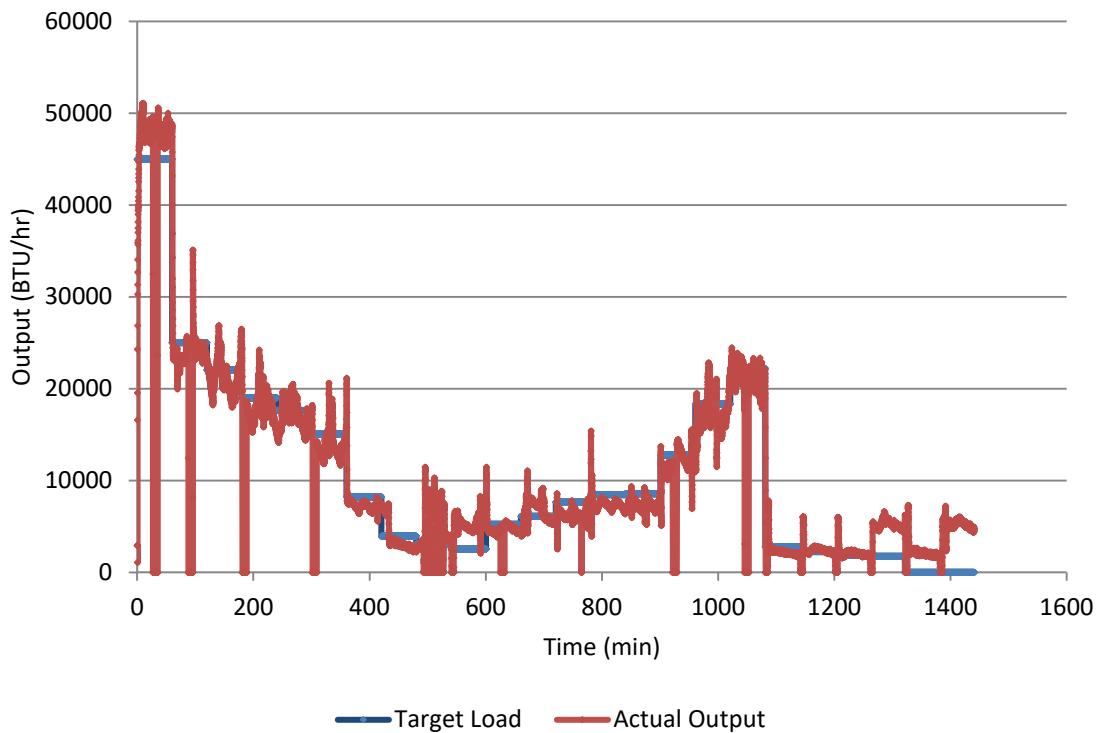
**Figure 72 Stack temperature, Test 10, April profile, no storage**



**Figure 73 Boiler outlet temperature, Test 10, April profile, no storage**



**Figure 74 Boiler return temperature, Test 10, April profile, no storage**



**Figure 75 Boiler output, Test 10, April profile, no storage**

## Results of Test 11 – January Profile, No Storage

### *Summary of conditions for test*

|                               |                              |
|-------------------------------|------------------------------|
| Test Date                     | May 13 & May 16, 2016        |
| Test Condition                | January 24 hour load profile |
| Storage                       | No                           |
| Storage Tank Capacity         | N/A                          |
| ΔT control change across tank | N/A                          |

### *Discussion of Test Condition*

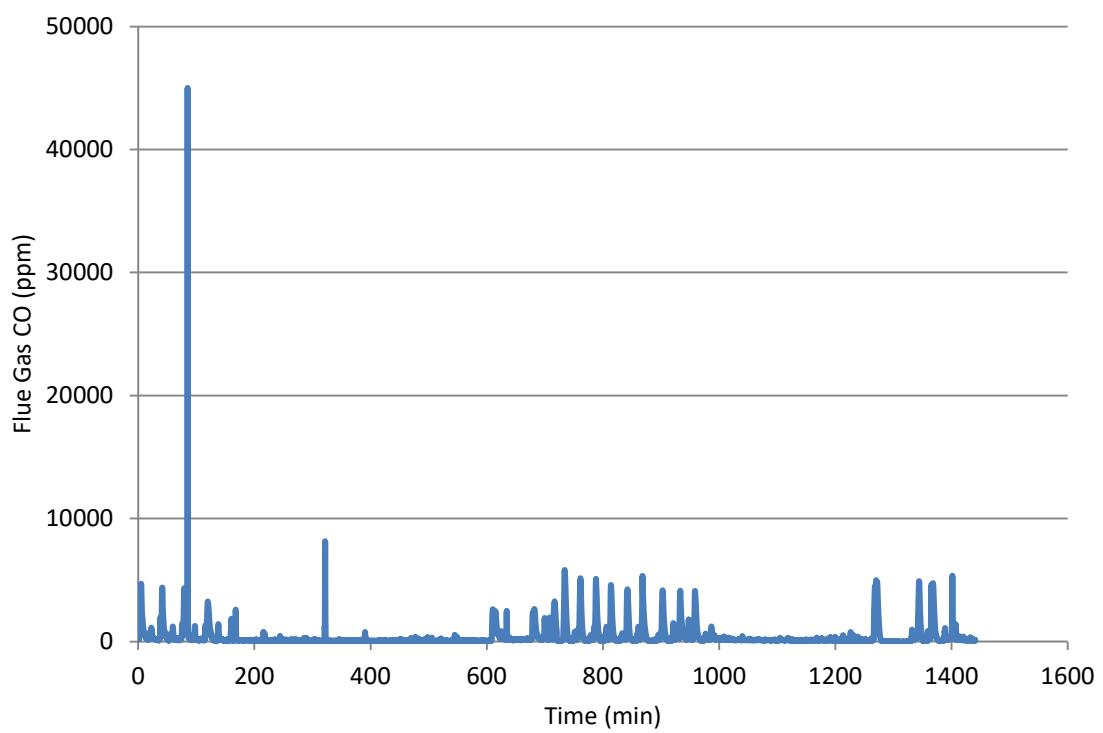
Twelve hours of testing was conducted on both May 13<sup>th</sup> and May 16<sup>th</sup> 2016 each day on May to give a 24 hour January load profile. The purpose of this test is to determine the emissions and efficiency of the boiler based on actual in home usage. In order to achieve this, a load pattern emulating the boiler output in one hour increments was applied to the boilers control system. The target load pattern was the output of the boiler for an average January weekday at a simulation home located in Albany, New York. The average output of the boiler over the combined 24 hour period was 38,035 Btu/hr.

### *Discussion of Test Results*

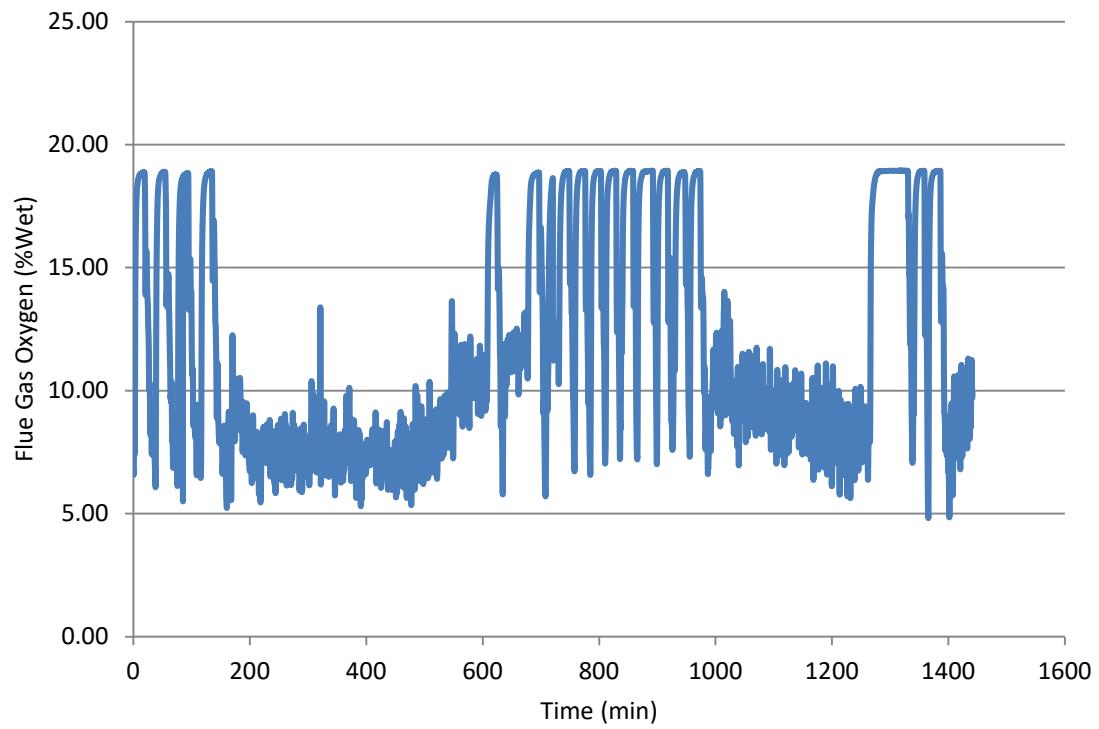
On May 13<sup>th</sup> 2015 particulate sampling in the dilution tunnel began at 7:09:00 am and ended at 7:09:00 pm. On May 16<sup>th</sup> 2015 particulate sampling in the dilution tunnel began at 8:15:00 am and ended at 8:15:15 pm. There was a combined sampling period of 24 hours (1440 minutes) for this entire test. The reason the test was split up into two 12 hour periods was due to a filter plugging issue. The total fuel consumed during the entire test was 142.9 lbs. From the included figures it can be seen that the boiler cycled approximately 20 times during the entire test period. During the test the input/output efficiency of the boiler was 77.0%. The overall particulate emission factor for the entire 24 hour test period was 0.15 lb/MMBtu.

*Emissions overview during sampling periods*

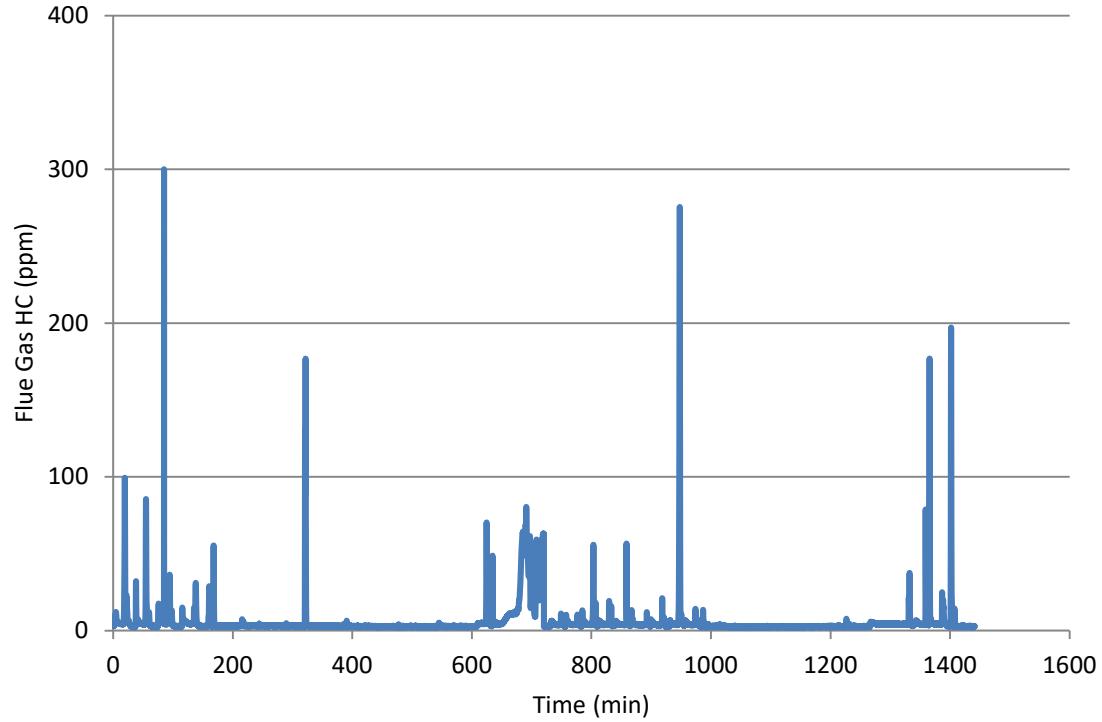
|                  |                        |
|------------------|------------------------|
| PM Concentration | 4.06 mg/m <sup>3</sup> |
| Emission Rate    | 2.60 g/hr              |
| Emission Index   | 0.96 g/kg fuel         |
| Emission Output  | 0.15 lb/MMBtu          |
| Avg. Stack CO    | 390 ppm                |



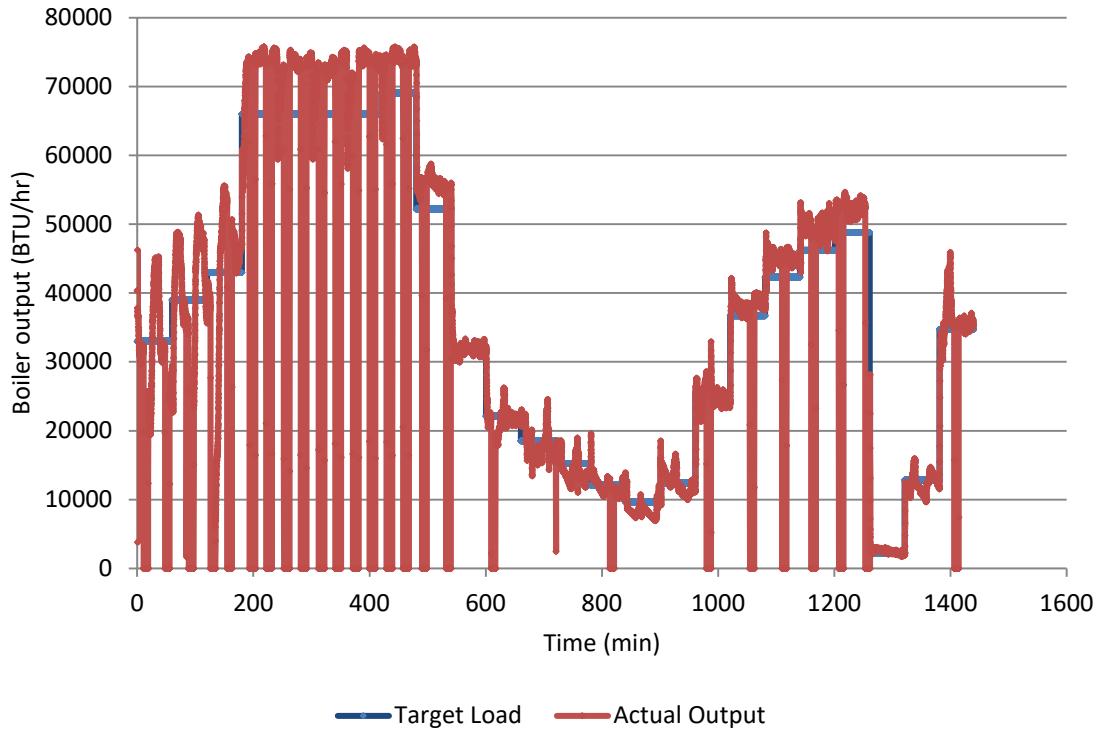
**Figure 76 Flue CO, Test 11 January profile, no storage**



**Figure 77 Flue O<sub>2</sub>, Test 11 January profile, no storage**



**Figure 78 Flue HC, Test 11 January profile, no storage**



**Figure 79 Boiler output, Test 11 January profile, no storage**

Note – on this test some of the temperature data is unavailable.

#### Results of Test 12 – March Profile, No Storage

*Summary of conditions for test*

|                                       |                            |
|---------------------------------------|----------------------------|
| Test Date                             | April 28 to 29, 2016       |
| Test Condition                        | March 24 hour load profile |
| Storage                               | No                         |
| Storage Tank Capacity                 | N/A                        |
| $\Delta T$ control change across tank | N/A                        |

#### *Discussion of Test Condition*

On April 28<sup>th</sup> to 29<sup>th</sup> 2015 a 24 hour March load profile test was conducted. The purpose of this test is to determine the emissions and efficiency of the boiler based on actual in home usage. In order to achieve this, a load pattern emulating the boiler output in one hour increments was applied to the boilers control system. The target load pattern was the output of the boiler for an average March weekday at a simulation home located in Albany, New York. This test was

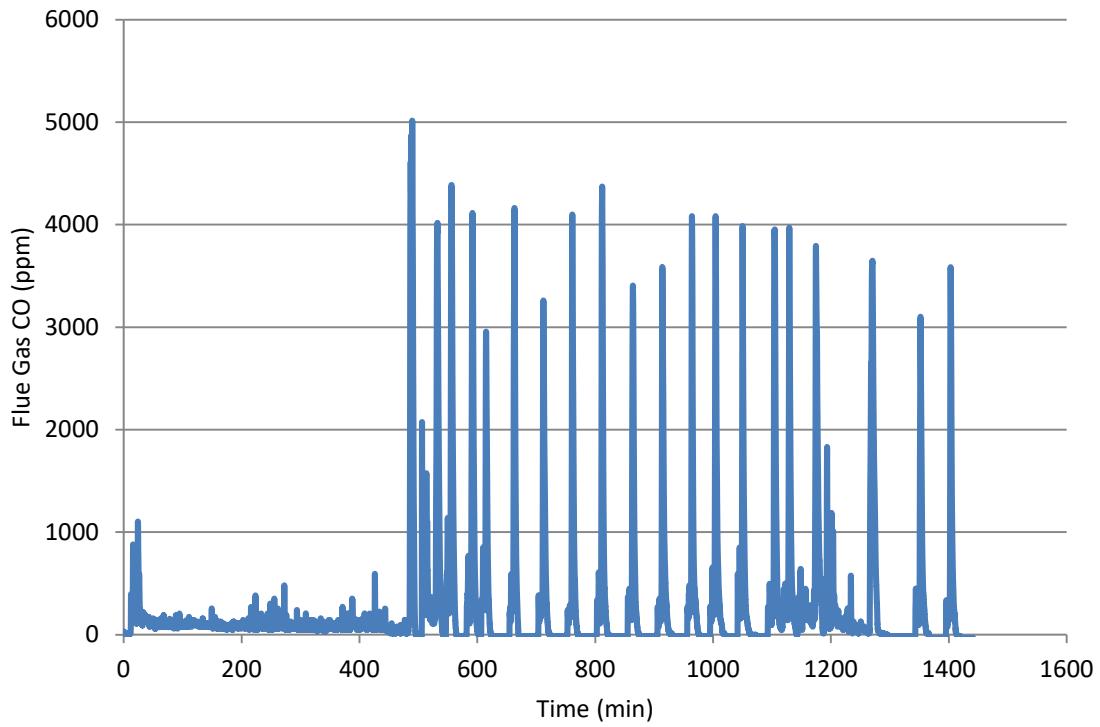
conducted without storage therefore the control change across the tank was 25 °C. The average output of the boiler during this test was 20,424 Btu/hr.

#### *Discussion of Test Results*

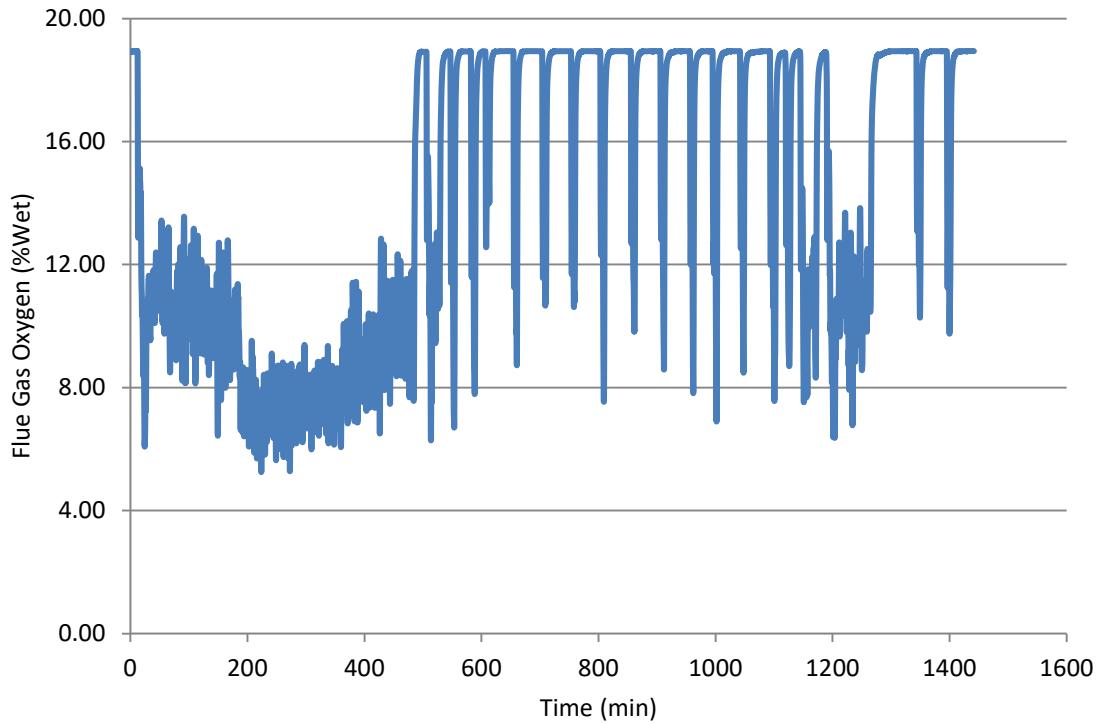
Particulate sampling in the dilution tunnel began at 12:22:30 pm on April 28<sup>th</sup> and completed at 12:22:30 pm on April 29<sup>th</sup> for a 24 hour (1440 minute) sampling period. The total fuel consumed during the test was 79.2 lbs. From the included figures, it can be seen that the boiler cycled approximately 20 times during the entire test period. During the test the input/output efficiency of the boiler was 76.4%. The overall particulate emission factor for the entire test period was 0.16 lb/MMBtu.

#### *Emissions overview during sampling periods*

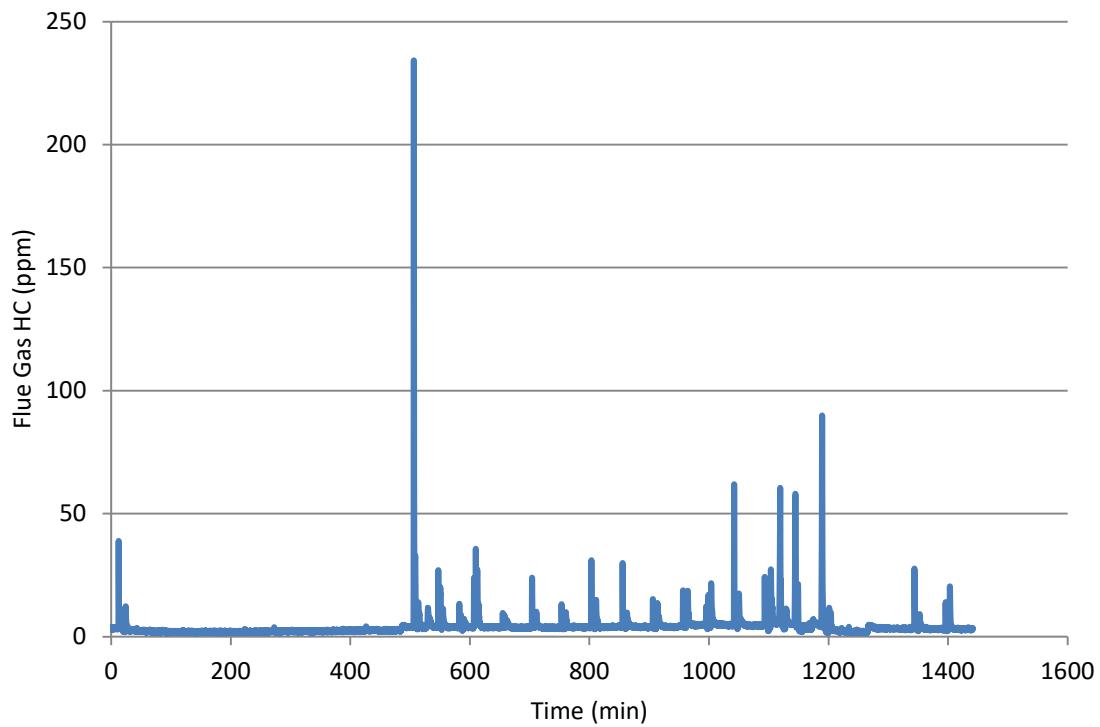
|                  |                        |
|------------------|------------------------|
| PM Concentration | 2.44 mg/m <sup>3</sup> |
| Emission Rate    | 1.56 g/hr              |
| Emission Index   | 1.04 g/kg fuel         |
| Emission Output  | 0.16 lb/MMBtu          |
| Avg. Stack CO    | 270 ppm                |



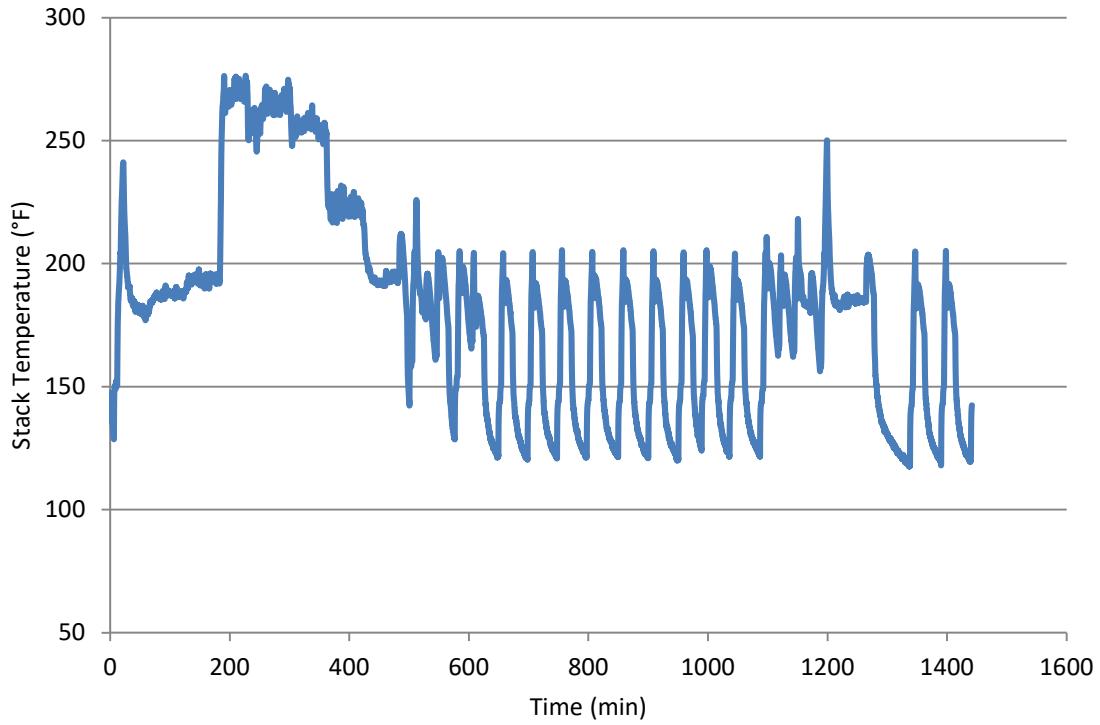
**Figure 80 Flue CO, Test 12, March profile, no storage**



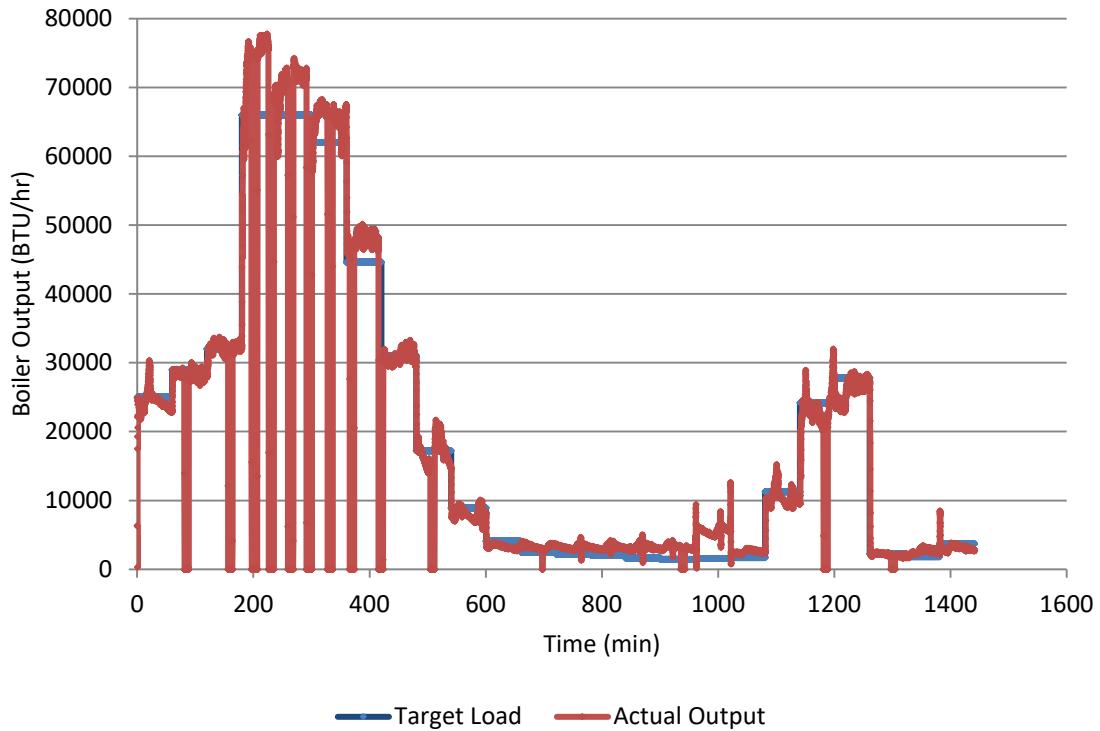
**Figure 81 Flue O<sub>2</sub>, Test 12, March profile, no storage**



**Figure 82 Flue HC, Test 12, March profile, no storage**



**Figure 83 Stack temperature, Test 12, March profile, no storage**



**Figure 84 Boiler output, Test 12, March profile, no storage**

Note – in Test 12 some of the temperature data is unavailable.

### Results of Test 13 – April Profile, 119 Gallons of Thermal Storage

#### *Summary of conditions for test*

|                               |                            |
|-------------------------------|----------------------------|
| Test Date                     | May 25 to 26, 2015         |
| Test Condition                | April 24 hour load profile |
| Storage                       | Yes                        |
| Storage Capacity              | 119 gallons                |
| ΔT control change across tank | 20 °F                      |

#### *Discussion of Test Condition*

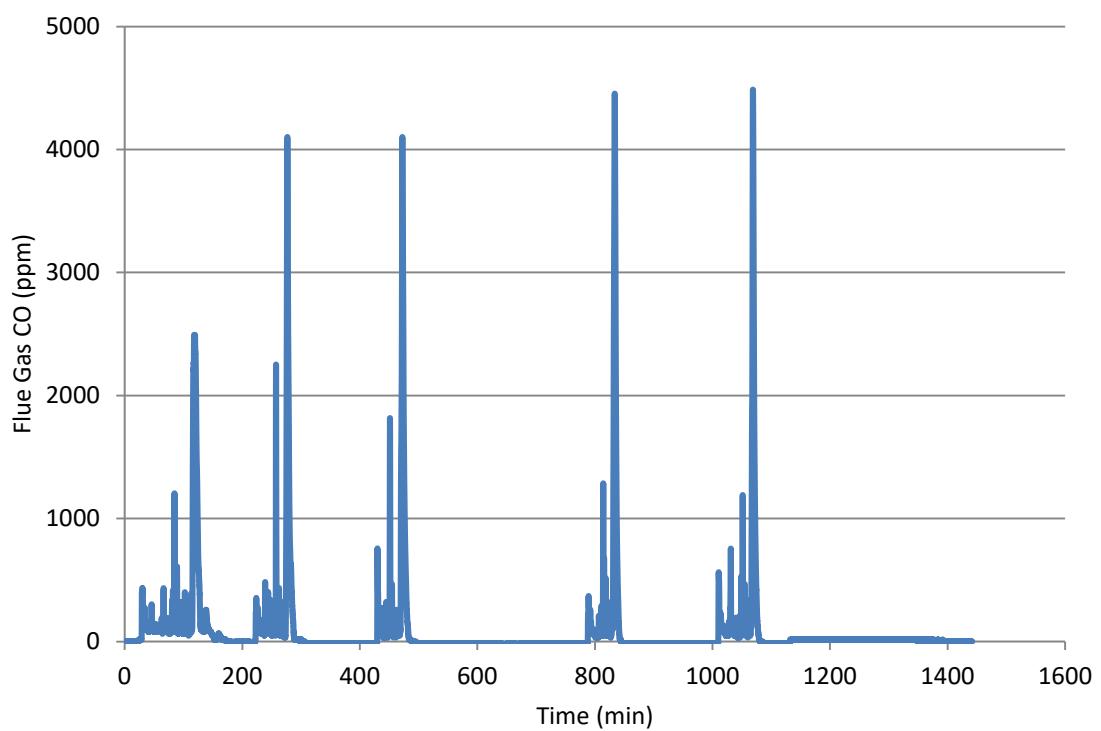
On May 25<sup>th</sup>-26<sup>th</sup> 2015 a 24 hour April load profile test was conducted with storage. The purpose of this test is to determine the emissions and efficiency of the boiler based on actual in home usage. In order to achieve this, a load pattern emulating the boiler output in one hour increments was applied to the boilers control system. The target load pattern was the output of the boiler for an average April weekday at a simulation home located in Albany, New York. The 119 gallon steel storage was used with an 20 °F temperature control change across the tank. The average output of the boiler during this test was 10,631 Btu/hr.

#### *Discussion of Test Results*

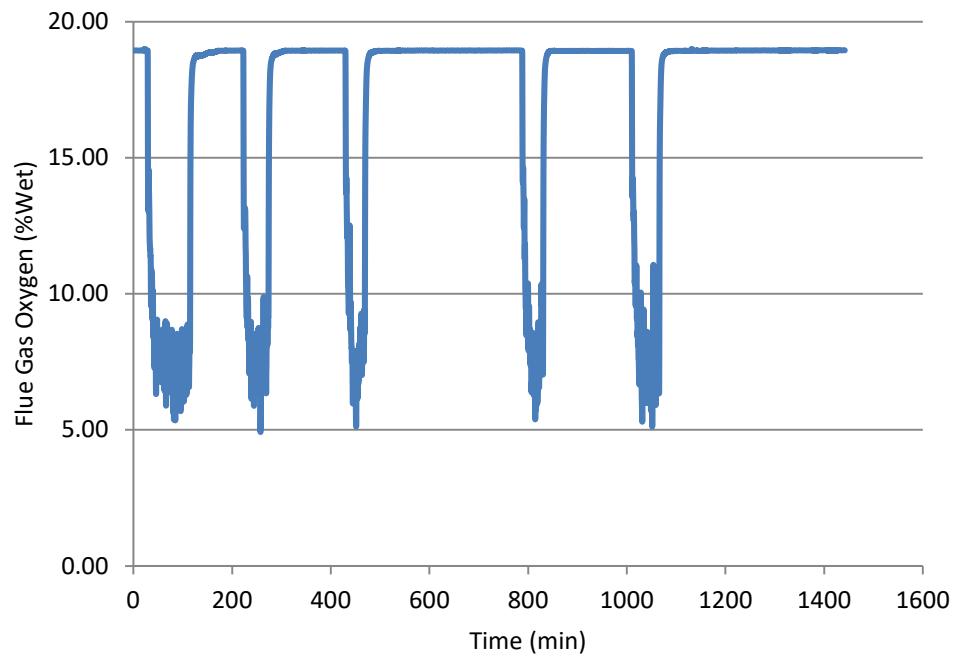
Particulate sampling in the dilution tunnel began at 1:56:00pm on May 25<sup>th</sup> and completed at 1:56:00pm on May 26<sup>th</sup> for a 24 hour (1440 minute) sampling period. The total fuel consumed during the test was 45.6 lbs. From the included figures, it can be seen that the boiler cycled five times during the entire test period. During the test the input/output efficiency of the boiler was 69.7%. The overall particulate emission factor for the entire test period was 0.15 lb/MMBtu.

*Emissions overview during sampling periods*

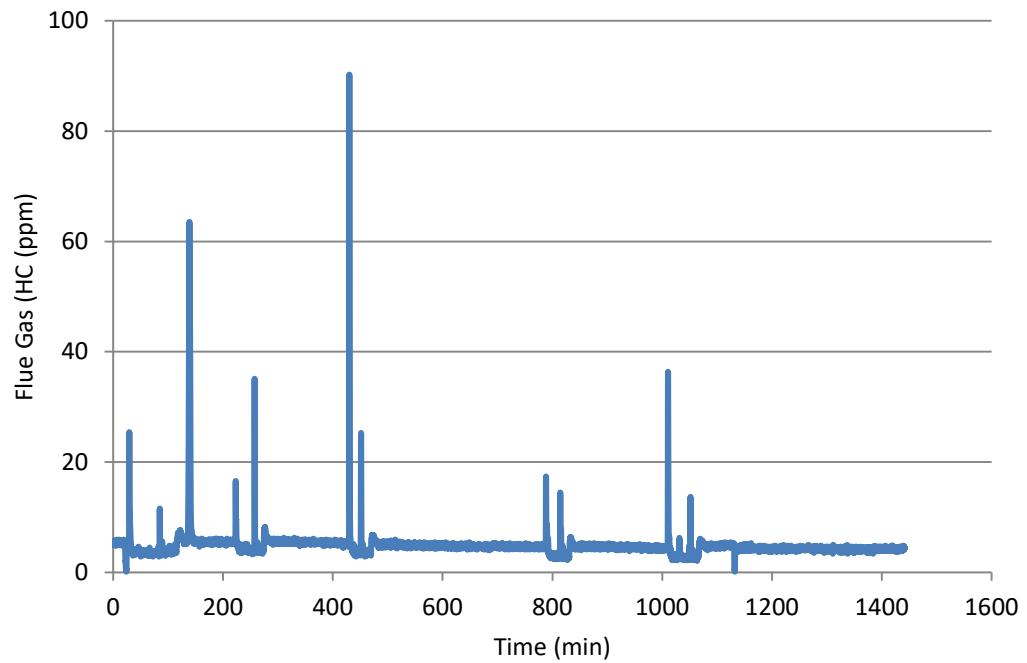
|                  |                        |
|------------------|------------------------|
| PM Concentration | 1.24 mg/m <sup>3</sup> |
| Emission Rate    | 0.77 g/hr              |
| Emission Index   | 0.89 g/kg fuel         |
| Emission Output  | 0.15 lb/MMBtu          |
| Avg. Stack CO    | 88 ppm                 |



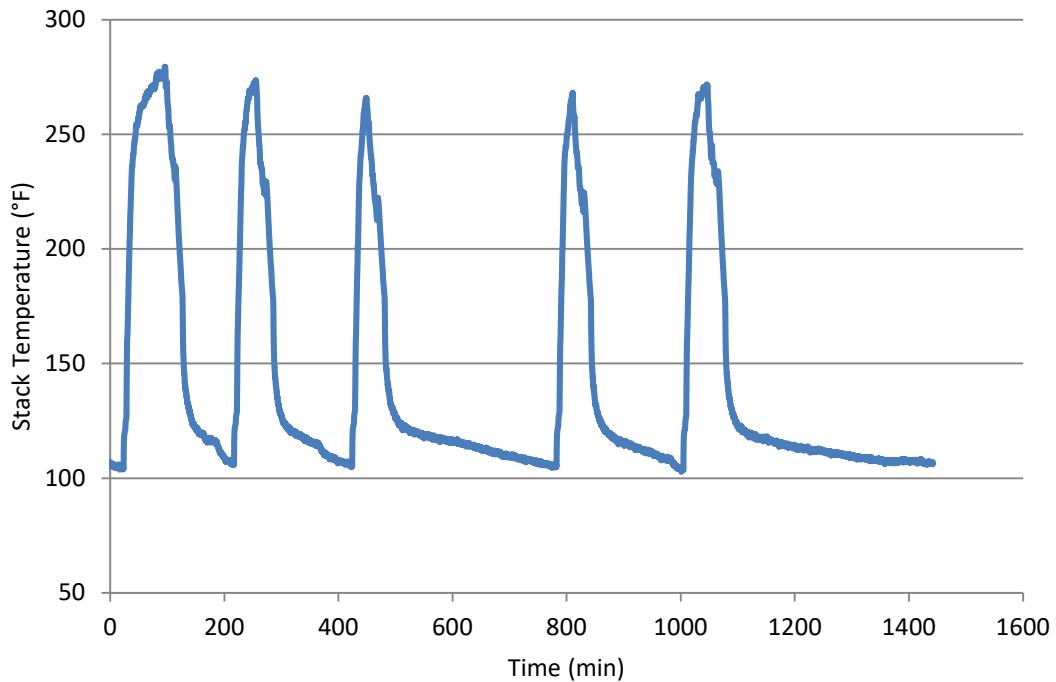
**Figure 85 Flue CO, Test 13, April profile, 119 gal. storage**



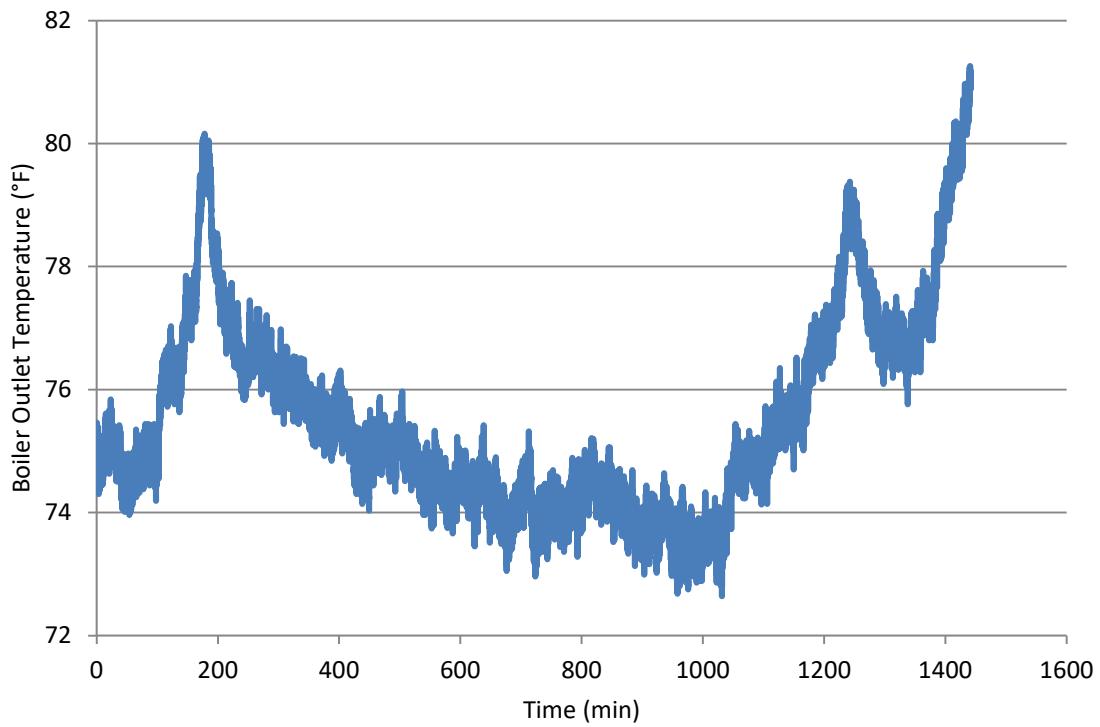
**Figure 86 Flue O<sub>2</sub>, Test 13, April profile, 119 gal. storage**



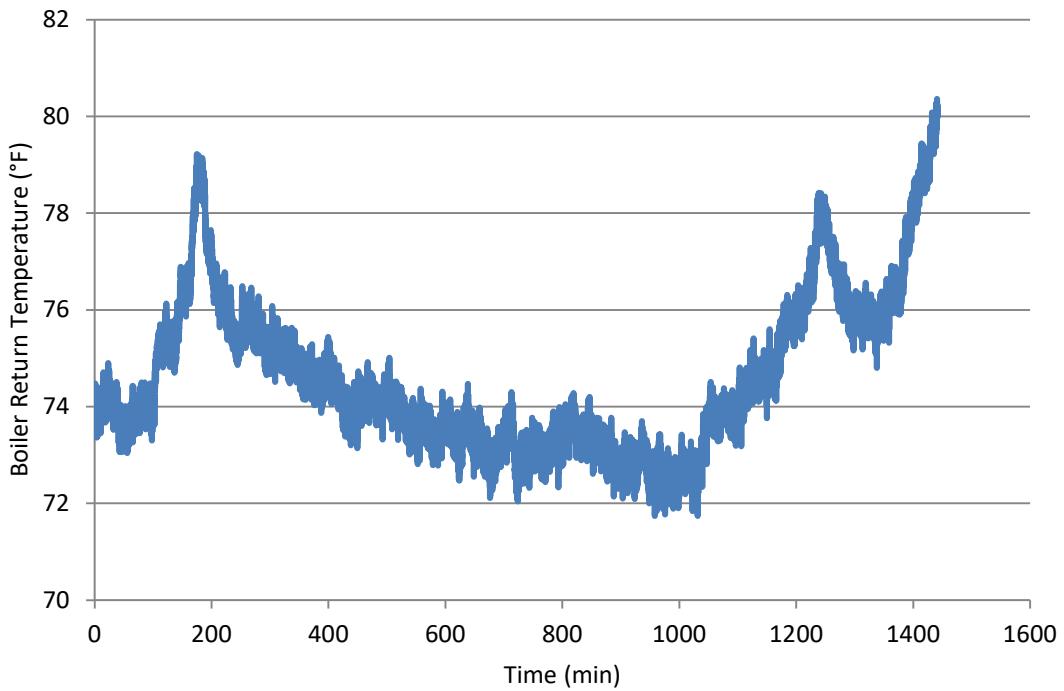
**Figure 87 Flue HC, Test 13, April profile, 119 gal. storage**



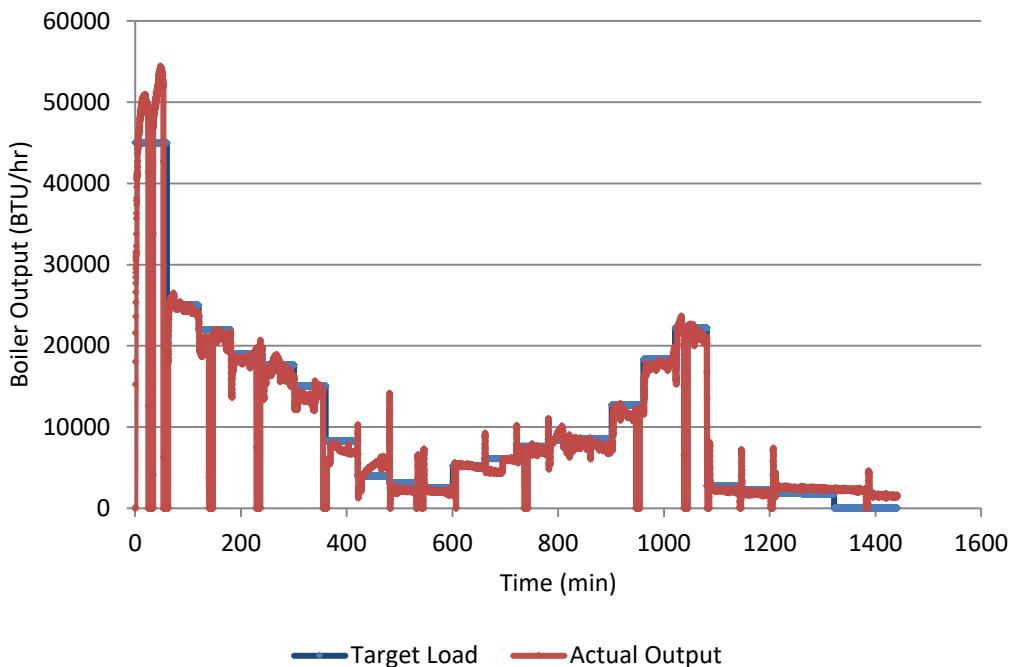
**Figure 88 Stack temperature, Test 13, April profile, 119 gal. storage**



**Figure 89 Boiler outlet temperature, Test 13, April profile, 119 gal. storage**



**Figure 90 Boiler return temperature, Test 13, April profile, 119 gal. storage**



**Figure 91 Boiler output, Test 13, April profile, 119 gal. storage**

## Results of Test 14 –January Profile, 119 Gallons of Thermal Storage

### *Summary of conditions for test*

|                               |                              |
|-------------------------------|------------------------------|
| Test Date                     | May 9 to 10, 2016            |
| Test Condition                | January 24 hour load profile |
| Storage                       | Yes                          |
| Storage Capacity              | 119 gallons                  |
| ΔT control change across tank | 20 °F                        |

### *Discussion of Test Condition*

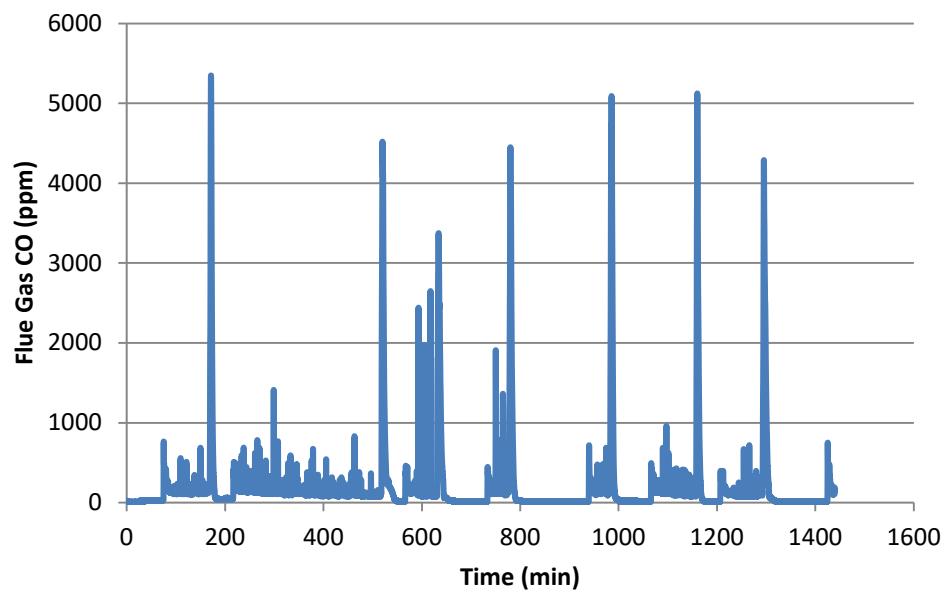
On May 9<sup>th</sup>-10<sup>th</sup> 2015 a 24 hour January load profile test was conducted with storage. The purpose of this test is to determine the emissions and efficiency of the boiler based on actual in home usage. In order to achieve this, a load pattern emulating the boiler output in one hour increments was applied to the boilers control system. The target load pattern was the output of the boiler for an average January weekday at a simulation home located in Albany, New York. The 119 gallon steel storage was used with an 20 °F temperature control change across the tank. The average output of the boiler during this test was 37,202 Btu/hr.

### *Discussion of Test Results*

Particulate sampling in the dilution tunnel began at 11:07:30 am on February May 9<sup>th</sup> and completed at 11:07:30 on May 10<sup>th</sup> for a 24 hour (1440 minute) sampling period. The total fuel consumed during the test was 133.8 lbs. From the included figures it can be seen that the boiler cycled \_\_\_\_ times during the entire test period. The input/output efficiency of the boiler was 80.8% during testing. The overall particulate emission factor for the entire test period was 0.12 lb/MMBtu.

*Emissions overview during sampling periods*

|                  |                        |
|------------------|------------------------|
| PM Concentration | 3.18 mg/m <sup>3</sup> |
| Emission Rate    | 2.03 g/hr              |
| Emission Index   | 0.75 g/kg fuel         |
| Emission Output  | 0.12 lb/MMBtu          |
| Avg. Stack CO    | 196 ppm                |



**Figure 92 Flue CO, Test 14, January profile, 119 gal storage**

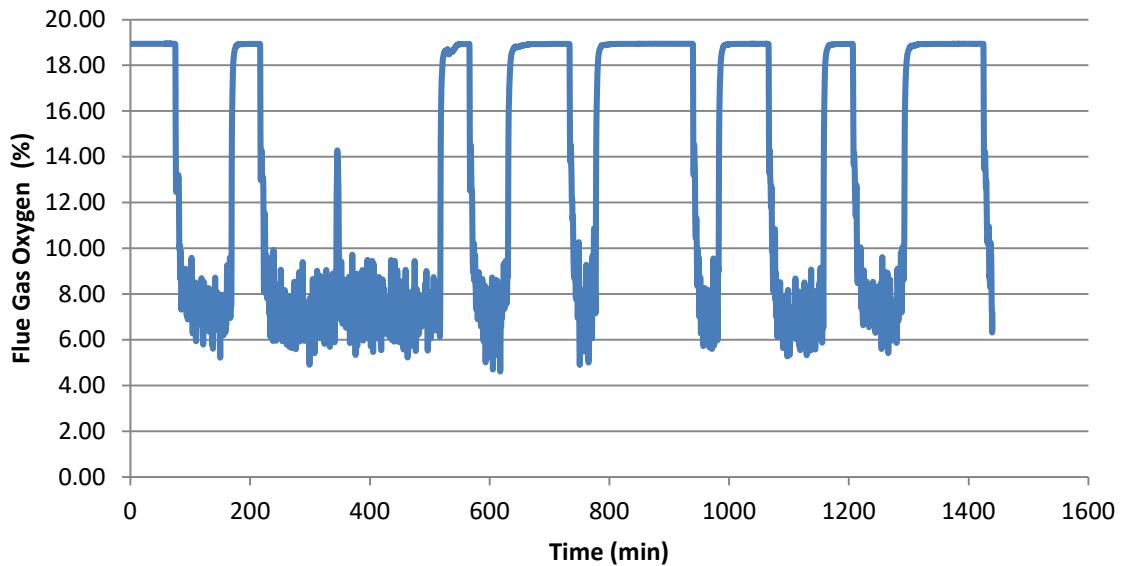


Figure 93 Flue O<sub>2</sub>, Test 14, January profile, 119 gal storage

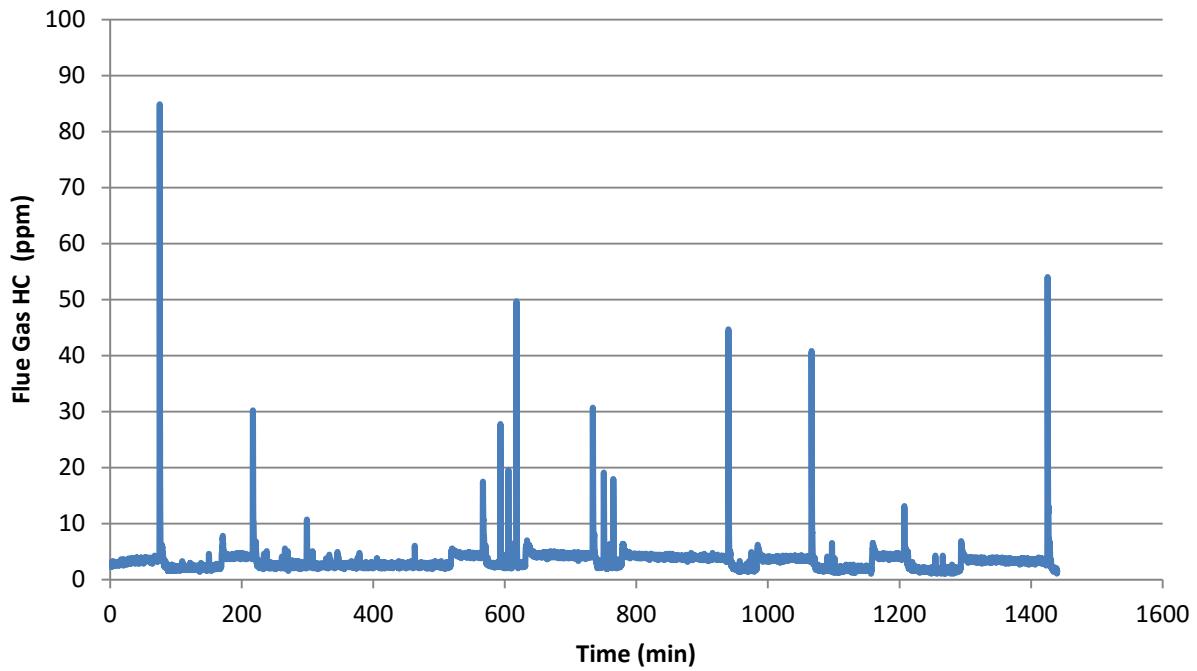


Figure 94 Flue HC, Test 14, January profile, 119 gal storage

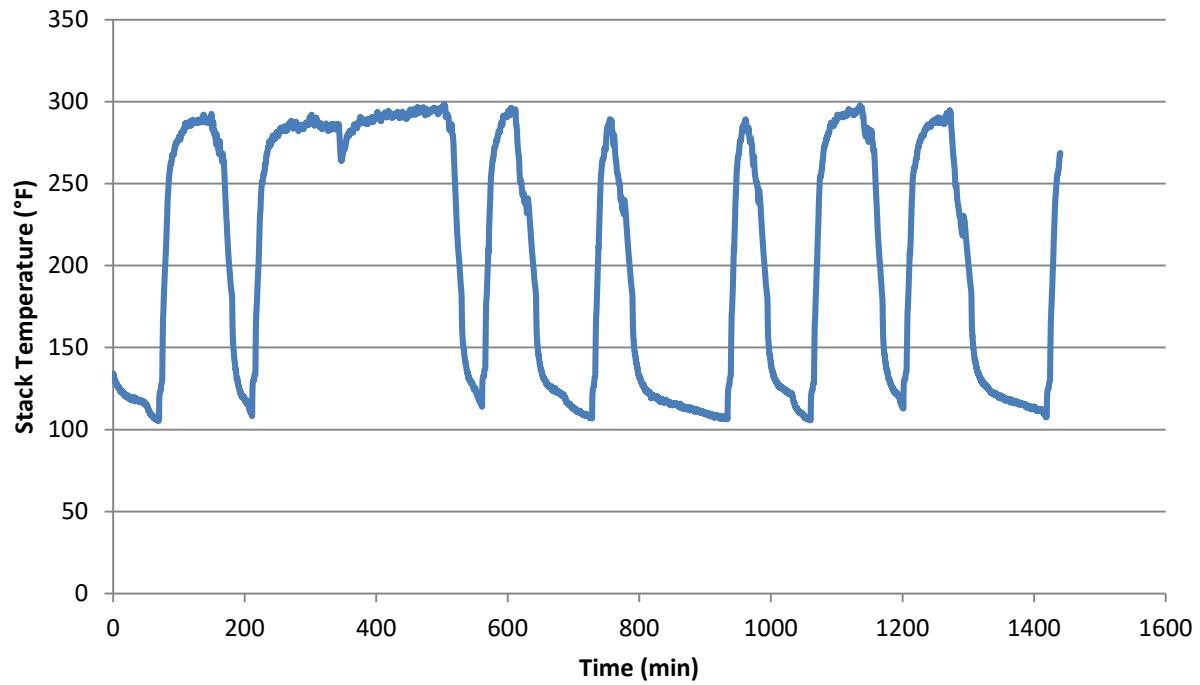


Figure 95 Stack temperature, Test 14, January profile, 119 gal storage

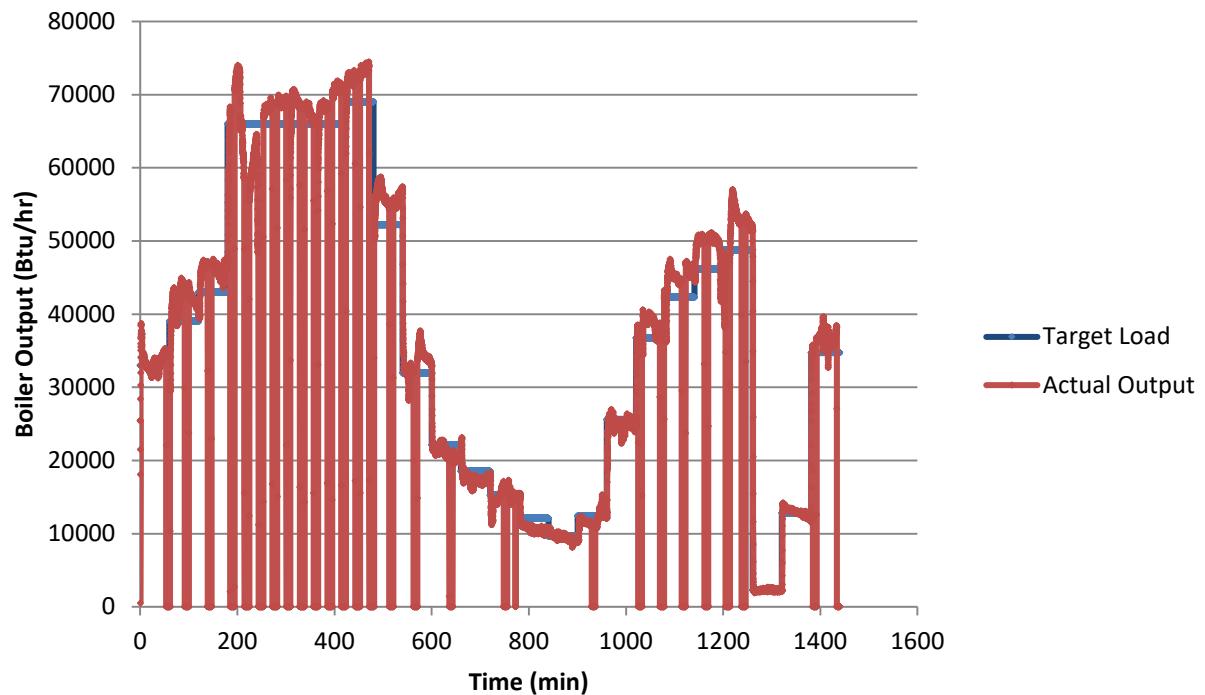


Figure 96 Boiler output, Test 14, January profile, 119 gal storage

Note – for this run the boiler supply and return water temperature data is not available.

### Results of Test 15 – March Profile, 119 Gallons of Thermal Storage

#### *Summary of conditions for test*

|                               |                            |
|-------------------------------|----------------------------|
| Test Date                     | February 1 to 2, 2016      |
| Test Condition                | March 24 hour load profile |
| Storage                       | Yes                        |
| Storage Capacity              | 119 gallons                |
| ΔT control change across tank | 20 °F                      |

#### *Discussion of Test Condition*

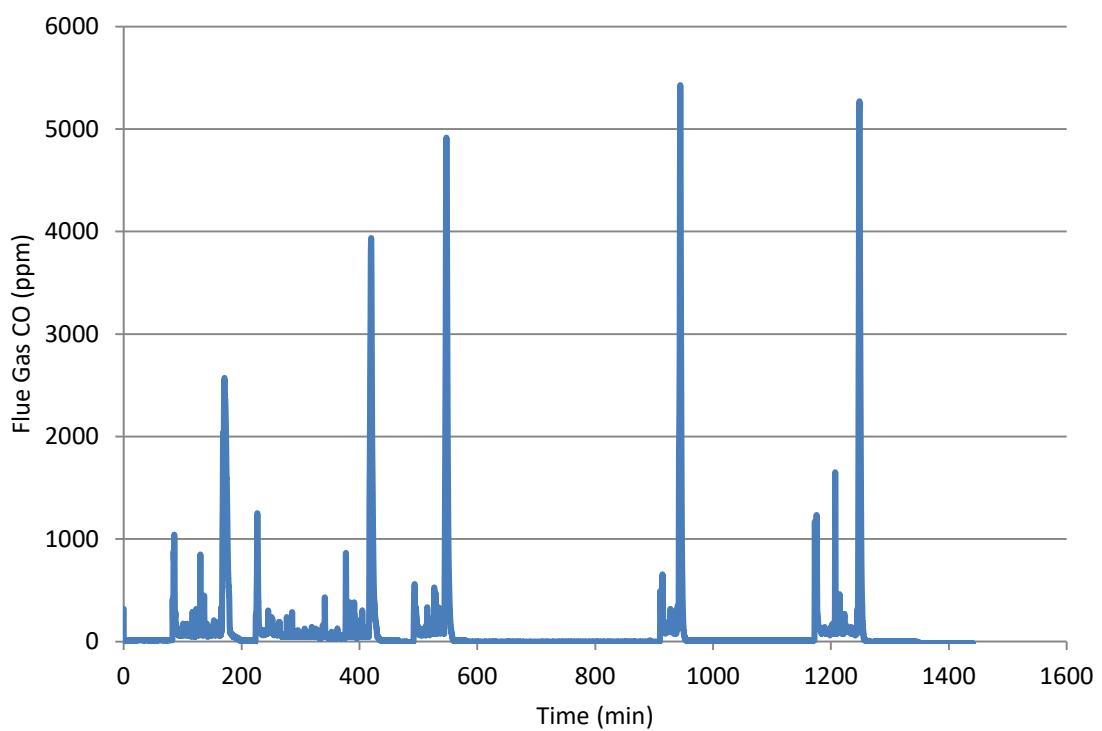
On February 1<sup>st</sup>-2<sup>nd</sup> 2016 a 24 hour March load profile test was conducted with storage. The purpose of this test is to determine the emissions and efficiency of the boiler based on actual in home usage. In order to achieve this, a load pattern emulating the boiler output in one hour increments was applied to the boilers control system. The target load pattern was the output of the boiler for an average March weekday at a simulation home located in Albany, New York. The 119 gallon steel storage tank was used with an 20 °F temperature control change across the tank. The average output of the boiler during this test was 18,777 Btu/hr.

#### *Discussion of Test Results*

Particulate sampling in the dilution tunnel began at 1:00:00pm on February 1<sup>st</sup> and completed at 1:00:00pm on February 2<sup>nd</sup> for a 24 hour (1440 minute) sampling period. The total fuel consumed during the test was 71.8 lbs. From the included figures it can be seen that the boiler cycled five times during the entire test period. During the test the input/output efficiency of the boiler was 75.4%. The overall particulate emission factor for the entire test period was 0.12 lb/MMBtu.

*Emissions overview during sampling periods*

|                  |                        |
|------------------|------------------------|
| PM Concentration | 1.60 mg/m <sup>3</sup> |
| Emission Rate    | 1.01 g/hr              |
| Emission Index   | 0.74 g/kg fuel         |
| Emission Output  | 0.12 lb/MMBtu          |
| Avg. Stack CO    | 105 ppm                |



**Figure 97 Flue CO, Test 15, March profile, 119 gal. storage**

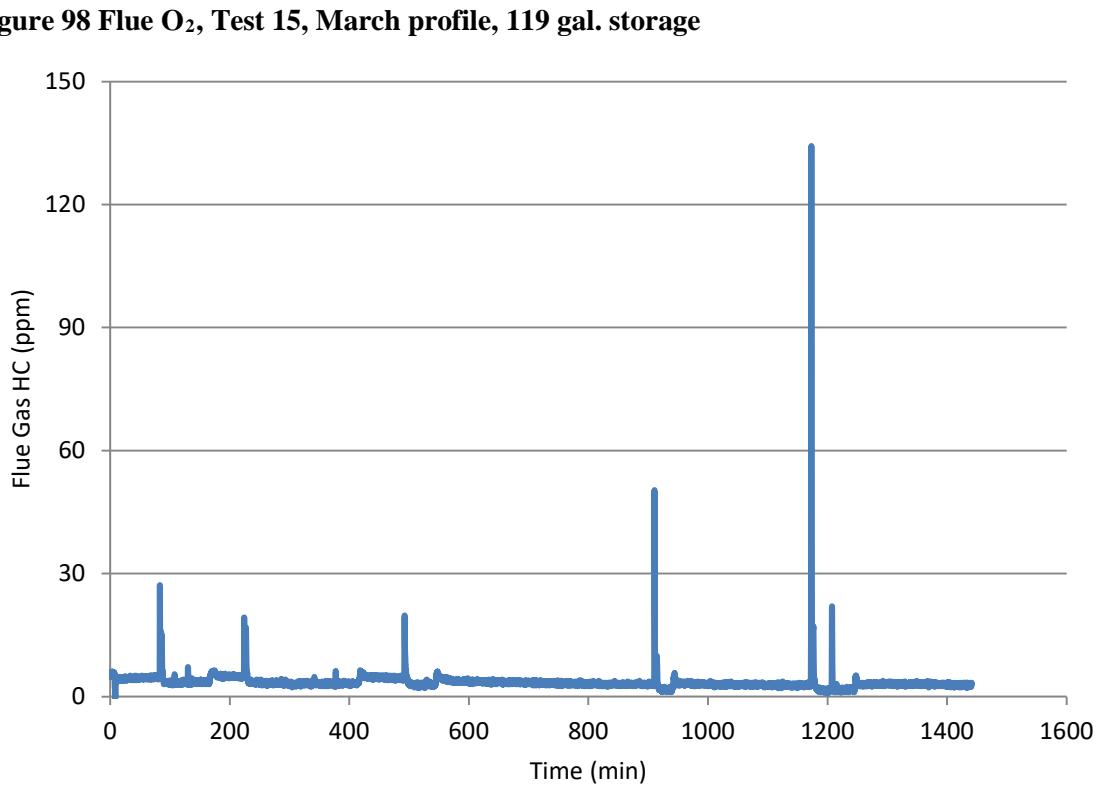
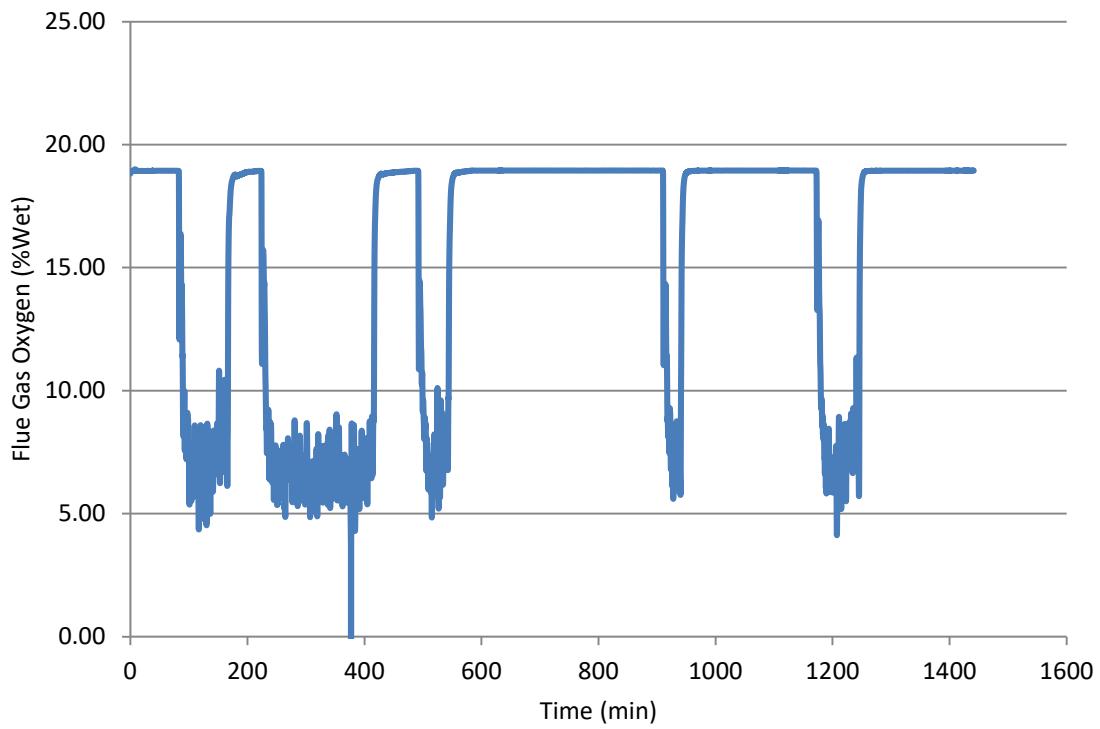
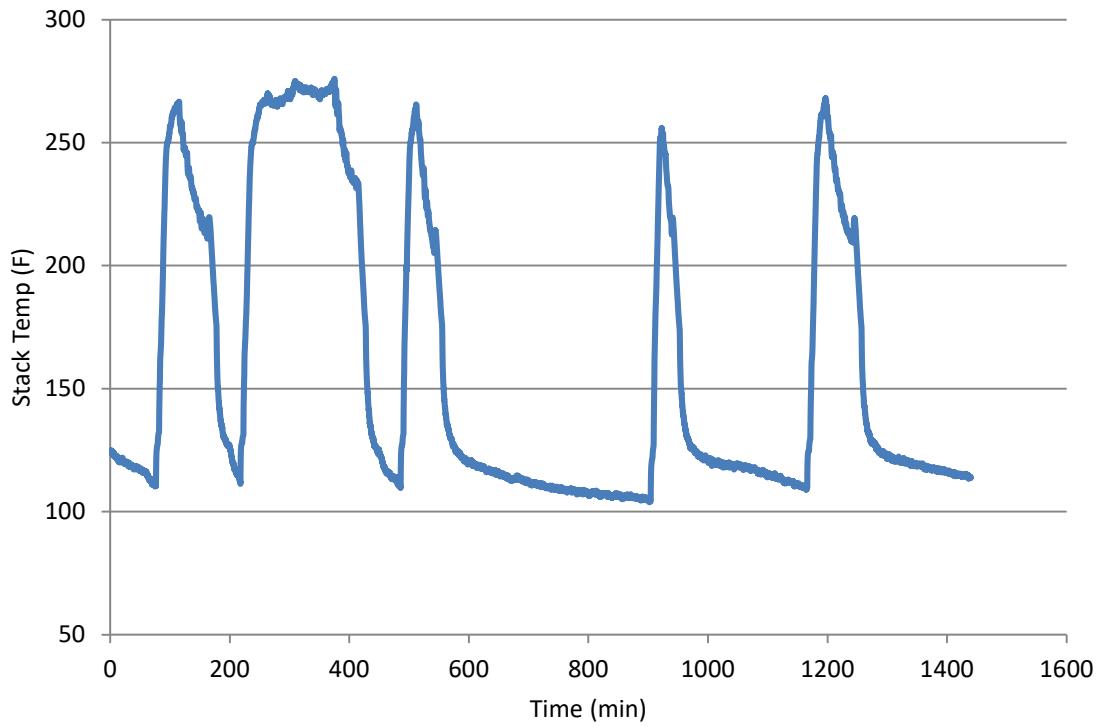
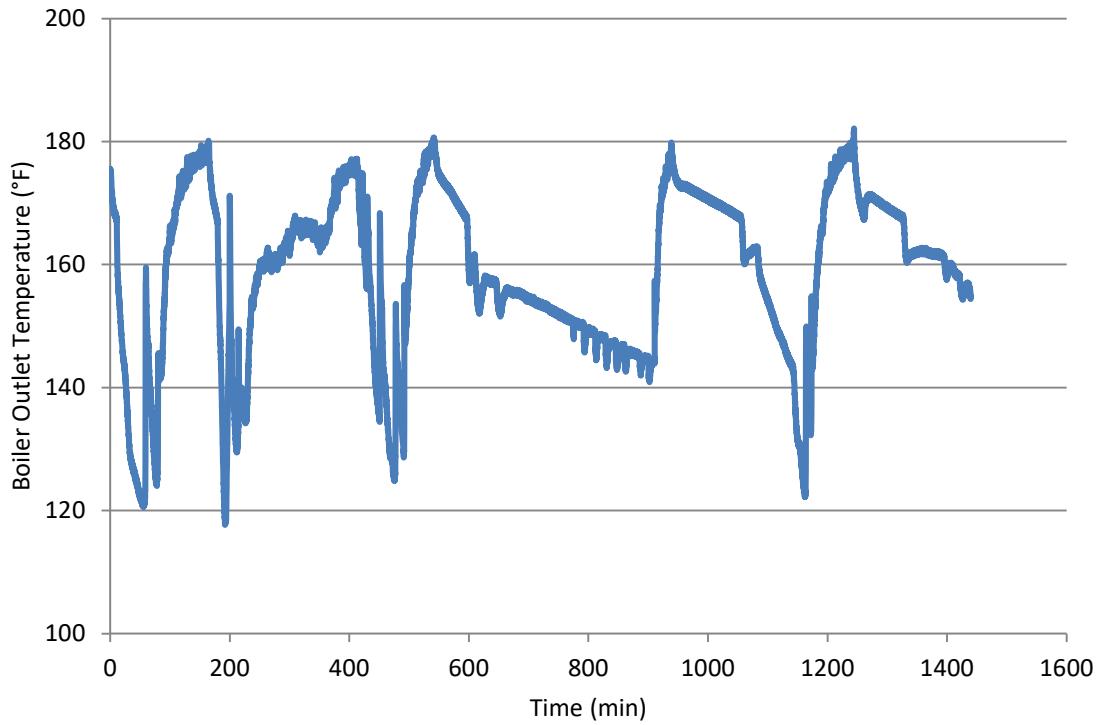


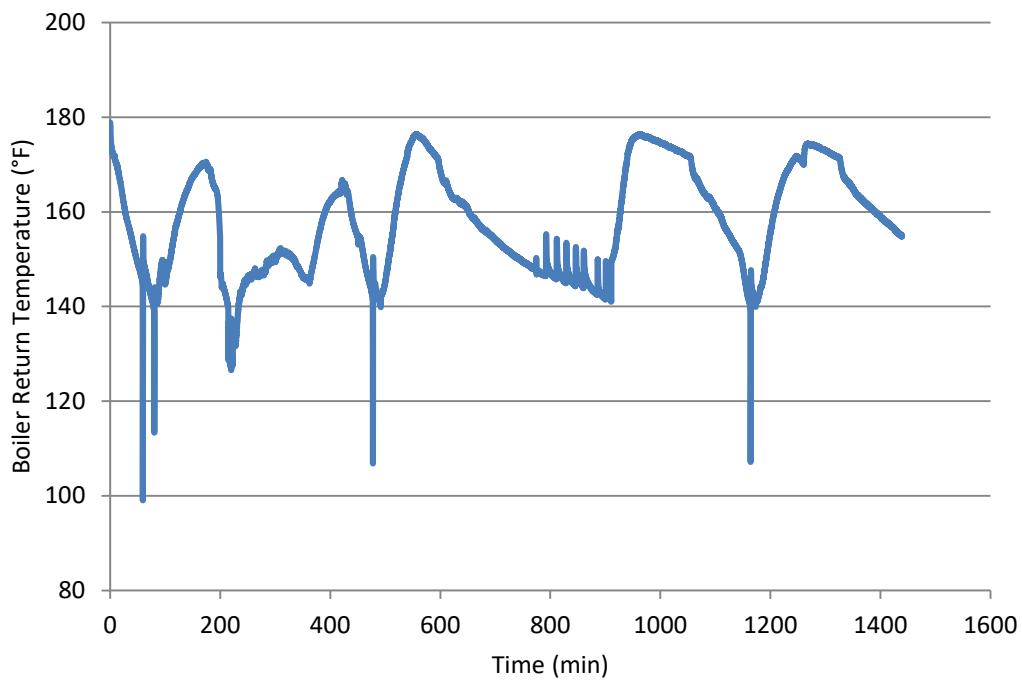
Figure 99 Flue HC, Test 15, March profile, 119 gal. storage



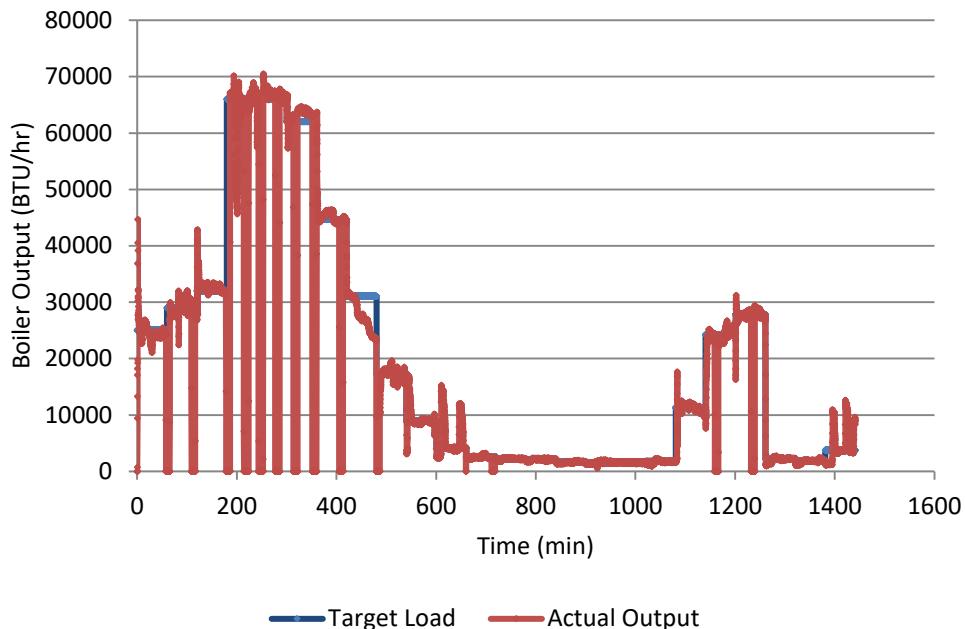
**Figure 100** Stack temperature, Test 15, March profile, 119 gal. storage



**Figure 101** Boiler outlet temperature, Test 15, March profile, 119 gal. storage



**Figure 102 Boiler return water temperature, Test 15, March profile, 119 gal. storage**



**Figure 103 Boiler output, Test 15, March profile, 119 gal. storage**

## Results of Test 16 – April Profile, 210 Gallons of Thermal Storage

### *Summary of conditions for test*

|                               |                            |
|-------------------------------|----------------------------|
| Test Date                     | November 10 to 11, 2016    |
| Test Condition                | April 24 hour load profile |
| Storage                       | Yes                        |
| Storage Capacity              | 210 gallons                |
| ΔT control change across tank | 20 °F                      |

### *Discussion of Test Condition*

On November 10<sup>th</sup>-11<sup>th</sup> 2016 a 24 hour April load profile test was conducted with storage. The purpose of this test is to determine the emissions and efficiency of the boiler based on actual in home usage. In order to achieve this, a load pattern emulating the boiler output in one hour increments was applied to the boiler's control system. The target load pattern was the output of the boiler for an average April weekday at a simulation home located in Albany, New York. This test used the 210 gallon highly insulated steel storage tank and the control change across the tank was 20 °F. The average output of the boiler during this test was 10,835 Btu/hr.

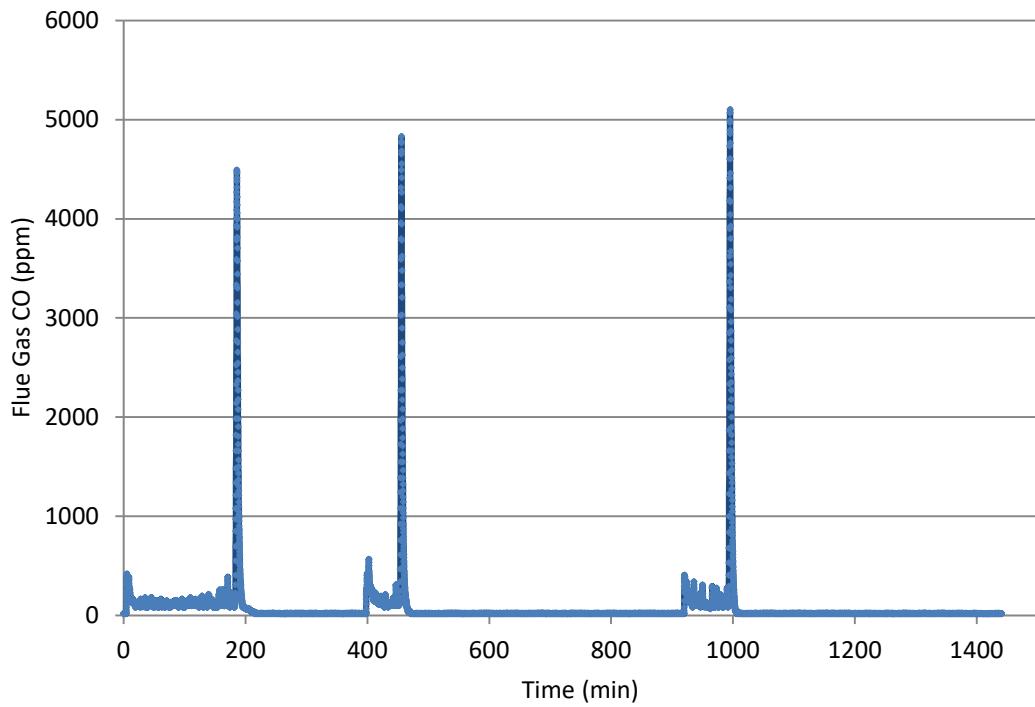
### *Discussion of Test Results*

Particulate sampling in the dilution tunnel began at 12:46 pm on November 10<sup>th</sup> 2016 and completed at 12:46 pm

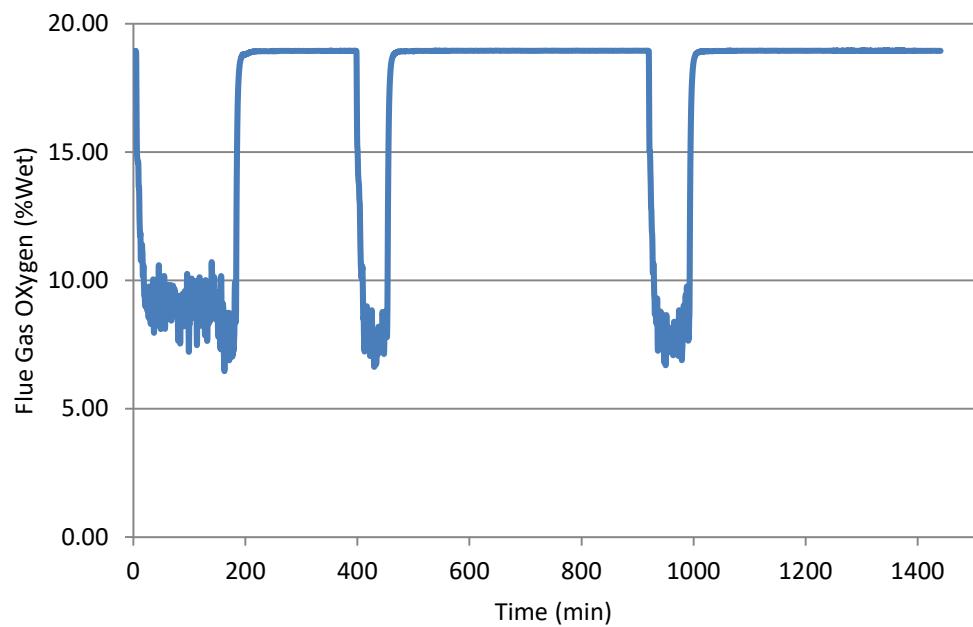
on November 11<sup>th</sup> 2016 for a 24 hour (1440 minute) sampling period. The total fuel consumed during the test was 31.2 lbs. From the figures provided it can be seen that the boiler cycled three times during the entire test period. During the test the input/output efficiency of the boiler was 73.6 %. The overall particulate emission factor for the entire test period was 0.20 lb/MMBtu.

*Emissions overview during sampling periods*

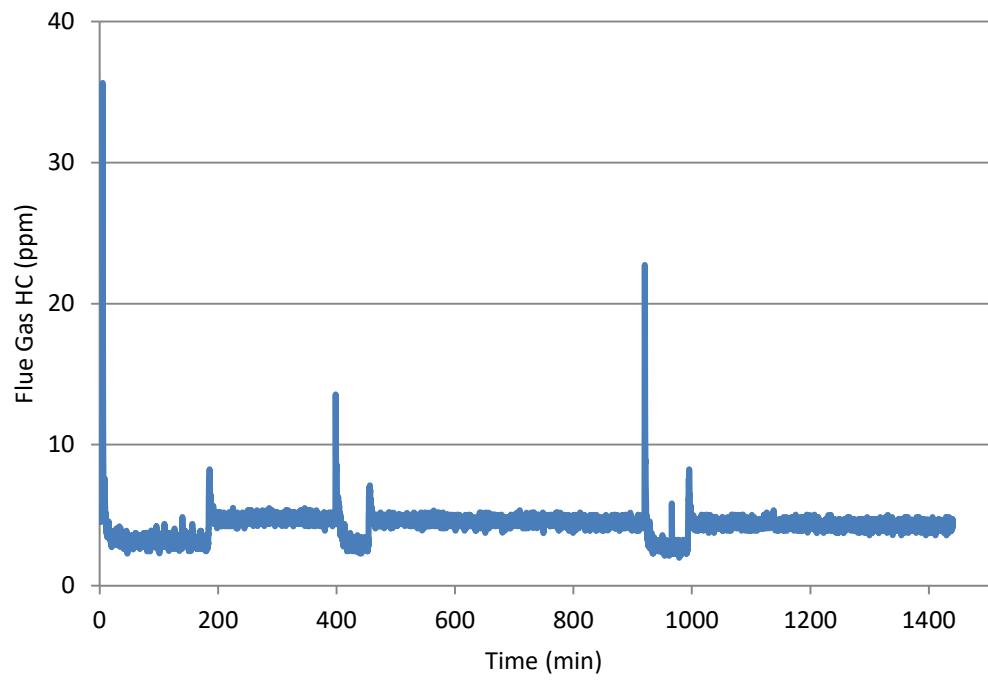
| PM Concentration | mg/m <sup>3</sup> |
|------------------|-------------------|
| Emission Rate    | 1.15 g/hr         |
| Emission Index   | 1.20 g/kg fuel    |
| Emission Output  | 0.20 lb/MMBtu     |
| Avg. Stack CO    | 80 ppm            |



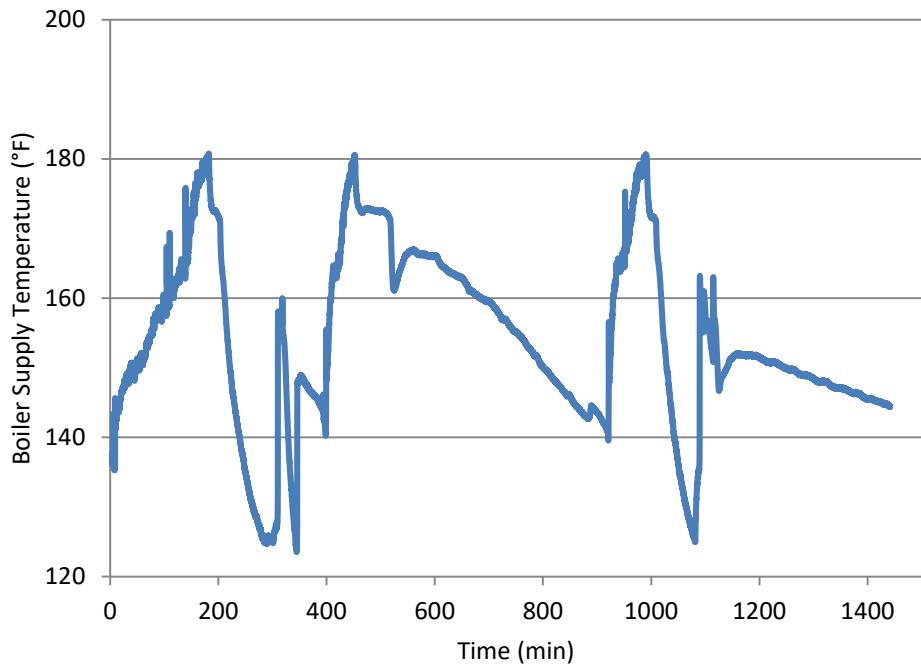
**Figure 104 Flue CO, Test 16, April profile, 210 gal. storage**



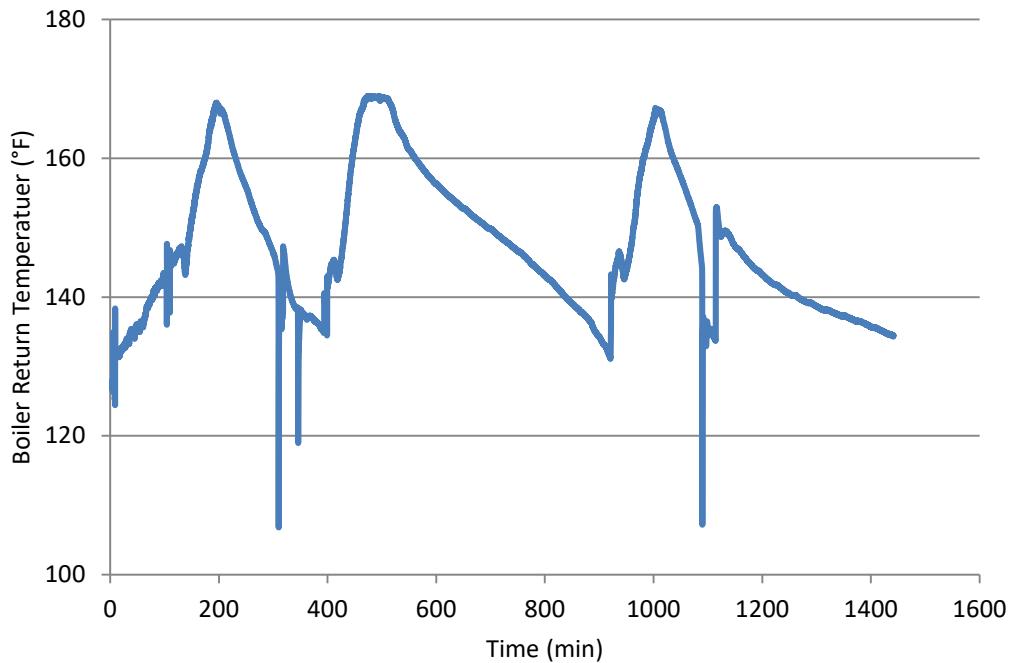
**Figure 105 Flue O<sub>2</sub>, Test 16, April profile, 210 gal. storage**



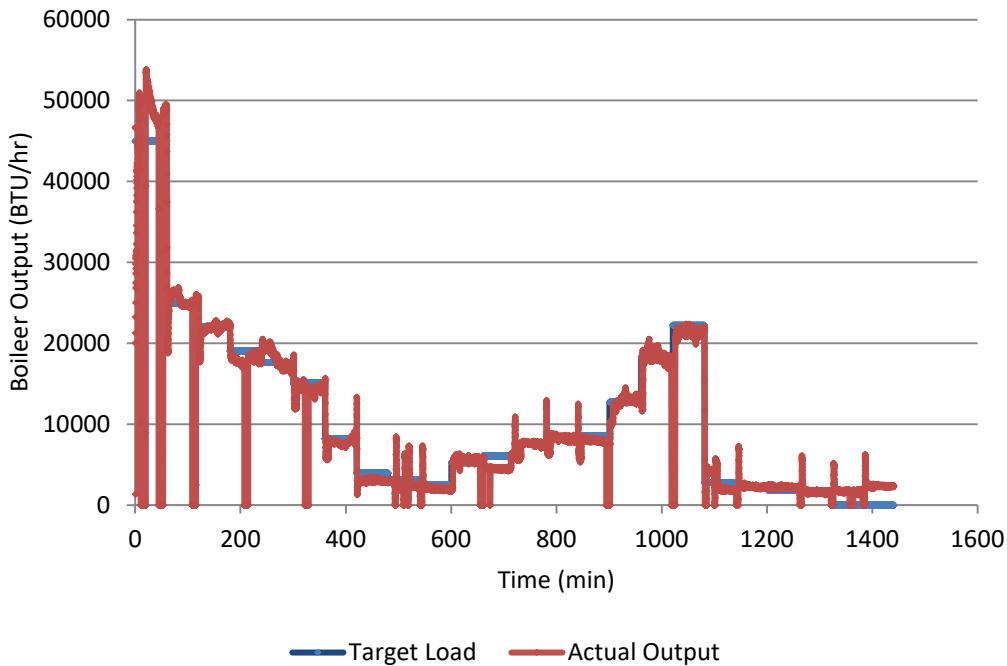
**Figure 106 Flue HC, Test 16, April profile, 210 gal. storage**



**Figure 107 Boiler supply temperature, Test 16, April profile, 210 gal. storage**



**Figure 108 Boiler return temperature, Test 16, April profile, 210 gal. storage**



**Figure 109 Boiler output, Test 16, April profile, 210 gal. storage**

#### Startup and Shutdown Particulate Emissions

Every time the pellet-fired boiler starts the control takes it through a set of steps. The steps and approximate times during startup are listed in the Table 5, below.

Table 5 Phases of Startup with the Tested Pellet Boiler

| Phase     | Time (min) |
|-----------|------------|
| Flush     | 2          |
| Fill      | 1 1/2      |
| Ignite    | 2          |
| Stabilize | 5          |
| Automatic | -          |

During the “Flush” phase the fan operates to clear out any residual combustible gases and the bottom ash door opens to dump any remaining ash into the pit below. Typically during this time

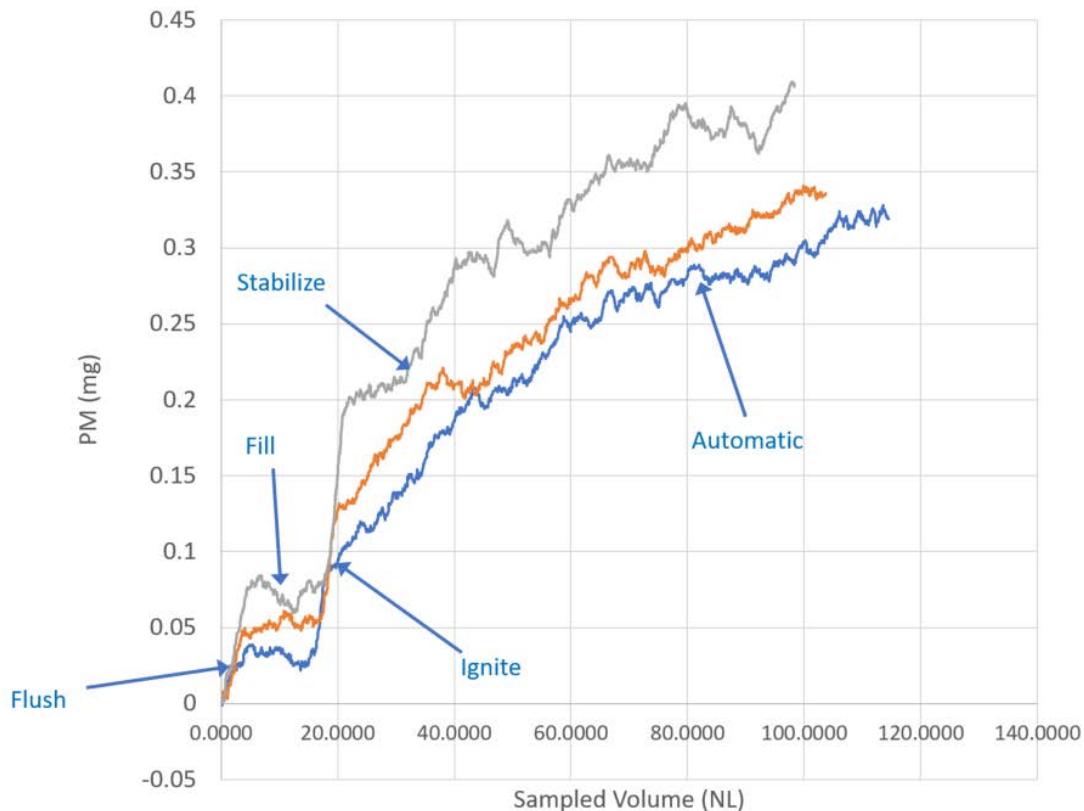
period there is a pulse of particulates emitted into the dilution tunnel. During the “Fill” stage pellets are delivered by auger onto the fire bed. During this period there typically is no significant particulate emission. In the ignite phase an electrically heated stream of air at very high temperature is directed onto the fresh pellet bed leading to ignition. This process takes about two minutes as the air and bed increase in temperature to the ignition point. During most of this time there is no clear combustion occurring. When the bed does ignite there is typically a short period with high particulate and CO emissions. Following ignition, the air feed rate is slowly ramped up as the flame spreads throughout the whole bed, the combustion chamber area heats and flame reaches its stable full output condition. After this period there is “Automatic” operation in which the firing rate can modulate based on the boiler temperature. This is typically the cleanest part of the operating cycle. With a steady load, the Automatic period will end when the boiler temperature rises to the operating limit. If the load on the system is at or above the maximum rated load the burner will continue to fire.

Table 6, below, shows the operating phases after the boiler has reached the operating temperature limit and shuts down the burner. The first phase is burnout in which no additional fuel is fed to the burner and the bed of pellets is allowed to burn out. As the flame gets weaker and cooler there is some increase in emissions. After this phase there is a post ventilation period to ensure all combustible gases are cleared from the chamber area. During this time the fan continues to operate moving cold air over the heat exchanger surface and carrying heat out the exhaust, with a negative impact on efficiency.

Table 6 Phases of Shutdown with the Tested Pellet Boiler

| Phase            | Time (min) |
|------------------|------------|
| Burnout          | 8 to 10    |
| Post ventilation | 3          |
| Standby          | -          |

Figure 110 shows the results of the transient particulate measurements during three consecutive startups during a Category I test. This figure is total collected particulates vs. total volume sampled by the instrument. The slope of the curve at any point, then, is the particulate emission rate from the dilution tunnel at that time. This figure shows a relatively consistent pattern between each startup cycle in which there is a significant emission of particulates during the fill and ignition phases, certainly higher than steady state.



**Figure 110 Dilution tunnel real-time particulate concentration measurement results.**

Comparison of Steady State Particulate Emissions at Low and High Fire

This purpose of this section is simply to communicate an observation about the nature of particulate emissions at low and high fire in steady state. Figure 111 shows a comparison of the filters in these two cases. At low fire, in addition to the particulates being obviously darker and more carbon-rich, the pressure drop across the filters at low fire rose much more rapidly than at high fire. In spite of this, it was generally observed that the particulate emission rate is lower at low fire than at high fire.



**Figure 111 Comparison of appearance of filters in steady state. Left = 30% output, Right = full output**

## Discussion

Table 7, below provides an overall summary of the results of the 16 full performance tests done during this project. From this some first observations can be made. The highest efficiency of about 81% was achieved during the high load steady state tests. This level of efficiency was also reached during the high load, January profile day, with 119 gallons of thermal storage. During these tests low particulate emissions were also achieved.

The lowest efficiency of about 56% was achieved during the low load Category I tests without storage. During these tests the highest particulate emissions were also measured.

During the Category I tests with 119 gallons of thermal storage, two different settings of the control differential were used. In tests 5 and 6 the differential was set at 7 °F and this was the as-received setting. As discussed above, this is the difference in temperature between the burner turn off and turn on temperatures. The turn off temperature was based on the temperature sensor located at the bottom of the tank and the turn on temperature was based on the temperature at the top of the tank. In tests 7 and 8 this differential was broadened to 20 °F based on discussions with the manufacturer. The rational for this was that such a broader setting would be more likely to be used in the field. This differential setting significantly increases the time period between turn off and turn on and this time period strongly affects cycling rate and performance. To provide a comparison of all Category I test results Table 8 provides a summary of just the Category I test conditions which includes the differential setting and the average “Period”. In a steady load, cycling test like the Category I runs, this is the average time period, for example from burner-off to burner-off.

Table 7 Summary of Selected Results

| Test Number | Category or Profile | Test Date        | Thermal Storage | Average Output Btu/hr | Efficiency % | PM Index g/kg fuel | PM Factor LB/MMBtu output | PM Rate g/hr |
|-------------|---------------------|------------------|-----------------|-----------------------|--------------|--------------------|---------------------------|--------------|
| 1           | Category IV         | 8/6/15           | No              | 77,155                | 80.0         | 1.03               | 0.15                      | 5.16         |
| 2           | Category IV         | 10/13/15         | No              | 73,109                | 80.7         | 0.88               | 0.13                      | 4.42         |
| 3           | Category I          | 8/31/15          | No              | 10,157                | 56.5         | 1.89               | 0.40                      | 1.97         |
| 4           | Category I          | 9/21/15          | No              | 10,828                | 56.2         | 1.99               | 0.42                      | 2.10         |
| 5           | Category I          | 8/28/15          | 119 gal         | 11,170                | 59.5         | 1.04               | 0.16                      | 1.11         |
| 6           | Category I          | 9/23/15          | 119 gal         | 9,754                 | 61.1         | 1.79               | 0.25                      | 1.50         |
| 7           | Category I          | 10/23/15         | 119 gal         | 12,104                | 68.1         | 0.87               | 0.15                      | 1.15         |
| 8           | Category I          | 11/18/15         | 119 gal         | 10,956                | 71.3         | 0.77               | 0.13                      | 1.16         |
| 9           | Category I          | 11/4/16          | 210 gal         | 11,057                | 74.1         | 0.83               | 0.14                      | 1.21         |
| 10          | Profile April       | 6/6-7/16         | No              | 10,194                | 58.7         | 1.73               | 0.34                      | 1.68         |
| 11          | Profile January     | 5/13 and 5/16/16 | No              | 38,035                | 77.0         | 0.96               | 0.15                      | 2.59         |
| 12          | Profile March       | 4/28-29/16       | No              | 20,424                | 76.4         | 1.04               | 0.16                      | 1.56         |
| 13          | Profile April       | 5/25-26/16       | 119 gal         | 10,631                | 69.7         | 0.89               | 0.15                      | 0.77         |
| 14          | Profile January     | 5/9-10/16        | 119 gal         | 37,202                | 80.8         | 0.75               | 0.12                      | 2.03         |
| 15          | Profile March       | 2/1-2/16         | 119 gal         | 18,777                | 75.4         | 0.74               | 0.12                      | 1.01         |
| 16          | Profile April       | 11/10-11/16      | 210 gal         | 10,835                | 73.6         | 1.20               | 0.20                      | 1.15         |

Table 8 Comparison of Category I Runs - Period

| Test | Storage | Storage Tank Differential | Period |
|------|---------|---------------------------|--------|
|      | (gal)   | (°F)                      | (min)  |
| 3    | None    | N/A                       | 34     |
| 4    | None    | N/A                       | 26     |
| 5    | 119     | 7                         | 97     |
| 6    | 119     | 7                         | 101    |
| 7    | 119     | 20                        | 196    |
| 8    | 119     | 20                        | 229    |
| 9    | 210     | 20                        | 337    |

For just these Category I tests Figure 112 presents the efficiency results and Figure 113 presents the particulate emission rate results with both as a function of the period from Table 8. Taken together, these show that adding thermal storage capacity, with volume of storage and increased storage tank differential has the positive effects of increasing efficiency and reducing particulate emissions under this low load, Category I condition. The importance of these low load periods was discussed in the Introduction section.

In this project the maximum storage tank differential used was 20 °F. Depending on the details of the building in which a system is installed and the heat emitters used it may be practical to use an even larger differential which, for a given tank size, would improve performance.

A comparison of the efficiency and particulate emissions for the January, March, and April profile runs is provided in Figure 114 and Figure 115. The results show for these complex load profile runs improved performance with storage generally, but this is most strongly evident at the low load April condition. The results for the March run are an obvious exception where the measured efficiency was slightly higher for the case with no storage.

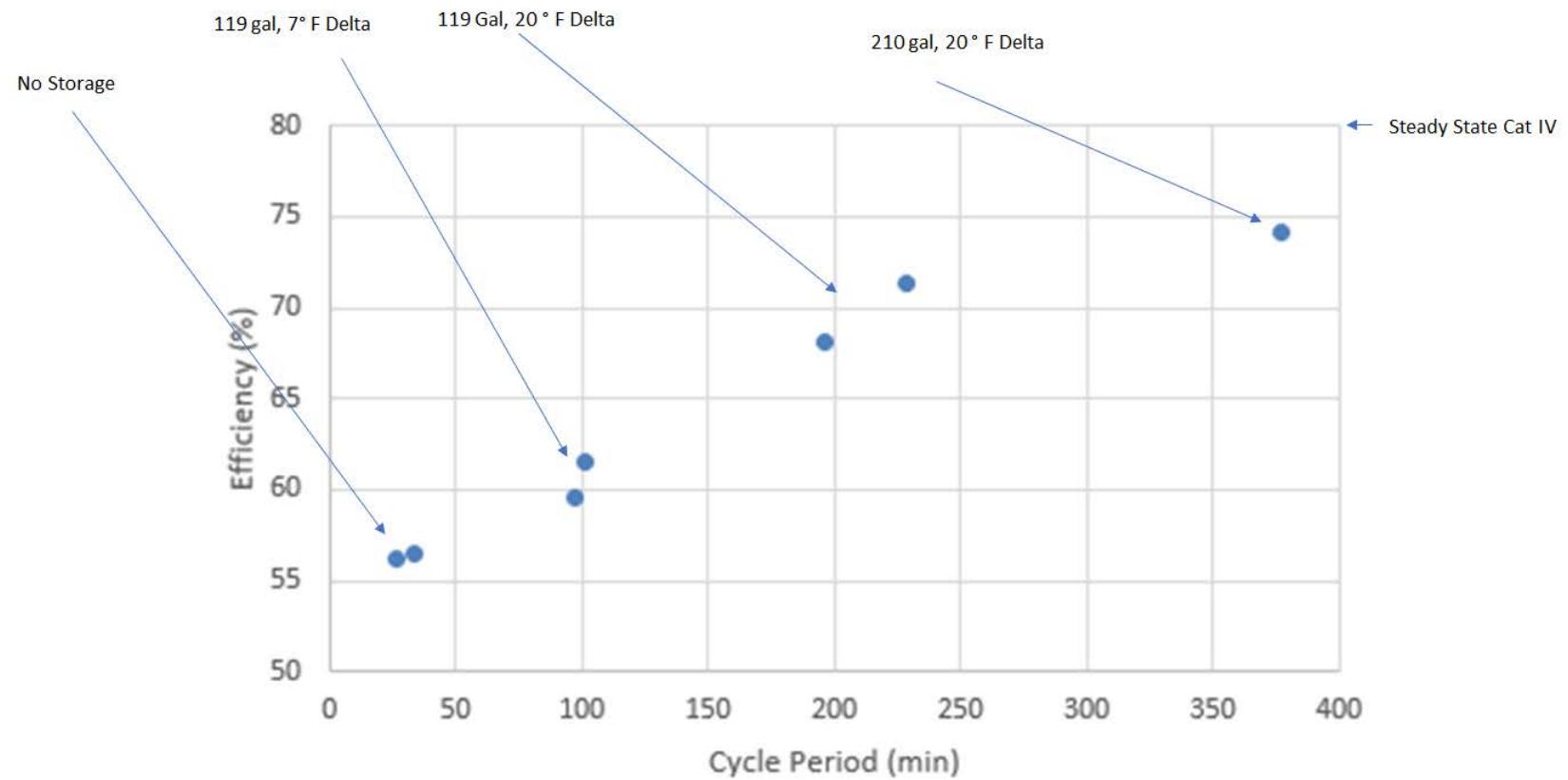


Figure 112 Category I runs, illustration of relationship between cycle period and efficiency

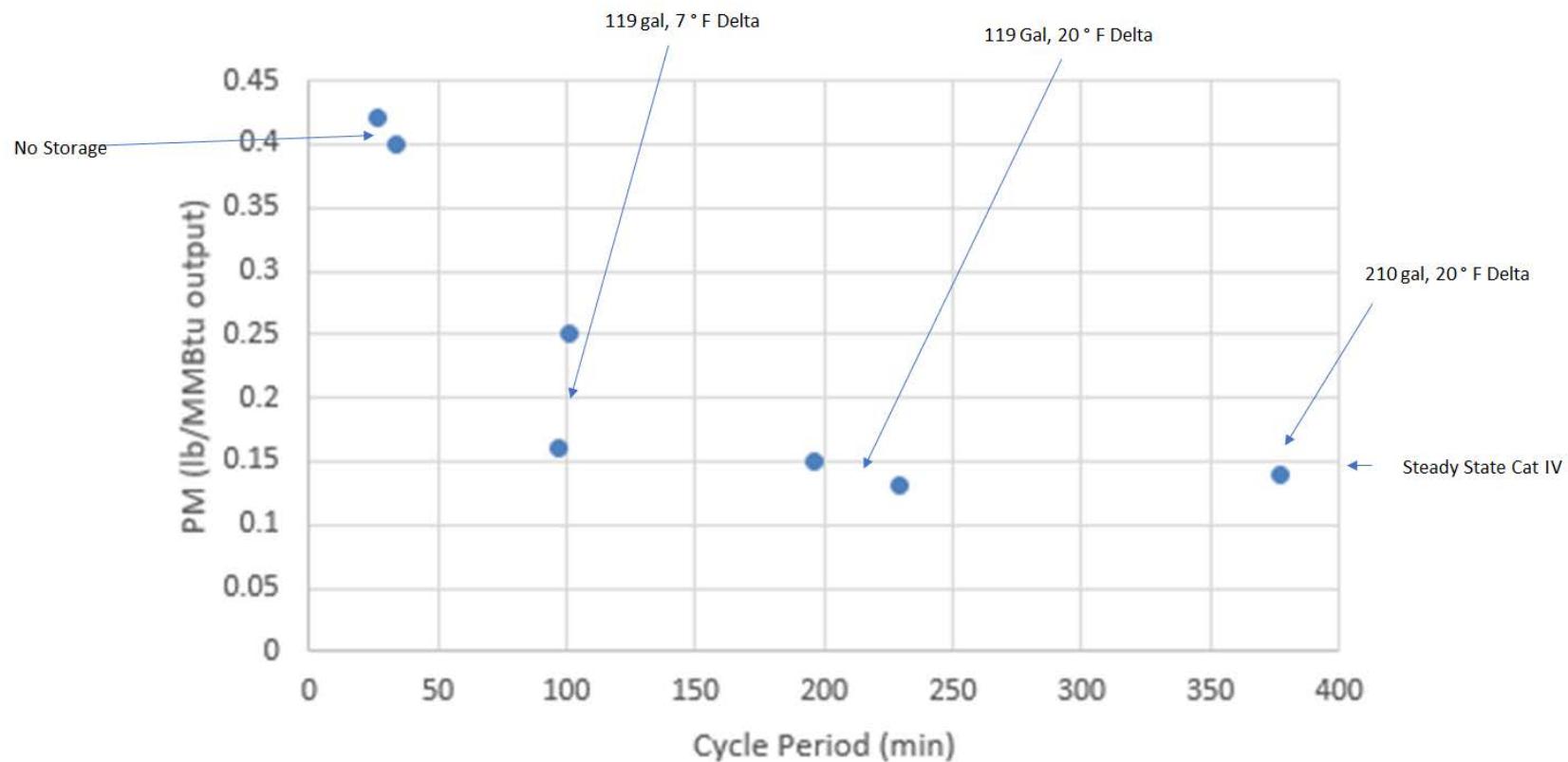
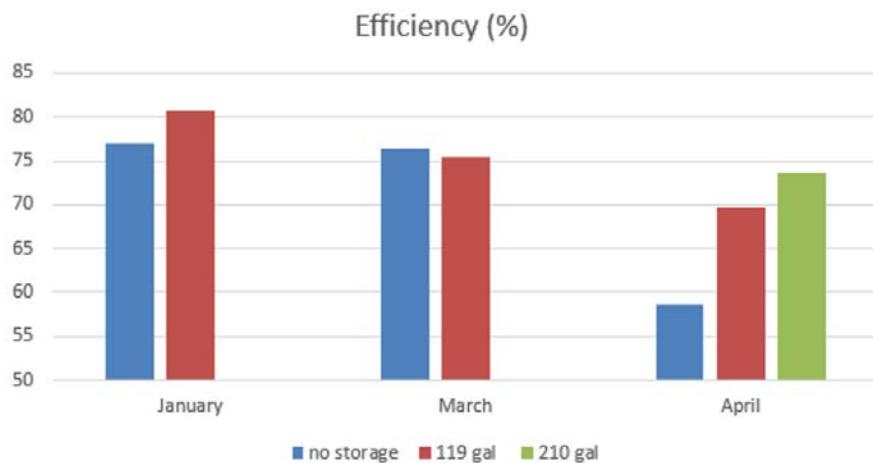
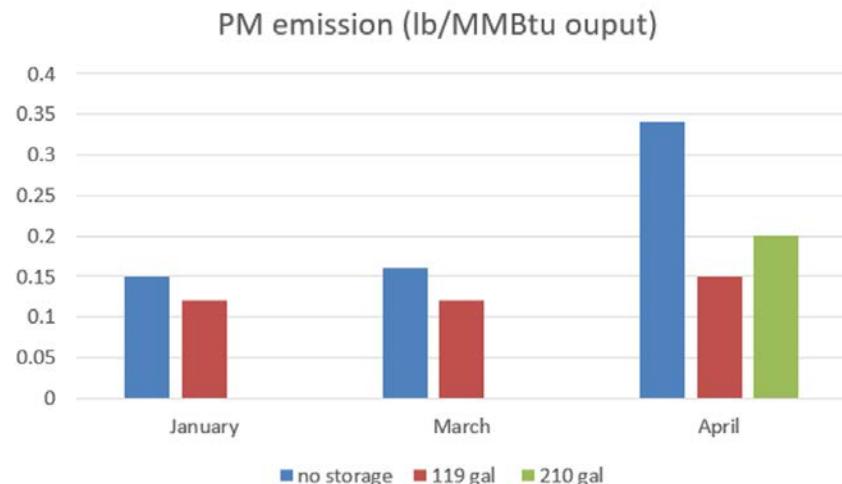


Figure 113 Category I runs, illustration of relationship between cycle period and particulate emission factor



**Figure 114 Profile runs, efficiency comparison**



**Figure 115 Profile runs, emission factor comparison**

Another important observation from the data is the similarity between the results of the steady load category tests and the profile tests. The emission factors for the January load tests are similar to those of the Category IV tests. As noted above, the efficiency for the January profile tests with storage are similar to those of the Category IV runs. Similarly, the low April load tests without storage can be compared to the Category I runs also without storage. The same comparison can be made for these low load cases with storage.

As discussed in the Introduction section, there currently isn't in the U.S. a standard test method for evaluating the efficiency and emissions of an automatic-feed boiler with thermal storage. An effort was made here, however, to calculate the annual performance factors by adopting the procedures used in EPA Method 28 WHH PTS which applies to cordwood-fired boilers. This was done for the 119 gal storage tank case with the 20 °F differential setting. Appendix III

provides the results tables for this in the format of this standard. The results lead to an Annual Efficiency of 71.8% and a particulate emission factor of 0.13 lb/MMBtu.

## Conclusions:

Based on all of the results of the studies performed the following conclusions can be drawn:

During cyclic operation, the pellet boiler studied goes through a standard series of steps including purge, cleaning, ignition, ramp-up to steady operation, steady operation, burnout, and post purge. These steps contribute to higher particulate emissions and lower efficiency under cyclic operation.

Thermal storage reduces cycling and this leads to increased efficiency and reduced particulate emissions. The thermal storage capacity can be increased through a wider control temperature differential as well as increased storage volume.

The benefits of thermal storage are greatest at low loads and it has been shown that units of this type operate for a very large fraction of the year at such low load conditions.

## References

1. Weiss, L., et al., *New York State Wood Heat Report: An Energy, Environmental, and Market Assessment*, in *NYSERDA Report 15-26*. 2016, New York State Energy Research and Development Authority.
2. NYSERDA. *Renewable Heat NY*. 2017 [cited 2017 July 12]; Available from: <https://www.nyserda.ny.gov/All-Programs/Programs/Renewable-Heat-NY>.
3. Nussbaumer, T., *Biomass Combustion in Europe - Overview on Technologies and Regulations*, *NYSERDA Report 08-03*. 2008.
4. McDonald, R., *Evaluation of Gas, Oil and Wood Pellet-Fueled Residential HEating System Emissions Characteristics BNL-90286-2009-IR*. 2009, Brookhaven National Laboratory.
5. Butcher, T. and N. Russell, *Review of EPA Method 28 Outdoor Wood Hydronic Heater Test Results*, *NYSERDA Report 11-17*. 2011.
6. EPA, *Standards of Performance for New Residential Wood Heaters, New Residential Hydronic Heaters and Forced-Air furnaces*, U.S. EPA, Editor. 2015: 80 Federal Register 50. p. 13672-13753.

## APPENDIX I ANALYSIS OF FUEL PROPOERTIES



### Analytical Test Report

|            |                                |                 |                              |
|------------|--------------------------------|-----------------|------------------------------|
| Client:    | Brookhaven National Laboratory | Signed:         | Stephen Sundeen              |
| Attention: |                                | Stephen Sundeen | Chemistry Laboratory Manager |
| PO No:     |                                | Date of Issue:  | 7/29/2015                    |

Report No: **USR:W215-0807-01**

Issue No: **1**

THIS DOCUMENT SHALL NOT BE REPRODUCED EXCEPT IN FULL

| <b>Sample Details</b>   |              |                     |                              |
|---|--------------|---------------------|------------------------------|
| Sample Log No:  | W215-0807-01 | Sample Date:        |                              |
| Sample Designation:   | July Testing | Sample Time:        |                              |
| Sample Recognized As:   | Pellets      | Arrival Date:       | 7/21/2015                    |
| <b>Test Results</b>   |              |                     |                              |
|   | METHOD       | UNITS               | MOISTURE AS<br>FREE RECEIVED |
| <b>Moisture Total</b>   | ASTM E871    | wt. %               | 3.77                         |
| <b>Ash</b>  | ASTM D1102   | wt. %               | 0.69 0.67                    |
| <b>Volatile Matter</b>  | ASTM D3175   | wt. %               |                              |
| <b>Fixed Carbon by Difference</b>   | ASTM D3172   | wt. %               |                              |
| <b>Sulfur</b>   | ASTM D4239   | wt. %               | 0.008 0.008                  |
| <b>SO<sub>2</sub></b>   | Calculated   | lb/mmbtu            | 0.018                        |
| <b>Net Cal. Value at Const. Pressure</b>  | ISO 1928     | GJ/tonne            |                              |
| <b>Net Cal. Value at Const. Pressure</b>  | ISO 1928     | J/g                 |                              |
| <b>Gross Cal. Value at Const. Vol.</b>  | ASTM E711    | J/g                 | 19966 19214                  |
| <b>Gross Cal. Value at Const. Vol.</b>  | ASTM E711    | Btu/lb              | 8584 8261                    |
| <b>Carbon</b>   | ASTM D5373   | wt. %               |                              |
| <b>Hydrogen*</b>  | ASTM D5373   | wt. %               |                              |
| <b>Nitrogen</b>   | ASTM D5373   | wt. %               |                              |
| <b>Oxygen*</b>  | ASTM D3176   | wt. %               |                              |
| *Note: As received values do not include hydrogen and oxygen in the total moisture. |              |                     |                              |
| <b>Chlorine</b>   | ASTM D6721   | mg/kg               | 13 12                        |
| <b>Fluorine</b>   | ASTM D3761   | mg/kg               |                              |
| <b>Mercury</b>  | ASTM D6722   | mg/kg               |                              |
| <b>Bulk Density</b>   | ASTM E873    | lbs/ft <sup>3</sup> | 42.95                        |
| <b>Fines (Less than 1/8")</b>   | TPT CH-P-06  | wt. %               | 0.06                         |
| <b>Durability Index</b>   | Kansas State | PDI                 | 99.3                         |
| <b>Sample Above 1.50"</b>   | TPT CH-P-06  | wt. %               | 0.3                          |
| <b>Maximum Length (Single Pellet)</b>   | TPT CH-P-06  | inch                | 1.600                        |
| <b>Diameter, Range</b>  | TPT CH-P-05  | inch                | 0.252 to 0.258               |
| <b>Diameter, Average</b>  | TPT CH-P-05  | inch                | 0.256                        |
| <b>Stated Bag Weight</b>  | TPT CH-P-01  | lbs                 | 0.0                          |
| <b>Actual Bag Weight</b>  | TPT CH-P-01  | lbs                 | 20.0                         |

## **APPENDIX II STUDY OF TANK HEAT LOSS**

## Introduction

The addition of a water storage tank, thermal storage system to a biomass-fired hydronic heater offers the potential for reduced cycling, reduced emissions, and improved thermal efficiency of the boiler. However, the addition of heat loss from the outer jacket of the storage tank can detract from system efficiency and needs to be considered in a comprehensive energy performance evaluation. During the tests of this boiler, several studies were done to measure the tank heat loss. It should be noted that in all of the Category and Load Profile tests reported on in the main body of this report already include the effects of tank heat loss since the output measurement is made “after” the tank. Measurement of the tank heat loss rate is still important for two reasons. First, understanding tank heat loss provides information on the magnitude of efficiency improvement which might be achieved by improving tank insulation or using other means to reduce the tank loss. Second, the tank heat loss can be used to estimate performance under conditions other than those at which the unit is tested. For example loads even lower than the 15% Category I load. This could include summer domestic hot water loads.

Initial tank heat loss measurements were done with the 119 gallon storage tank with ~ 1.5 inches of fiberglass insulation. Figure 2 of the main body of the report provides an illustration of the installed system including the storage tank.

In developing a method for estimating tank heat loss rate different basic approaches were considered including:

Method 1. Using internal water temperature, surrounding air temperature, and use construction of the tank to estimate an overall heat transfer conductance and heat transfer rate.

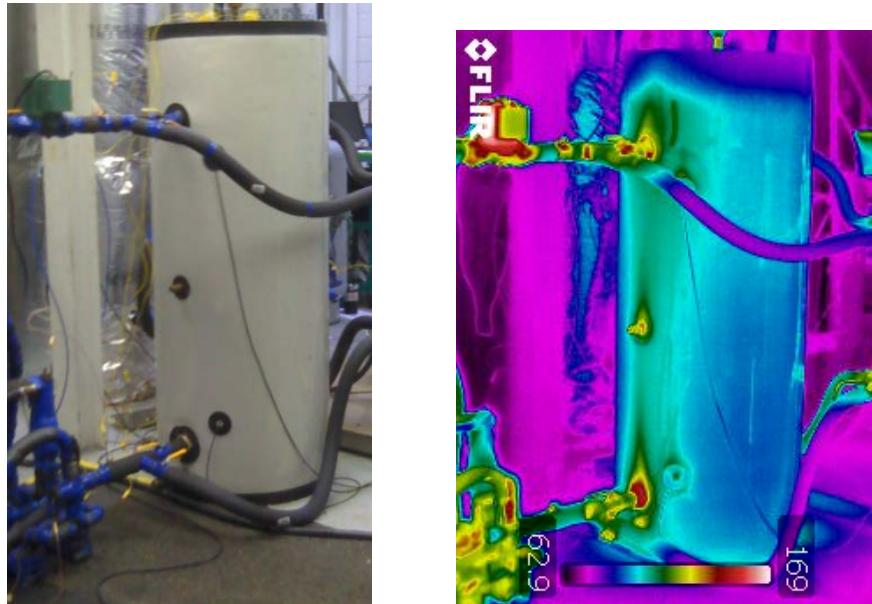
Method 2. Measure surface temperature; estimate from engineering correlations the rate of heat transfer by convection and radiation.

Method 3. Run an external circulation pump continuously through an insulated loop and measure the rate of decay of the tank temperature.

Method 4. Run an external circulation pump through an insulated loop at the start and end of a test period to determine the tank average temperature at both times.

Method 5. Measurement of the internal tank vertical centerline tank temperature at the start and end of the test.

Method 1 requires the use of some estimations that limit its accuracy. It requires determination of overall conductance which combines the internal convective heat transfer coefficient, the thermal resistance of the tank metal, the thermal resistance of the insulation, the outside convective heat transfer coefficient and the emissivity of the outer surface. The inside and outside convective coefficients can be determined from standard engineering correlations. Since the controlling thermal resistance will be that of the insulation, the accuracy of the determination of the convective coefficients is not very critical.



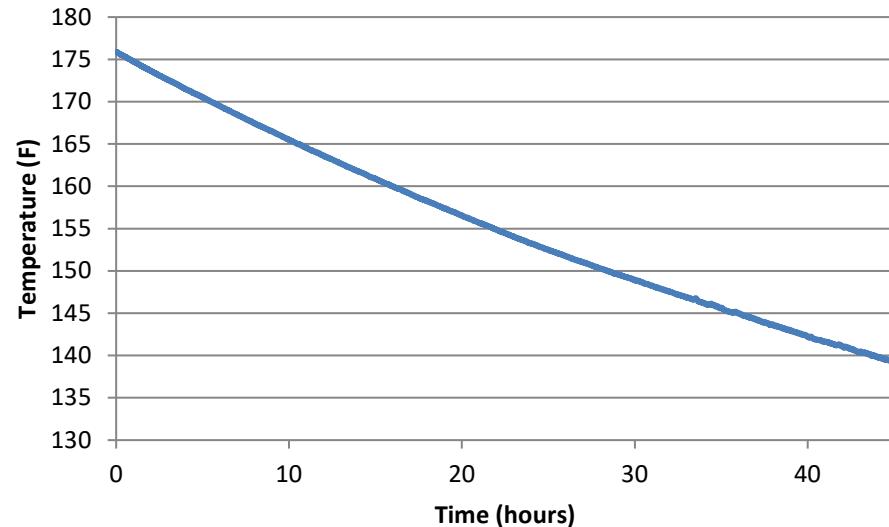
**Figure AII-116 Photo and IR image of 119 gallon thermal storage**

In Method 2 the tank temperature and then the jacket heat loss is calculated. This again requires use of an outside convective heat transfer coefficient and emissivity of the outer surface. This method is currently used in the ASHRAE 103 Standard [1] to determine jacket loss from residential boilers and in the draft ASHRAE 155P [2] standard to determine jacket loss from commercial boilers.

A determination of the heat loss from the 119 gallon tank was made using Method 2. With the tank at its operating temperature the average difference between the surface and the room was found to be on the order of 5 °F, providing a heat loss rate of 348 Btu/hr.

A key concern with Methods 1 and 2, is that they neglect heat loss from piping and sensor fittings and penetrations in the tank. Figure 1 shows a photo and IR image taken of the test tank and this clearly shows the potential significance of these.

Method 3 is relatively simple to implement and potentially quite accurate. Several runs with this method were done during this project. Figure 2 shows, for example, the measured temperature profile during one weekend-long run.



**Figure AII-117 Rate of temperature decay during a long storage period with 119 gallon thermal storage tank – continuous circulation.**

Based on the decay in temperature from 170 °F to 150 °F over 22.94 hours the rate of decay in tank temperature is 0.87 °F/hr, resulting in a tank heat loss rate of 886 Btu/hr.

Two factors should be considered with the continuous external loop. The first is heat loss from the external loop. This can be minimized by insulation and the test method does not have to specify the minimum level of insulation. It is expected that the manufacturer or test lab would run this test with the best practical level of insulation. A second factor is heat which can be added into the loop from the circulating pump.

In one set of special tests a room temperature tank was set to circulate continuously overnight with the end result that the tank increased by roughly 8 °F, leading to a heat input from the pump of 500 Btu/hr. This pump used in this test has a nominal power draw of 220 watts, or 750 Btu/hr. The energy added into the water is not from pumping work but rather from electric heat in the motor windings. Our best current estimate is that 50% of the energy from the motor power should be added to the tank heat loss if a continuous circulation approach is used.

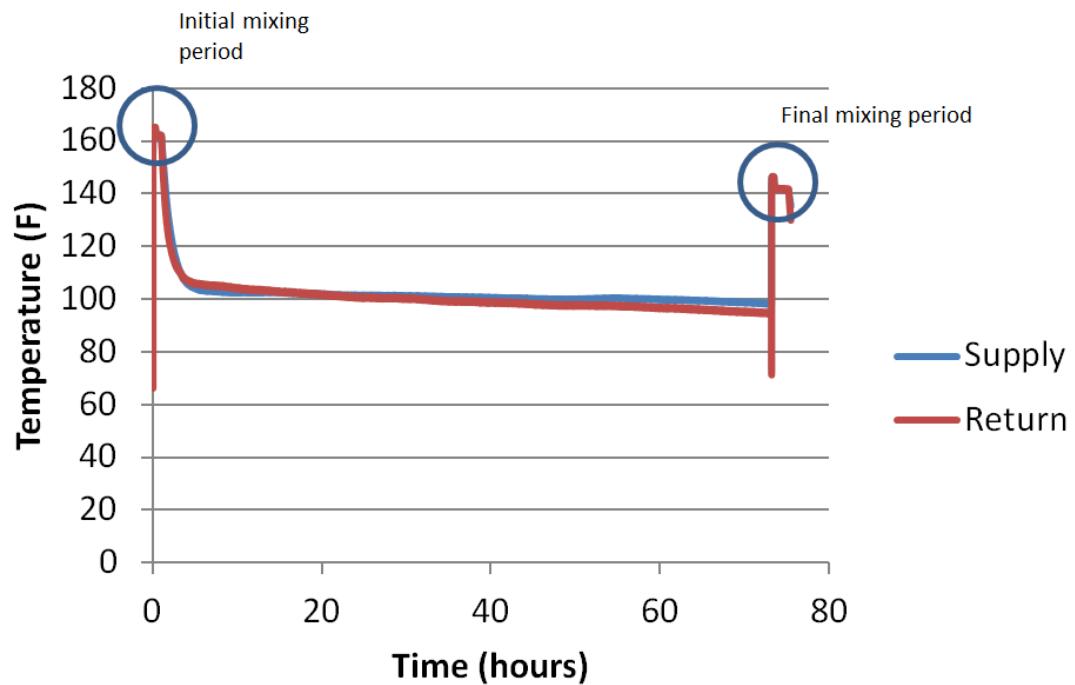
For the test results in Figure 2, a lower power circulator was used with a power input of 70 watts. Using this approach, 120 Btu/hr is added to the measured tank heat loss for a total heat loss rate of 1006 Btu/hr.

This specific boiler has a maximum rated heat input rate of 85,000 Btu/hr. At full load output, the tank heat loss would reduce efficiency by 1.1%. Under a Category IV (15% of nominal output) test condition, however, this heat loss rate would reduce efficiency by 7.9%.

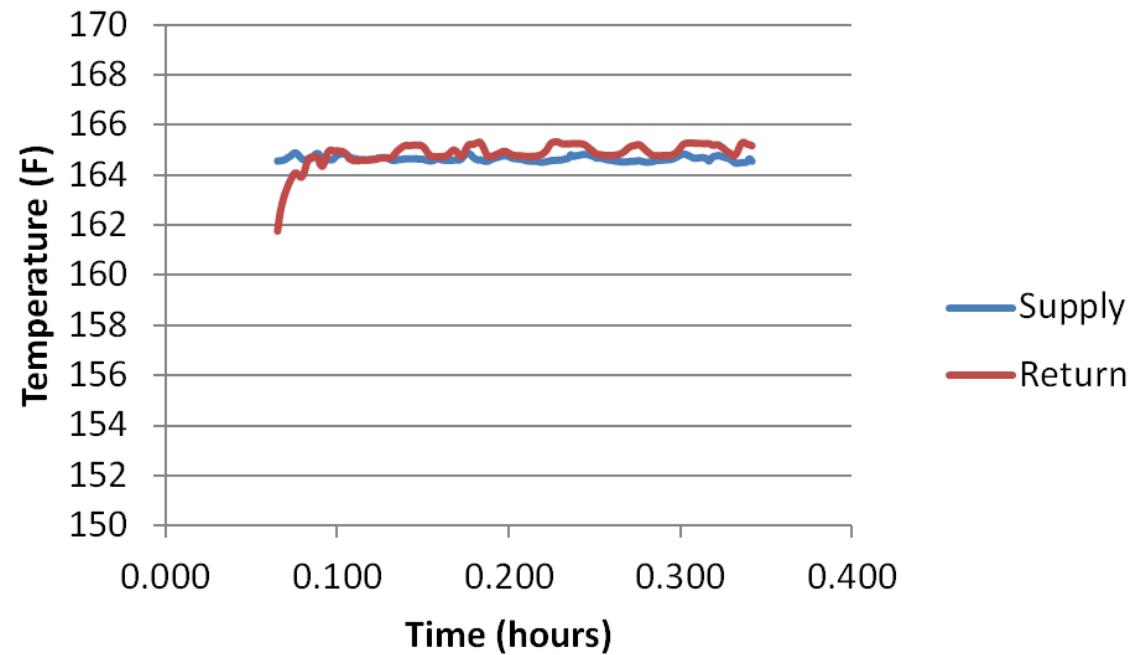
In a test, it would seem most practical and accurate to use a circulating pump with as low an electric power draw as possible. Newer, brushless DC pumps can dramatically reduce the power demand, to the 20 watt range and would reduce the influence of this factor.

Method 4 is an attempt to eliminate both positive and negative bias due to the continuous operation of the circulating pump. This approach is similar to that of Method 3 but the pump is only run at the beginning and end of the test period to get an average start and end tank temperature. This approach is also simple and potentially attractive but there are several concerns. During a long idle period some stratification can occur in the tank leading to a temperature/time profile in the tank. It is certainly possible to develop a pre- and post-test circulation strategy for the tank to determine the effective average tank temperature. This approach is already used, for example in the EPA test method 28 WHH PTS [3]. However, in the tank loss test the changes in tank temperature from start to end are much smaller than in the BNL-PTS test method. The tank heat loss rate test should be done over a smaller range of temperature, more typical of what might be expected in actual operation. Further, during the idle period, the external loop will cool down, perhaps to room temperature, and when the pump is restarted the cold loop will slightly cool the water in the tank. This cooling effect can be minimized by keeping the volume of the external loop as small as possible.

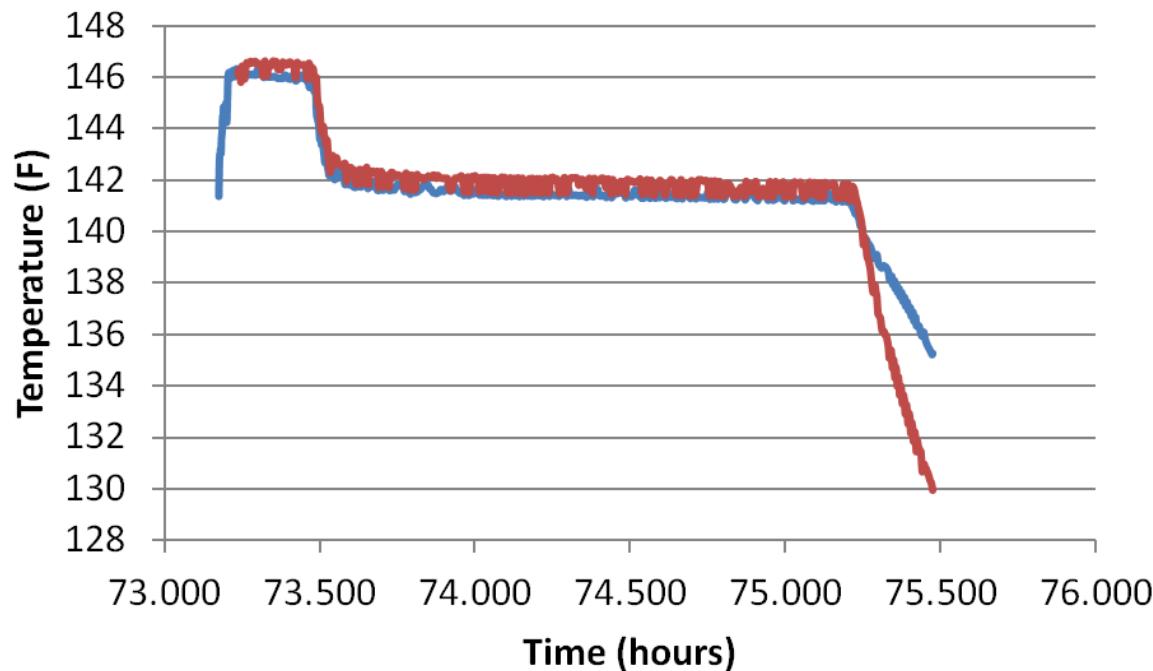
In this study, Method 4 was used to determine the heat loss rate from the 210 gallon tank used. Temperature in the recirculation loop was measured at two points – one as the hot water from the top of the tank enters the recirculation loop – “supply temperature” and the other as the water returns back to the bottom of the loop – “return temperature”. Since is simple closed loop without a heat exchanger is used these two temperatures should be the same. The test was run over a 3 day (76 hour) period. Figure 3 shows the temperature in the circulation loop over the whole period. As shown in this figure, the temperature in the recirculation loop does decrease to approach room temperature during the long idle period when the recirculation loop pump is not running. Figures 4 and 5 provide expansions of the initial and final circulation periods respectively. The initial circulation period for determination of the average tank temperature was relatively short but the tank had already been mixed prior to this period. When the final circulation period started there is a peak in temperature reflecting stratification in the tank. After a brief period, the temperature becomes quite uniform, enabling an average temperature to be determined. Based on this test the average rate of heat loss from this tank over the whole period has been determined to be 550 Btu/hr. This is considerable lower than the rate of heat loss from the 119 gallon tank and this is primarily because the insulation thickness is much greater ( 6 inches of foam insulation) on the larger tank.



**Figure AII-3 Heat loss test with 210 gallon thermal storage tank with operation of the circulation loop pump only at the start and end of the test period. Temperatures measured over the entire period.**



**Figure AII-118 Heat loss test with 210 gallon thermal storage tank with operation of the circulation loop pump only at the start and end of the test period. Expansion of the initial circulation period.**



**Figure AII-119 Heat loss test with 210 gallon thermal storage tank with operation of the circulation loop pump only at the start and end of the test period. Expansion of the final circulation period.**

Method 5 involves the addition of a long temperature sensor probe or linear array to measure the tank internal vertical temperature profile. This approach is now commonly used in oil- and gas-fired residential water heating testing. The vertical tank is divided into 6 equal volumes and the temperature measured at the center of each volume. This approach was used in efficiency testing of the 25 kW wood-pellet fired boiler studied in this project. When operating with storage, the tank temperature was measured at the start and end of each 4 hour run. This approach eliminates some of the concerns in Methods 3 and 4 but leads to others. First, with stratification it is not certain that the measured temperature in the center of each volume represents the actual average. Second, manufacturers recognize the value of a strong degree of temperature stratification within the tank and seek to design the tank system with baffles and

other arrangement that inhibit the placement of a temperature sensor array or probe along the tank centerline. Many tanks also may not have ports necessary for the addition of this probe.

Considering all options, it is the recommendation of the project team that Method 3 be adopted with the recommendation that the external circulation piping be made as short and well insulated as practical and that a low electric power circulating pump be used with a penalty assigned at 50% of the pump energy input rate.

References:

- [1] American Society of Heating Refrigeration, and Air Conditioning Engineers, "Standard 103-2007 Method of Testing for Annual Fuel Utilitation Efficiency of Residential Central Furnaces," ASHRAE, Atlanta, 2007.
- [2] American Society of Heating, Refrigeration and Air Conditioning Engineers, "SPC 155P Method of Testing for Rating Commercial Space Heating Boiler Systems (Currently in Advisory Public Review)," ASHRAE, Atlanta, 2016.
- [3] "Standards of Performance for New Residential Wood Heaters, New Residential Hydronic Heaters and Forced-Air Furnaces" 80 Federal Register 50, (March 16, 2015), pp. 13672-13753.

## **APPENDIX III DATA SUMMARY FOR ANNUAL EFFICIENCY and PARTICULATE EMISSION RATING**

In this appendix, an effort is made to evaluate the annual efficiency and particulate emission rating following the approach of EPA Method 28 WHH-PTS. This is a cordwood test standard but as noted in the body of the report an approved test method for automatic feed boilers, such as the one tested here, does not exist currently.

Under Method 28 WHH-PTS, test procedures are defined for four load categories as discussed in the Introduction section. There is, however, the option to assume that the results for load category I (< 15%) are also applicable in the Category II and III cases, avoiding the need to run those tests. This option was taken here since the particulate emission factors for the Category I and IV tests were the same where storage is used.

|                              |        |                 |             |             |             | $\Theta$      | $W_{fuel}$           | $MC_{ave}$    | $Q_{in}$   | $Q_{out}$   |
|------------------------------|--------|-----------------|-------------|-------------|-------------|---------------|----------------------|---------------|------------|-------------|
| Category                     | Run No | Load % Capacity | Target Load | Actual Load | Actual Load | Test Duration | Wood Weight as-fired | Wood Moisture | Heat Input | Heat Output |
|                              |        |                 | Btu/hr      | Btu/hr      | % of max    | hrs           | lb                   | % DB          | Btu        | Btu         |
| Nov. 18 <sup>th</sup> , 2015 | I      | < 15% of max    | 10,966      | 10,956      | 15.0        | 7.58          | 16.0                 | 3.77          | 116,475    | 83,046      |
|                              | II     | 16-24% of max   | —           | —           | —           | —             | —                    | —             | —          | —           |
| Oct. 13 <sup>th</sup> , 2015 | III    | 25-50% of max   | —           | —           | —           | —             | —                    | —             | —          | —           |
|                              | IV     | Max capacity    | 73,109      | 73,109      | 100         | 2.00          | 22.0                 | 3.77          | 181,187    | 146,218     |

Figure AIII-120 Data Summary Part A

\*\*\*\* Not measured. Assumed to be equal to the Category I test results, as per BNL PTS method

|                              |        |                 | T2 Min                 | $E_T$              | $E$             | $E$             | $E_{g/hr}$ | $E_{g/kg}$ | $\eta_{del}$         | $\eta_{SLM}$          |
|------------------------------|--------|-----------------|------------------------|--------------------|-----------------|-----------------|------------|------------|----------------------|-----------------------|
| Category                     | Run No | Load % Capacity | Min Return Water Temp. | Total PM Emissions | PM Output Based | PM Output Based | PM Rate    | PM Factor  | Delivered Efficiency | Stack Loss Efficiency |
|                              |        |                 | ° F                    | g                  | lb/MMBtu Out    | mg/MJ           | g/hr       | g/kg       | %                    | %                     |
| Nov. 18 <sup>th</sup> , 2015 | I      | < 15% of max    | 136                    | 5.56               | 0.13            | 55.6            | 0.73       | 0.77       | 71.3                 | 84.1                  |
| Oct. 13 <sup>th</sup> , 2015 | II     | 16-24% of max   | —                      | —                  | 0.13****        | 55.6****        | 0.98       | 0.77****   | 71.3****             | —                     |
|                              | III    | 25-50% of max   | —                      | —                  | 0.13****        | 55.6****        | 1.47       | 0.77****   | 71.3****             | —                     |
|                              | IV     | Max capacity    | 132                    | 8.84               | 0.13            | 55.6            | 4.42       | 0.88       | 80.7                 | 85.2                  |

Figure AIII- 121 Data Summary Part B

|                           |              |      |                                     |
|---------------------------|--------------|------|-------------------------------------|
| MANUFACTURER:             |              |      |                                     |
| MODEL NUMBER:             |              |      |                                     |
| ANNUAL EFFICIENCY RATING: | $\eta_{avg}$ | 71.8 | <b>(Using higher heating value)</b> |
|                           |              |      | (Using lower heating value)         |
| PARTICLE EMISSIONS:       | $E_{avg}$    | 1.18 | GRAMS/HR (average)                  |
|                           |              | 0.13 | LBS/MILLION Btu/hr <u>OUTPUT</u>    |

Figure AIII- 122 Hang Tag Information

| Category      | Weighting Factor (F <sub>i</sub> ) | n <sub>del,i</sub> x F <sub>i</sub> | E <sub>mg/MJ,i</sub> x F <sub>i</sub> | E <sub>g/kg,i</sub> x F <sub>i</sub> | E <sub>lb/MMBtu Out,i</sub> x F <sub>i</sub> | E <sub>g/hr,i</sub> x F <sub>i</sub> |
|---------------|------------------------------------|-------------------------------------|---------------------------------------|--------------------------------------|--|--------------------------------------|
| I             | 0.437                              | 31.2                                | 24.3                                  | 0.34                                 | 0.06   | 0.32                                 |
| II            | 0.238                              | 17.0                                | 13.2                                  | 0.18                                 | 0.03   | 0.23                                 |
| III           | 0.275                              | 19.6                                | 15.3                                  | 0.21                                 | 0.04   | 0.40                                 |
| IV            | 0.050                              | 4.04                                | 2.78                                  | 0.04                                 | 0.01   | 0.22                                 |
| <b>Totals</b> | <b>1.000</b>                       | <b>71.8</b>                         | <b>55.6</b>                           | <b>0.78</b>                          | <b>0.13</b>                                  | <b>1.18</b>                          |

Figure AIII-123 Annual Weighting