Linkageless Burner Retrofits for Steam Boilers:
Going Beyond Carburetor Technology in a Large Segment of the NYS Market

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Executive Summary

This document is a technical brief of the research conducted to evaluate linkageless burner retrofits with respect to energy savings and carbon reductions as well as qualitative and non energy benefits. This study also focuses on quantifying the seasonal efficiency of intermediate-sized high mass steam boiler plants, addressing this gap in the industry's knowledge.

For well-tuned high mass steam boilers, the seasonal efficiency was found to be 80% - 85%. Off-cycle heat losses for the pre-retrofit period were 0.3% - 1.3%, which was lower than anticipated. After the burners were retrofitted with linkageless controls, the off-cycle losses were eliminated. M&V testing and data showed that the combustion air damper is the primary determinant of off-cycle heat loss, while the flue damper position had little to no effect. This is because the combustion air damper's small effective leakage area (ELA) makes it the choke point for air flow through the boiler during the off-cycle period. Linkageless burner controls eliminate this off cycle loss by allowing the combustion air damper to fully close during the off cycle. With traditional linkage burner controls, it is not possible to fully close the combustion air damper during the off cycle; the combustion air damper remains partially open at the low fire position.

The effect of linkageless controls on combustion efficiency was evaluated by comparing the post-retrofit linkageless system against a sample set of well-tuned linkage burners. Combustion efficiency was observed to be slightly higher, with an increase of 1.1% - 1.4% over the entire range of firing rates for linkageless burners versus linkage burners.

The following is a summary of recommendations concluded from the study:

- In most cases, retrofitting a burner with linkageless controls before end of useful life (EUL) has an extended payback of 7 – 9 years. However, there is a lower cost retrofit package coming to market that may reduce the payback to 3 – 5 years (*Note: the 'lower cost' retrofit package requires further evaluation*). In cases where large steam boilers run year round, such as in buildings with absorption chillers, the economics will be more favorable.
- Adding linkageless controls to a new burner at time of replacement has an incremental construction cost of $5,000 - $10,000. For all boilers above 100 Hp, the incremental payback for adding linkageless controls to a new burner is less than 5 years. SWA recommends linkageless controls on all new multifamily boilers above 100 hp output (4,200 MBH input). Commercial buildings typically have lower operating hours so the payback will reflect this.
- Linkageless burner controls enable the installation of VFDs for the burner motors, and VFDs were observed to result in burner electric savings of 66% - 92%. SWA recommends including VFDs as

part of the linkageless controls system on all new burner motors above 5 Hp. VFDs also allow for soft start, which extends the useful life of the motors.

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Acronyms and Abbreviations

A	Area
AC	alternating current
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BMU	Burner Mate Universal (Preferred MFG)
BTU	British thermal unit
CFM	cubic feet per minute
CO_2e	CO_2 equivalents
DC	direct current
DHW	domestic hot water
eff	efficiency
ELA	effective leakage area
°F	Fahrenheit
ft	feet
ft^2	square feet
ft^3	cubic feet
g	gravitational acceleration, $32 ft/s^2$
HDD	heating degree day
HVAC	heating, ventilation, and air conditioning
in. w.c.	inches of water column as pressure
kWh	kilowatt hours
lb	pounds
MMBTU	million BTU
NG	natural gas flow rate
NYSERDA	New York State Energy Research and Development Authority
OAT	outside air temperature
P_{gauge}	Gauge
Pa	pascals
°R	Rankine
rho (ρ)	density of a substance, in this case air, in lbm/ft^3
rpm	rotations per minute
SA	surface area
s	seconds
SCFH	standard cubic feet per hour of air (volumetric flow rate)
SWA	Steven Winter Associates, Inc.
T	temperature
T_A	temperature of ambient air (boiler room)
T_{OAT}	temperature of outside air (same as OAT)
T_F	temperature of flue
U	U-value
VFD	variable frequency drive

1. Background

Space heating and domestic hot water generation represent two of the biggest energy end uses in New York State. More than 70 percent of all New York City buildings utilize steam for space heating (One City built to Last, 2015). The vast majority of these distribution systems are supplied by high mass steam boiler plants.

The most common air:fuel control for these boilers is a mechanical linkage that connects a single servo motor to both the combustion air damper and the fuel control valve(s). The linkage thus determines the air:fuel ratio as well as the firing rate. Adjusting one part of the linkage's movement affects fuel and air rates elsewhere in the range, making accurate adjustment difficult. Moreover, the linkage's geometry introduces nonlinearities into burner response. Modern linkageless controls use separate servo motors to operate the fuel control valves, combustion air damper, and (in some cases) the flue damper, allowing for finer control.

This document is a technical brief of the research conducted to evaluate linkageless burner retrofits on two buildings with respect to energy savings and carbon reductions as well as qualitative or non energy benefits. Previous studies (ASHRAE-Katrakis, 1993) (ASHRAE-Landry, R.W. et al., 1993) have focused on evaluating the seasonal efficiency of small (<30 HP) boilers with fixed firing rates. There is no existing data or study that focuses on the seasonal efficiency of intermediate-sized high mass steam boiler plants with fully modulating burners. This study addresses this gap in the industry's knowledge.

1.1 Literature Review

Multiple research papers and studies were reviewed to better understand the existing research and data on the seasonal efficiency of high mass steam boiler plants as well as linkageless burner controls.

Many of the existing studies utilize models and theoretical calculations to quantify seasonal efficiency and energy consumption. Some of these studies focus on modeling control strategies, heating loads, and combustion conditions such as excess air to determine the savings of advanced control strategies or linkageless controls. In addition, some studies focused on combustion efficiency (Poncia 2012), excess air (Carpenter 2005), or developing diagnostic tools such as time-to-make steam. These key performance indicators were considered when developing this study's methodology, but seasonal efficiency was ultimately chosen as the metric for the comparison between linkage burner control and linkageless burner control. Evaluating seasonal efficiency allows for a more complete analysis of the energy savings from the linkagless burner controls than combustion efficiency alone would show. This approach also eliminates unrelated changes to the building energy consumption, such as changes to the distribution system or building load.

The majority of relevant studies found were conducted in two Midwest cities, Chicago and Minneapolis. These studies focused on multifamily buildings ranging from 6 to 36 units, the largest of which was one quarter the size of the smallest building studied in this paper. These older studies focused on smaller cast-iron boilers with atmospheric burners, as opposed to the scotch marine fire tube boilers with power burners studied in this paper.

SWA contacted major boiler and burner manufacturers to request any studies and data for seasonal efficiency and off-cycle losses. No hard data was received from the manufacturers. Some case studies were provided, but pre-retrofit conditions such as burner type were not stated. In addition, savings appeared to be based on reduction in energy cost, with no methodological details provided, even for important factors like weather normalization.

The literature review showed that no existing data or study focused on the seasonal efficiency of intermediate-sized high mass steam boiler plants with fully modulating burners. This study addresses this gap in industry knowledge. In addition, this study utilizes real time data collection and intensive measurement to quantify seasonal efficiency, rather than the models and theoretical calculations that existing studies relied upon.

1.2 Mechanical Linkage System

The most common type of air:fuel control for steam boilers is single-point positioning. This utilizes a mechanical linkage to modulate both the combustion air damper and the fuel (natural gas and/or oil) control valve(s). The damper and valves are connected by a mechanical linkage to a jack shaft, which rotates the entire assembly. The jack shaft is typically driven by “Modutrol” motor (also known as a “mod motor”).

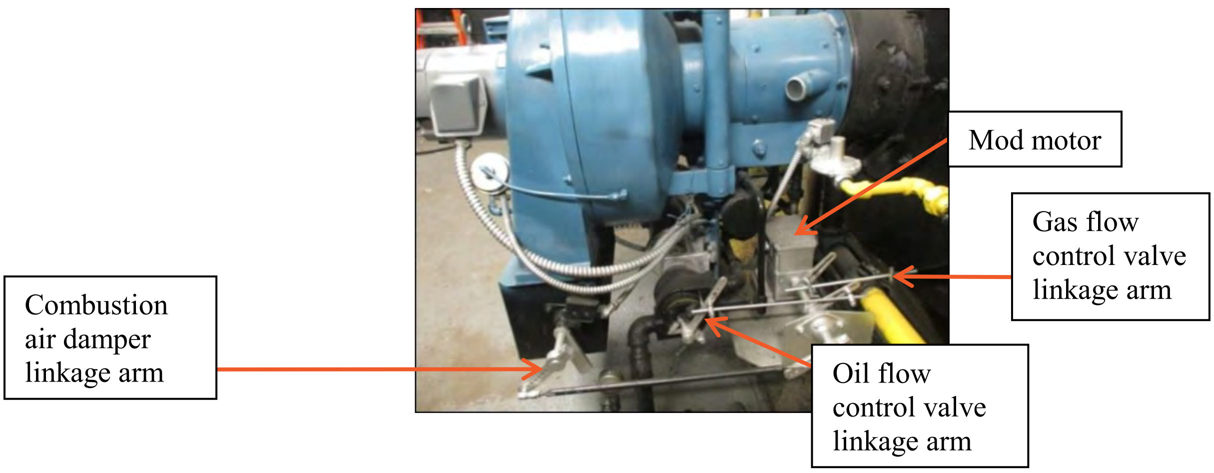


Figure 1: Mechanical Linkage System

The linkage’s operation is nonlinear, because the rods’ motions are tangential to the shafts. As a result, the effects of incremental adjustments vary erratically, making adjustment more difficult. This burner control configuration has remained largely unchanged since the linkage burner control was first patented in the early 1900s.

Several factors make linkages difficult to adjust:

- Optimizing the air:fuel ratio in one portion of the burner’s firing range changes the settings through the rest of the range, and can the throw the burner mostly out of tune.
- Different amounts of oxygen (fresh air) are needed for combusting natural gas versus fuel oil, due to their different chemical compositions. But a linkage can’t change the air damper’s stroke when the fuel is changed, making it impossible to achieve the same firing rate and efficiency on both fuels in a dual-fuel burner.
- Over time, a linkage can drift out of calibration as parts wear or slip.

- Mechanical linkages are not compatible with blower fan variable frequency drives (VFD). Not being able to slow down the fan makes it harder to tune large boilers at low fire. It also rules out the electrical savings of a VFD.

Another way mechanics cope with linkages is by restricting their firing range. A burner that should be able to operate as low as 20% capacity (called 5:1 turndown) will often be set to go no lower than 30% - 50%. The inability to achieve low firing rates is due to the minimum combustion air damper position, which is based on the burner's light off configuration. This is the minimum configuration needed to ignite the first flame. A lower firing rate is technically achievable, but the simple linkage burner controls do not separate the light off position from the control sequence. Therefore, the light off position is inherently the low fire position in most mechanical linkage burner controls. Matching the firing rate to the load is important to optimizing the distribution system performance and balancing. Heating and DHW loads are dynamic, so a boiler must be able to modulate through its full firing range, while still combusting efficiently. These requirements are difficult to meet with a linkage.

1.2.1 Draft Control

Boiler draft is controlled either by a barometric damper or by a motorized draft regulator. These should be set to maintain a predetermined smokebox or furnace pressure, as specified by the boiler manufacturer, to ensure proper flame size and shape.

A barometric damper is set by adding counterweights. A motorized draft regulator uses a motor to position the damper, its movements governed by an electronic control that monitors draft via a sensor on the boiler.

In practice, motorized draft regulators are usually left on the fully open position, whether overridden or abandoned and barometric dampers are often stuck open or unweighted.

Some linkageless control systems are capable of integrating boiler draft control. In other words, draft is controlled by the burner panel as opposed to a separate standalone control. This study includes a high level evaluation of the draft / boiler flue damper position on boiler seasonal efficiency.

Figure 2: Barometric Damper

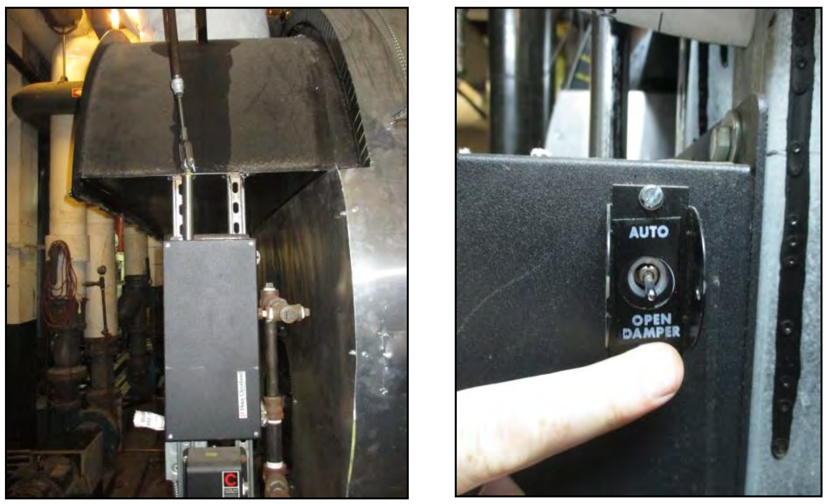


Figure 3: Draft Regulator (left), Set to fixed open position (right)

1.3 Linkageless System

Linkageless controls eliminate mechanical connections between fuel control valve(s) and combustion air damper. Instead, the fuel control valve(s), combustion air damper, and sometimes even the draft damper are each controlled by dedicated servo motors. Each servo is wired to the burner control panel. A typical control sequence for linkageless controls involves tuning the control valve(s) and combustion air damper once via software. O2 trim is available as an option for linkageless burner controls and is discussed in more detail in subsequent sections.

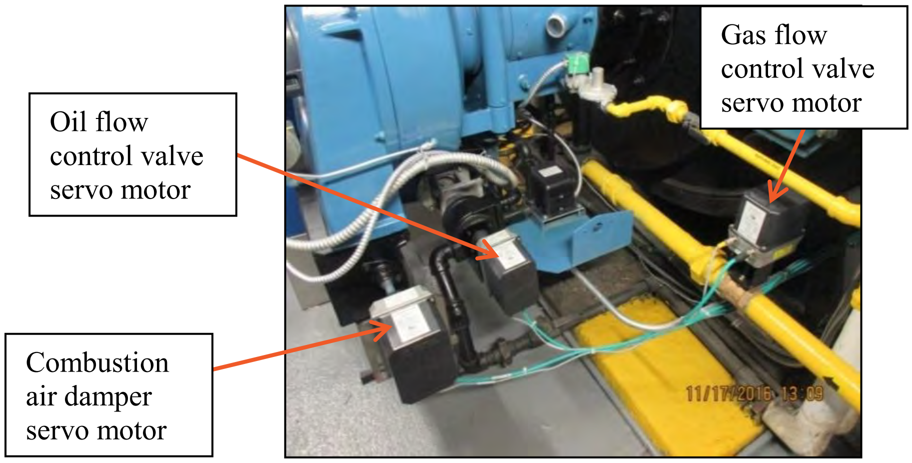


Figure 4: Linkageless System

As previously mentioned, some linkageless control systems include integrated boiler draft control. In these versions, a dedicated servo motor is connected to the boiler draft damper and wired back to the burner control panel. When the boiler is off, the flue damper is closed fully or, if applicable, to a minimum code regulated position. The effectiveness of damper control on seasonal efficiency will be discussed in subsequent sections.

Figure 5: Draft Control Module (left), Flue Damper Servo (right)

Linkageless controls can be much easier to commission and tune (typically done with a computer interface) than standard mechanical linkage systems once the technician is properly trained. Training programs are currently available through manufacturers for linkageless system commissioning, operation, programming and troubleshooting, as well as many other categories. Anecdotal feedback from boiler contractors is that the newer generation of boiler technicians are more adept to the technology required to tune and service linkageless controls.

Linkageless systems display the status of the control conditions on a digital monitor. Most systems can also monitor and communicate with building automation systems, which can allow users to log data and remotely monitor operating conditions. For dual-fuel systems, the burner can be set up with independent air-fuel curves for each fuel type, eliminating the need to readjust or retune when switching fuels.

Furthermore, linkage burner controls only shut the combustion air damper to the low fire position. In contrast, linkageless burner controls can fully close the combustion air damper eliminating the leakage area through the combustion air damper.

1.3.1 O2 Trim and/or Variable Frequency Drive (VFD)

Other linkageless control capabilities include O2 trim and VFDs. O2 trim was not installed or evaluated as part of this study. O2 trim enables burners to automatically adjust the combustion air damper to maintain the optimal air:fuel ratio across various firing rates and ambient conditions (which can vary the density of the combustion air). The additional control reduces the safety protocol to set excess air slightly higher than desired and essentially allows combustion to approach stoichiometric conditions.

VFDs, paired with compatible motors and sophisticated burner controls, enable the blower motor to operate at variable speeds. When the VFD reduces the frequency, it inherently reduces the electrical energy flowing to the motor. Electrical energy consumption reductions are shown in the results section of this report.

1.4 Seasonal Efficiency

Seasonal efficiency, as used in this report, is represented as a percentage calculated by dividing the useful heat output of a heating plant over the fuel input in to the heating plant. Useful heat output is the fuel input minus combustion losses, off-cycle losses, purge losses, and jacket losses.

The seasonal efficiency in this study was determined in part by using the ‘Flue Loss’ method, in which the latent and sensible heat losses are determined from the flue products leaving the boilers. This method has been used by a number of previous studies (Katrakis 93) and is deemed to be a well-accepted method to measure seasonal efficiency. The methodology used in these previous studies assumes that both the energy transferred to the distribution system and boiler jacket losses are useful heat. For the purposes of this study, the methodology has been altered to assume that the jacket losses are not useful heat. It can be argued that the boiler jacket losses are lost to the unconditioned basement space as well as the exterior of the building via boiler room vents and the chimney. Regardless, the boiler jacket losses do not vary significantly for pre-and post-retrofit period, and therefore they have a negligible effect on the retrofit energy savings.

The following is a summary of the equations used to calculate seasonal efficiency. Further detail is in subsequent sections.

$$Seasonal\ Efficiency = \frac{(Useful\ Heat\ Output)}{Input}$$

$$Input = Fuel\ Consumption$$

$$Useful\ Heat\ Output = Input - Total\ Heat\ Losses$$

$$Total\ Heat\ Losses = Combustion\ Losses + Off\ Cycle\ Losses + Purge\ Losses + \text{Jacket Losses}$$

$$Combustion\ Losses = 1 - Combustion\ Efficiency$$

2. Testing Methodology to Quantify Seasonal Efficiency

2.1 Participating Properties

Linkageless controls were retrofitted onto existing burners at two demonstration sites in New York City. The first demonstration site is 2980 W 28th St, Brooklyn, NY, also known as Seapark East. This is a 333-unit, 24-floor, ~454,000 square foot affordable residential building constructed in 1970. The size of this building and its boiler plant, coupled with the presence of a steam to hot water distribution system, make this building a definitive example of a post-war / modern-style NYC building.

Heating is generated by two natural gas-fired Best Boilers 5D-200 200 HP fire-tube, low pressure steam boilers with dual-fuel fully modulating Industrial Combustion (model DLG-84P) burners that were installed in 2013. The boilers are controlled by a Heat Timer HWR Platinum and a Heat Timer Multi-Mod. Steam passes through a steam to hot water heat exchanger for heating hot water distribution. During the heating season, the steam boilers generate domestic hot water (DHW) via tankless coils; however, part of the DHW load is provided by a cogeneration plant which runs year round. During the non-heating season, the steam boilers are shut down and DHW is generated by separate water heaters and the cogeneration plant. The building is on a firm gas rate but the burners were setup for dual fuel with #2 oil as a backup fuel.

The burners were retrofitted in mid-October 2016 with Preferred Utilities BurnerMate Universal (BMU) linkageless controls, burner panels, integrated draft controls and VFDs for the blower fan motors. Construction was completed over a 3-4 week period. Optimization and commissioning was completed in January 2017.

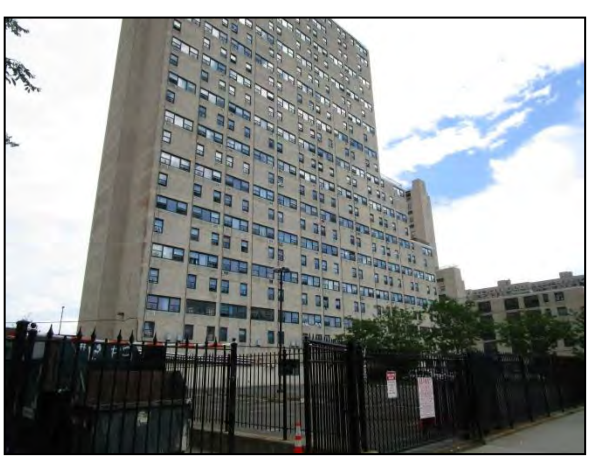


Figure 6: Building and boilers of Seapark East

The second demonstration site is 295 Central Park West, New York, NY. This is a 136-unit, 19-floor, ~145,000 square foot market rate residential building constructed in 1941. This building is representative of the significant post-war boom in multifamily housing, and is early enough in the period that it also shares many of the same characteristics of the thousands of pre-war buildings which dot the landscape in both NYC and NYS.

Heating and DHW is generated by two Federal FST-150 150 HP, low pressure steam boilers with fully modulating dual-fuel Industrial Combustion (model DEG-63P) burners that were installed in 2001. The boilers are controlled by a US Energy Group Energy Management System and a Heat Timer Multi-Mod. The building has a 2-pipe steam distribution system. The building is on a firm gas rate but burners are setup for dual fuel with #2 oil as a backup fuel.

The burners were retrofitted in September 2016 with Preferred Utilities BMU linkageless controls, burner panels and integrated draft controls. Construction was completed over a 3-4 week period. Optimization and commissioning was completed in early November 2016.

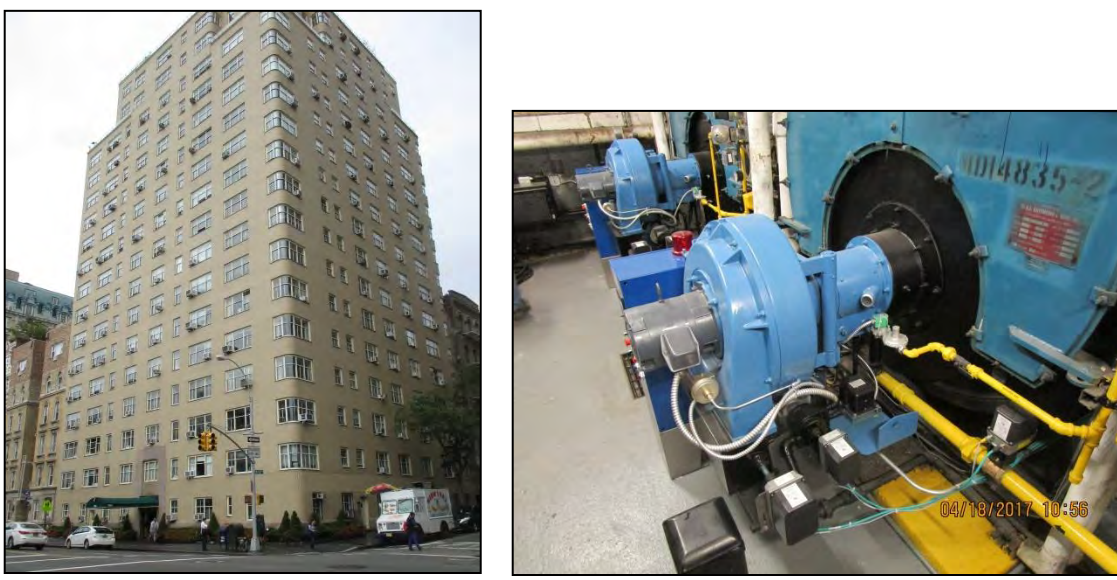


Figure 7: Building and boilers of 295 CPW

2.1.1 Pre- and Post-Retrofit Building Parameters and Conditions

Building parameter and conditions were largely unchanged for the pre- and post-retrofit periods. Aside from the linkageless burner retrofits, no upgrades or improvements were made to the building envelope or building systems. In particular, set points and settings for the heating system controls were consistent throughout the pre- and post-retrofit M&V data periods. Building occupancy levels were also consistent throughout the pre- and post-retrofit periods.

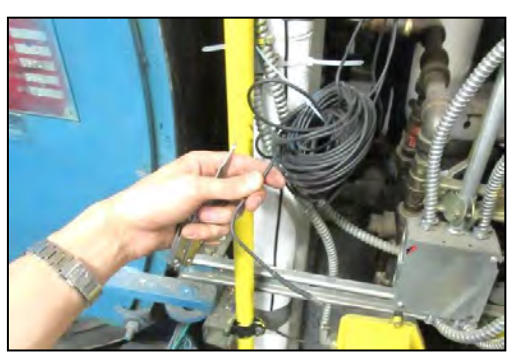
2.2 Data Collection and Testing Equipment

SWA monitored the following data points in order to quantify the boiler seasonal efficiency and measure energy savings for the linkageless control retrofits. Monitoring equipment was installed for the 2015/2016 heating season to establish a baseline for the pre-retrofit period and was left in place over the 2016/2017 heating season for the post- retrofit period. The following is a summary of the data collection and monitoring equipment that was used at the demonstration sites.

- **Fuel consumption.** Fuel consumption was measured by daily readings taken from the utility gas meter by the building staff. HHV values were used for fuel consumption.

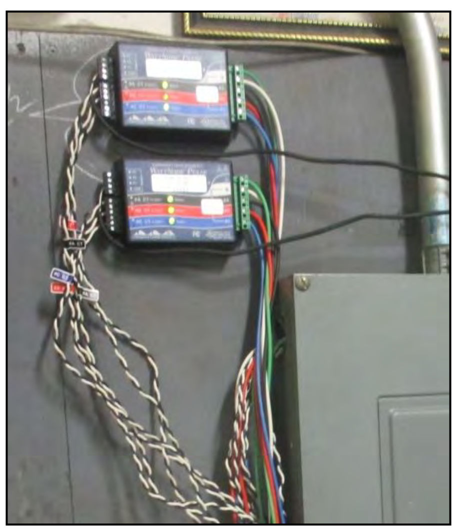
- **Outdoor temperature.** The outdoor temperature provided information on the weather conditions and was used to normalize the data between different time periods. Temperature was measured by an Onset 12-bit smart sensor.

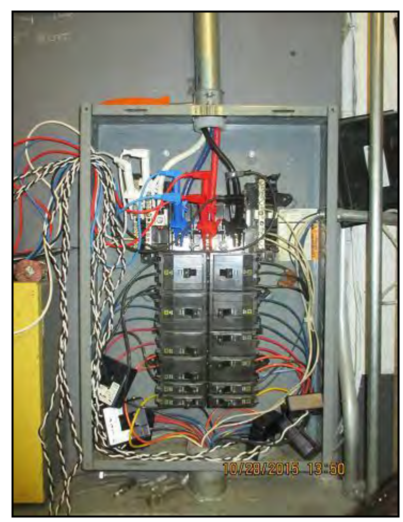
- **Boiler room temperature.** The boiler room temperature was measured and used to monitor the combustion air temperature supplied to the burners. Boiler room temperature was measured by an Onset 12-bit smart sensor.



- **Steam supply pressure.** Steam supply pressure was measured and provided information on the operation and stability of the system during the pre- and post- retrofit phases. Steam supply pressure was measured at the steam header with an Ashcroft gauge pressure sensor.

- **Burner fan energy consumption.** The energy consumed by each boiler's burner fan motor was measured with a WattNode kWh transducer sensor. The burner fan's energy consumption also provided boiler run time and number of pre- and post-purge cycles.

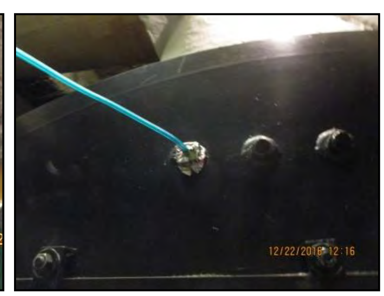




- **Remote Monitoring Station.** Measurements from all of the above sensors were logged by a HOBO RX3000 remote monitoring station and were accessible over the internet.

- **Boiler Flue Gas, Flue Temperature and Flue Pressure Monitoring.** The combustion products from each boiler were measured with Testo 350 combustion analyzers. The combustion analyzers collected O_2 %, CO, flue temperature, and air flow (via pressure sensor) measurements in real time. The measurements were collected during both on- and off-cycle, and were used to quantify off-cycle and purge heat loss up the boiler flue as well as combustion efficiency. The data was collected and logged on a laptop with Testo software and downloaded weekly via remote access. The Testo 350 combustion analyzers were calibrated according to manufacturer's guidelines bi-weekly to ensure accuracy using EPA protocol calibration gas.


- **Boiler Flue Pressure.** While the boiler flue / smokebox pressure was measured by the Testo 350 combustion analyzer during pre- retrofit conditions, Veris PXPLX01S pressure transducers were calibrated and used for post- retrofit conditions. The Veris pressure transducers were installed because the Testo pressure sensors were downstream of the retrofitted flue damper and did not provide a useful reading post-retrofit.

- **Off-cycle CFM.** Off-cycle air flow rates in cubic feet per minute (CFM) through the boiler were measured using a one-time direct measurement in which a formula was created to relate boiler smokebox / flue pressure to a CFM value. Further details are in subsequent sections.

2.3 Total Heat Losses

As described in earlier sections, the seasonal efficiency in this study was determined in part by using the 'Flue Loss' method, in which the latent and sensible heat losses are determined from the flue products leaving the boilers. For this study, the methodology used in previous studies has been altered to assume that the jacket losses are not useful heat. The losses, or non-useful heat, summarized in the following sub sections include combustion losses, off-cycle losses, purge losses, and jacket losses.

2.3.1 Combustion Loss

Combustion efficiency is the ratio of heat transferred to the water/steam to the total fuel energy supplied (Carpenter, 2005). Combustion loss, also known as stack loss, is a measure of the heat carried away by dry flue gases and the moisture loss. The flue temperature is the temperature of the combustion gases (dry and water vapor) leaving the boiler and reflects the energy that did not transfer from the fuel to the steam.. The combustion loss is calculated using the following equation.

$$Combustion\ Losses\ (\%) = (1 - Combustion\ Efficiency) * 100$$

$$Combustion\ Losses\ (btu) = \frac{Fuel\ Input * (1 - Combustion\ Efficiency)}{Fuel\ Input}$$

$$Testo\ Combustion\ Efficiency\ (\%) = 100 - [(T_F - T_A) * \left[\frac{A2}{(21 - O_2) + B}\right] - XK]$$

The Testo Combustion Efficiency is calculated by the internal algorithm of the Testo 350 equipment, using flue temperature (T_F), ambient temperature (T_A), O_2 content, and a series of fuel input specific coefficients (A2, B, XK). See the appendix for definitions of each component of the combustion efficiency equation, as defined in the "Heating Measurement Technology Practical Handbook" (Testo-2004).

2.3.2 Off-cycle Loss

The off-cycle loss is the heat loss carried through the boiler and up the flue when the burner is off. The pressure and temperature difference between the air inside the boiler and the outdoor air, is the mechanism that pulls cooler outside air into the boiler room, through the boiler (cooling the boiler), and up the flue. This phenomenon is also known as stack effect. In order to quantify the off-cycle loss, pressure inside the boiler flue / smokebox (before flue damper) was logged (with respect to the boiler room pressure) throughout the monitoring period. A test was conducted in order to create a mathematical relationship between pressure in the smoke box and air flow through the boiler. The test consisted of constructing a plenum that was connected and sealed to the burner's combustion air inlet. A Minneapolis Duct Blaster fan with speed control was connected to the plenum (see below), along with an Energy Conservatory DG-700 Digital Pressure and Flow Gauge to measure CFM of air supplied to the plenum. A static pressure probe was installed in the smokebox, and measured the pressure with respect to the plenum. (see graphic below). The plenum was pressurized by the duct blaster fan, resulting in a pressure differential between the plenum (higher pressure) and the smokebox (lower pressure). The resulting pressure differential and air flow was correlated to the pressure differential between the boiler flue / smoke box and boiler room (atmosphere) caused by the natural stack effect during off-cycles. A range of the differential pressures were measured to quantify the pressure and flow observed during the pre- and post- retrofit periods.

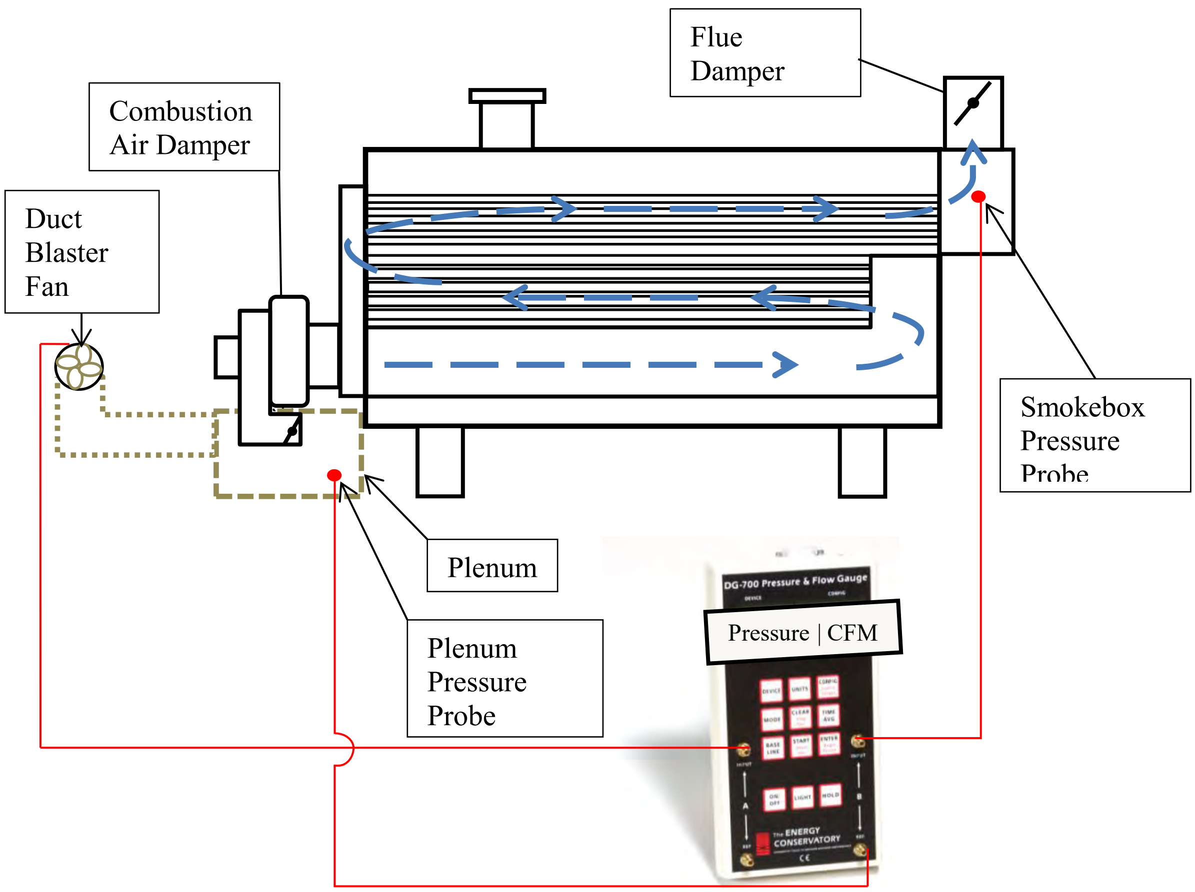


Figure 8: Measurement Setup

Figure 9: Off-cycle CFM testing, Duct Blaster set-up

The combustion air damper position and draft control damper position were manipulated to simulate an assortment of conditions and air leakage areas. The table below summarizes the damper positions/conditions tested.

Testing Condition	Flue Damper Position	Combustion Air Damper Position
1 (Post- Retrofit Condition)	**Shut**	**Shut**
2	100% Open	Shut
3	100% Open	100% Open
4	100% Open	75% Open
5	100% Open	50% Open
6	100% Open	25% Open
7 (Pre-Retrofit Condition)	**100% Open**	**10% Open**
8	Shut	100% Open
9	Shut	75% Open
10	Shut	50% Open
11	Shut	25% Open
12	Shut	10% Open

Table 1: Draft Air Flow Testing Conditions

The data was recorded and plotted on a graph to show the relationship between measured pressure in the smokebox and CFM. A power line of best fit was applied to the modeled pre- and post- retrofit conditions. The resulting equation was used to calculate off-cycle air flow CFM for each pressure data point collected. An example of the graph constructed is found below. A graph with all testing conditions listed in Table 1 can be found in the appendix.

Figure 10 below shows that the position of the combustion air damper is the primary driver of air flow through the boiler. The position of the flue damper had little or no effect on the air flow. The data also shows that the air flow through the boiler during off-cycle is much lower than anticipated. The boiler smokebox pressure measured during pre- and post- periods never exceeded 1.5 inches of water column (in. w.c.) which means that the off-cycle air flow was typically below 150 CFM. These low off-cycle air flow figures result in lower than expected heat losses during the off-cycle periods.

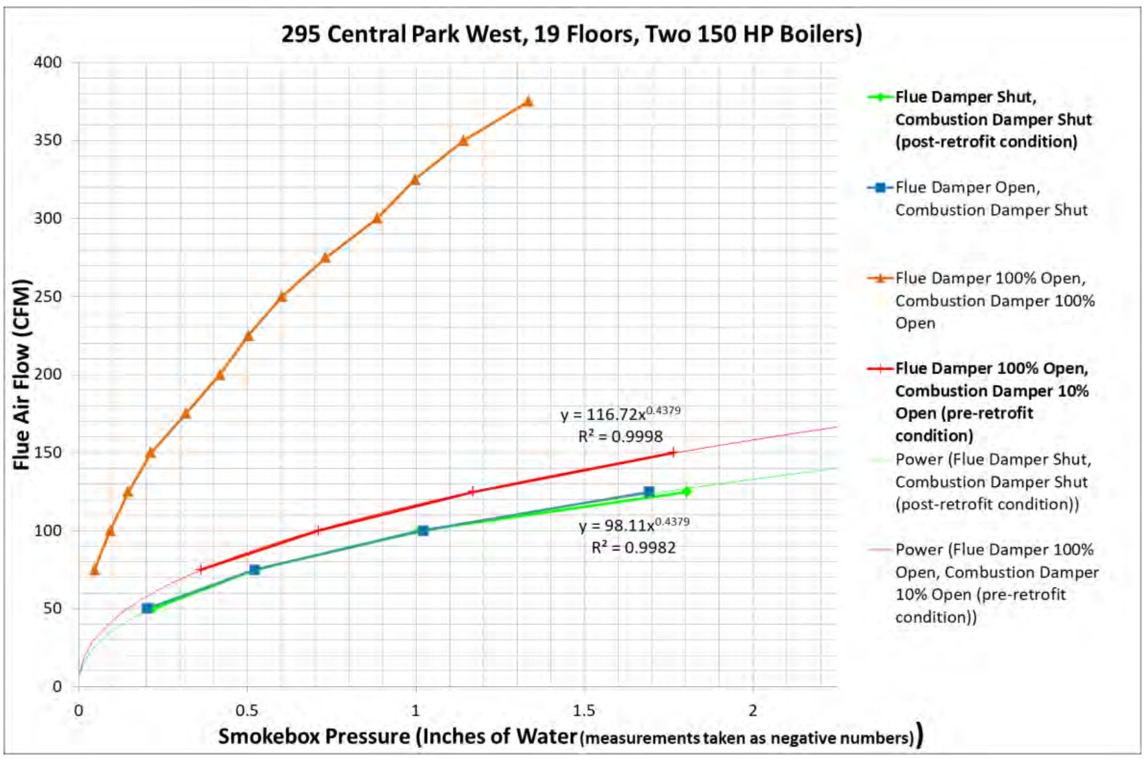


Figure 10: Smokebox Pressure vs. Flue Air Flow Mathematical Relationship and Chart

Once the mathematical relationship between CFM and pressure was established, CFM was deduced from the smokebox pressure data collected. Off-cycle heat loss (in btus) was then quantified by using the following equation:

$$Off\ Cycle\ Loss\ (btu) = \ CFM * (T_F - T_A) * 0.24 * \rho$$

- CFM: Cubic feet per minute, calculated from pressure data
- T_F: Flue temperature (°F)
- T_A: Ambient Air Temperature (°F)
- .24: Specific heat value (btu/lb/°F)
- ρ: Density of air (lb/cubic feet)

$$\rho = 2.7 * \frac{P_{gauge} + 14.7}{T_{oat} + 459.7}$$

- 2.7: conversion factor for ideal gas law (lb/ft^3 $°R$)
- P_{gauge}: Assumed to be zero
- 14.7: Atmospheric pressure at sea level (psi)
- T_{oat}: Temperature (°F)
- 459.7: To convert (°F) to Rankine

Figure 11 shows the cross sectional area and effective leakage area (ELA) of the combustion air damper and the flue damper during post-retrofit conditions for a sample boiler at one of demonstration sites. The blue squares represent the combustion air damper ELA and combustion air inlet cross sectional area. The red squares represent the flue damper ELA and flue cross sectional area. For illustrative purposes, the areas of the four squares are scaled to highlight the differences in area and ELA. The combustion air damper ELA is minute (barely visible below) when compared to the flue damper ELA. This data reinforces the findings of the testing in figure 10.

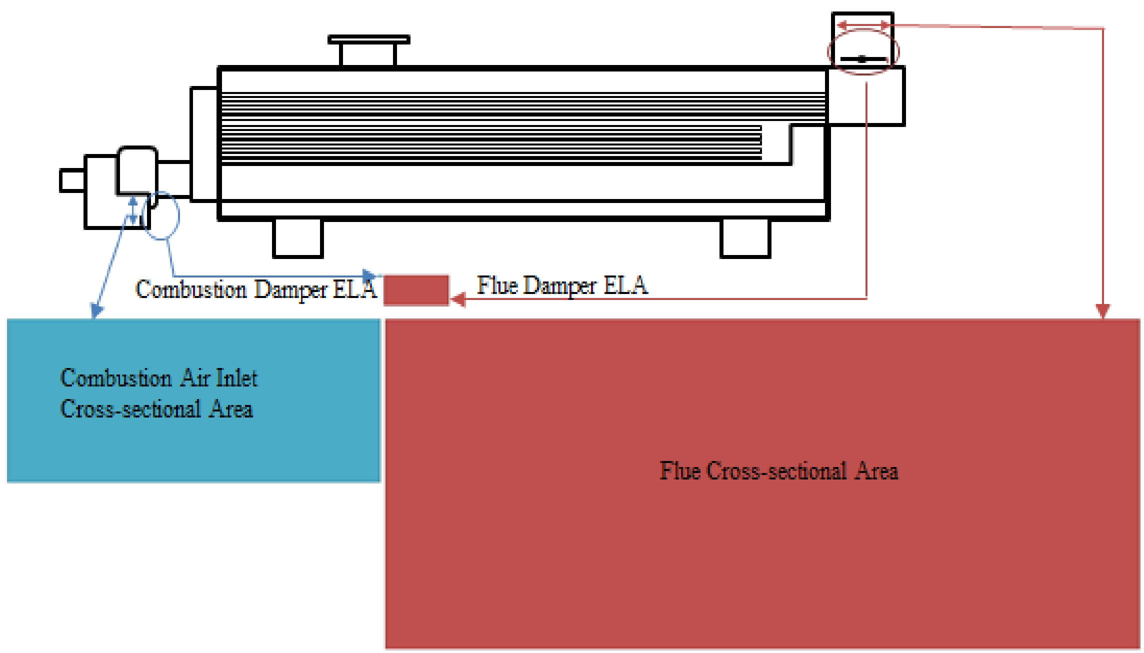


Figure 11: Combustion Air Damper ELA vs. Flue Damper ELA (left), Combustion Air Inlet Cross Sectional Area vs. Flue Cross

Figure 12: Combustion Air Inlet and ELA Cracks (left), Flue Damper ELA Crack (right)

The following graph illustrates the extremes of the combustion air damper position and its effect on off-cycle loss. The graph was modeled using the logged smokebox pressure and the aforementioned off-cycle CFM testing. The graph shows that off cycle losses are unlikely to exceed 2% even for burners where the combustion air dampers are mostly open during the off cycle.

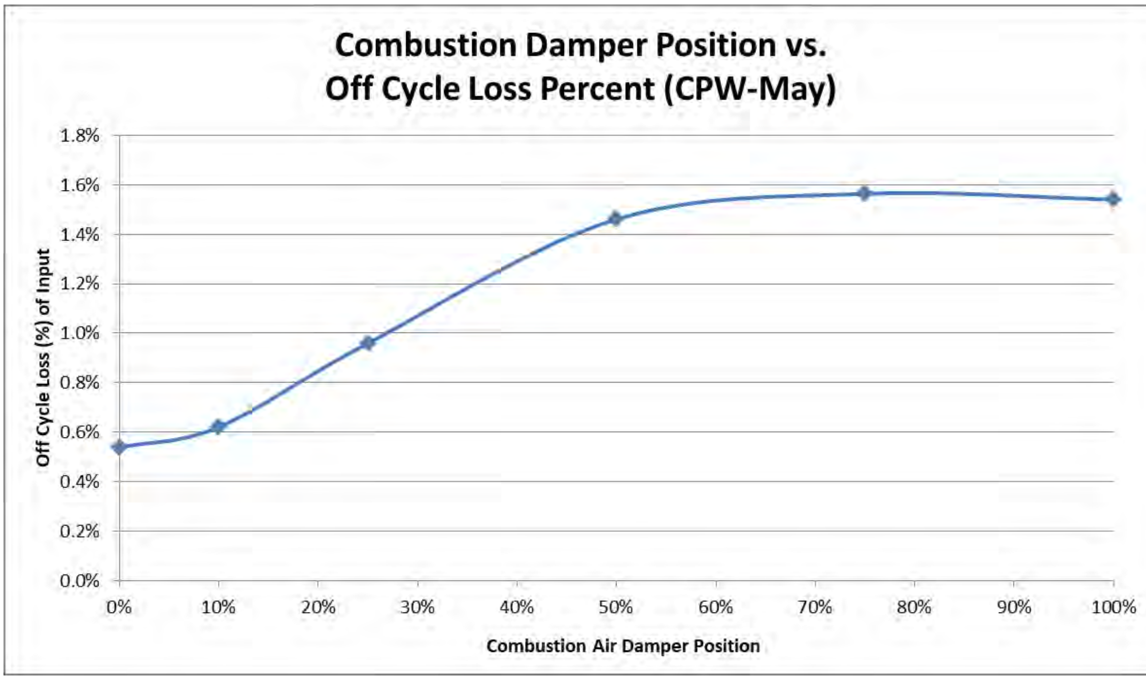


Figure 13: Combustion Air Damper Position Effect on Off-Cycle Loss
*The flue damper was fully open during the measurements

2.3.3 Purge Loss

The purge loss occurs when air is pushed through the boiler and up the flue by the burner fan motor during a boiler's pre- and post- purge cycles. The pre- and post- purges are a safety feature designed to carry excess unburnt fuel away from the boiler to prevent the accumulation of combustible gases.

The quantity of air purged per cycle, for pre- and post- retrofit scenarios, was calculated by using the high fire natural gas flow rate (obtained by clocking the gas meter). Excess air and O_2 content in the flue gas were measured using the combustion analyzer during gas flow rate testing. Each volume of natural gas takes approximately 10 times the volume of air to completely burn, and the excess air indicates the additional air that is supplied to the burner. Typically the fan motor will run at high fire for 60 seconds during the pre-purge cycle and 15 seconds during post-purge. Therefore, the quantity of air moving through the boiler during a purge cycle is ten times the natural gas flow rate multiplied by one plus the percent excess air (see equation below). A more detailed value than the estimated factor of 10 was not used, as it was not feasible to determine the exact natural gas composition.

$$SCFH = \left(1 + \frac{EA\ (\%)}{100}\right) * 10 * NG\ (SCFH)$$

- $SCFH$: Standard Cubic Feet per Hour of Air
- EA: Excess Air in percentage (measured at each site)
- 10: Approximate cubic feet of air needed to combust 1 cubic foot of natural gas
- NG: Natural Gas Volumetric Flow Rate in SCFH

The purge times differ slightly for each burner, but it is typical the blower fan runs at high fire for approximately 60 seconds during pre-purge and 15 seconds during post-purge. The table below shows the pre- and post- purge CFMs at both demonstration sites. The difference in pre- and post- retrofit CFMs are due to the tuning of the burners after the retrofit work.

Demonstration Site - Seapark East	Boiler 1 Purge CFM	Boiler 2 Purge CFM
Pre-Retrofit	2125	1932
Post-Retrofit	1420	1417

Demonstration Site - Central Park West	Boiler 1 Purge CFM	Boiler 2 Purge CFM
Pre-Retrofit	1099	1179
Post-Retrofit	1107	1193

Table 2: Purge Air Flow (CFM) Values

2.3.4 Jacket Loss

Jacket loss refers to the radiative and convective heat transfer from the outer surface of the boiler (Modera 1988). Heat is transferred from the water / steam in the boiler to the exterior of the shell. Heat may transfer throughout the inside of the building or out of the building depending on the basement's air tightness and connection to the occupied sections of the building. For the purposes of this study, jacket losses are considered to be lost to the exterior of the building. Detailed M&V to quantify jacket loss would require a temperature sensor array for the boiler, this was not performed because of project costs constraints. However, SWA calculated an estimated range for the jacket losses based on boiler geometry, materials, and system run times.

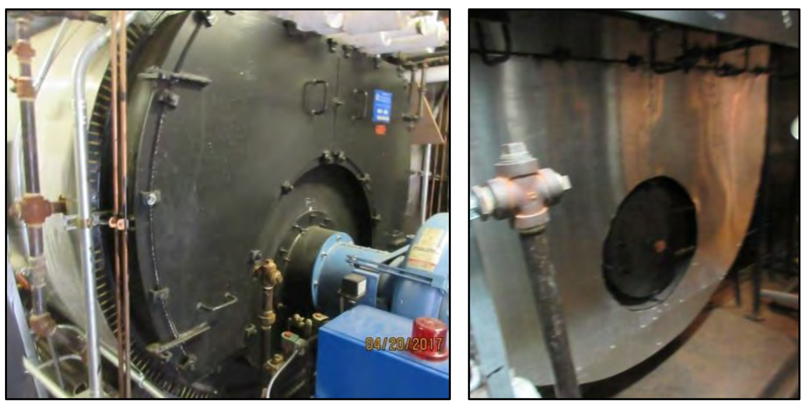


Figure 14: Uninsulated front and insulated sides (left), insulated rear (right)

3. Measurement and Verification Data Analysis and Results

3.1 Baseline / Pre-Retrofit Seasonal Efficiency and Losses

Figure 13 shows a breakdown of the boiler losses and provides a baseline seasonal efficiency for intermediate-sized, high mass steam boilers. These figures are based on the M&V data collected at both demonstration sites during the pre-retrofit stage of the project.

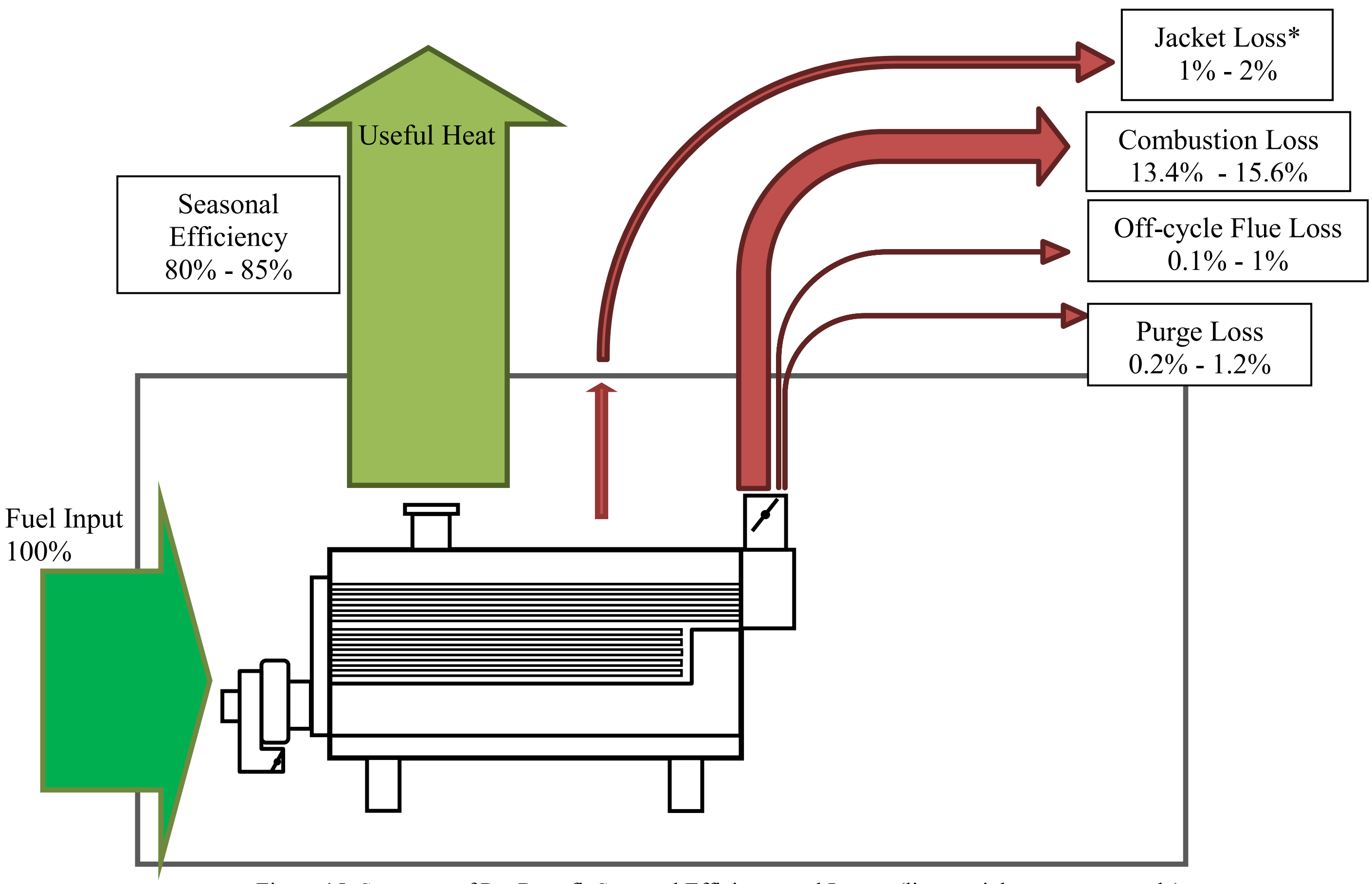


Figure 15: Summary of Pre Retrofit Seasonal Efficiency and Losses (lines weights are not to scale)

*Jacket loss was estimated based on high level calculations

3.2 Pre- and Post-Retrofit Seasonal Efficiency and Losses

The following tables summarize the pre- and post- combustion and seasonal efficiencies, as well as breakdown of the losses for each of the demonstration sites.

Central Park West		
	Average Combustion Efficiency	Average Seasonal Efficiency
Pre-retrofit	85.2% (Range of 84.3% - 86.2%)	83.1% (Range of 82.0% - 84.1%)
Post-retrofit	84.4% (Range of 84.2% - 84.5%)	83.6% (Range of 83.3 % - 83.9%)

Table 3: Pre- and Post-Retrofit Efficiencies for Central Park West

Seapark East		
	Average Combustion Efficiency	Average Seasonal Efficiency
Pre-retrofit	85.9% (Range of 84.5%-87.2%)	84.2% (Range of 82.8%-85.6%)
Post-retrofit	84.7% (Range of 84.3% - 85.1%)	84.4% (Range of 83.6% - 85.2%)

Table 4: Pre- and Post-Retrofit Efficiencies for Seapark East

During the pre-retrofit period, combustion efficiency was 84.3% - 87.2%. These high efficiency figures seemed to indicate that the burners were well tuned and maintained. However, the data showed that some of the burners were operating with high CO figures which represented an unsafe condition. In addition, the stack temperatures on low fire were observed to be below 250°F which can cause flue gases to condense leading to corrosion of the boiler tubes and flue. For the post- retrofit period, the low stack temperature and high CO conditions were corrected to ensure safe and optimal combustion. This meant that there was no room for improvement in terms of combustion efficiency at the demonstration sites.

	Sample Sites (15) – Linkage Burners (Well Tuned)*	Central Park West – Post Retrofit Linkageless Combustion Efficiency**	Seapark East - – Post Retrofit Linkageless Combustion Efficiency
High Fire Average	82.4%	83.9%	81.4%*
Medium Fire Average	83.2%	85.3%	82.9%*
Low Fire Average	84.8%	85.6%	85.4%*
Overall Average (across entire firing range)	**83.3%**	**84.4%**	**84.7%**

Table 5: Linkage Burner Combustion Efficiency versus Linkageless Burner Combustion Efficiency

*Data from recent SWA boiler retro-commissioning **Data measured during setup / commissioning

Due to the particulars of the pre-retrofit conditions of the demonstration sites, the effect of linkageless controls on combustion efficiency was evaluated by comparing the post-retrofit linkageless system against a sample set of well-tuned linkage burners. The sample site data shown in table 5 was collected from fifteen buildings with similar sized boilers on a firm gas rate. The combustion data was screened by eliminating burners with high carbon monoxide figures and low stack temperatures to ensure only well tuned burners were included in the data set. Combustion efficiency was observed to be slightly higher for linkageless burners versus this sample of linkage burners. Therefore, this study concludes that an increase of 1.1% - 1.4% can be expected for the linkageless system's combustion efficiency over the range of the burners' firing rate. The New York City Department of Environmental Protection (NYC DEP) requires burners to maintain a combustion efficiency of at least 80% for natural gas-fired boilers and 83% for oil-fired boilers. This is verified through triennial inspections, and can be used as a proxy for the majority of New York City's boiler combustion efficiencies.

Central Park West			
	Combustion Loss	Purge Loss	Off-cycle Loss
Pre-retrofit	13.5%-16.1%	0.7%-1.4%	0.3%-1.3%
Post-retrofit	15.5%-15.7%	0.5%-0.9%	0% (Negligible)

Table 6: Pre- and Post-Retrofit Losses for Central Park West

Seapark East			
	Combustion Loss	Purge Loss	Off-cycle Loss
Pre-retrofit	13.6%-14.8%	0.1%-0.3%	0.1%-0.2%
Post-retrofit	14.3%-17.1%	0.1%-0.1%	0% (Negligible)

Table 7: Pre- and Post-Retrofit Losses for Seapark East

The relatively large difference in off-cycle loss between the two sites is attributable to the building's distribution system. Seapark's steam-to-hot-water heat exchanger requires the boilers to run for longer lengths of time, thus reducing the total off-cycle time and loss.

For the post- retrofit period, purge losses were reduced by a fractional percentage which can be attributed to a decrease in cycling of the boilers. The graphs shown in section 3.6 (Number of Cycles per Day vs. Outdoor Air Temperature) indicate that boiler cycles were for the most part reduced during the post-retrofit period. During the post- retrofit period, the boiler smokebox pressure was a slightly positive or zero value (with respect to boiler room pressure) as opposed to a negative pressure reading during the pre-retrofit period. Therefore off-cycle losses were deemed to be eliminated. The reduction in purge and off-cycle heat losses resulted in a minimal increase in seasonal efficiency for the post- retrofit period. However, combustion efficiency savings were not possible due to sub optimal pre retrofit conditions. Some burners were operating with high CO figures and stack temperatures below 250°F on low fire.

Savings for the sites' burner retrofits were offset or eliminated by burners that were setup for unsafe and sub optimal combustion conditions.

3.3 Variable Frequency Drive Savings

The burner fan motors at the Seapark East site were retrofitted with variable frequency drives (VFD). The burner fan motors are 7.5 HP; one is manufactured by Baldor Reliance and the other by Marathon Electric.

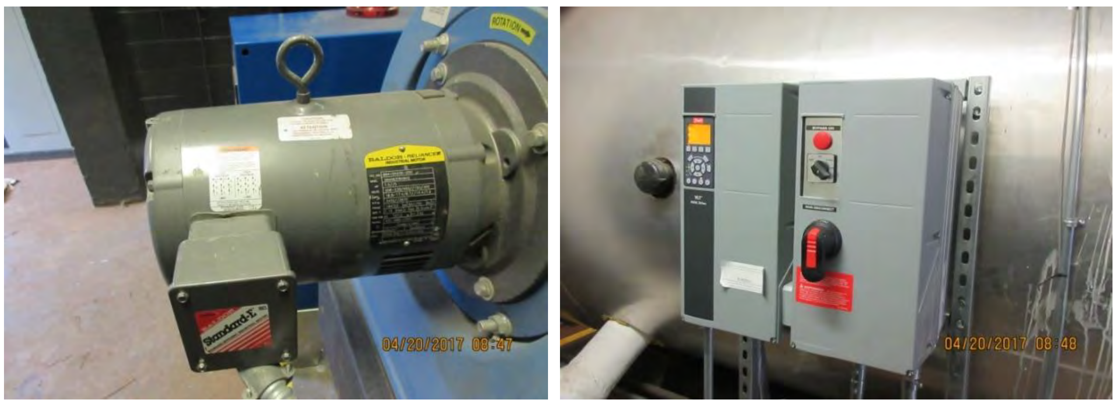


Figure 16: Burner 1 Motor (left), Variable Frequency Drive Control Panel (right)

The kWh consumption data was weather normalized by calculating monthly kWh/HDD consumption for the pre- and post-retrofit conditions. The results show a 66% - 92% reduction in electrical energy consumption across both burners (shown in the table below) with an average reduction of 78%. Some time periods were excluded due to lack of reliable data and the construction timeline.

Condition	Month & Year	Burner 1 (kWh/HDD)	Burner 2 (kWh/HDD)	Average (kWh/HDD)
Pre-Retrofit	December 2015	4.24	-	2.84
	January 2016	1.26	0.54	
	March 2016	4.14	1.21	
	April 2016	2.63	3.16	
	May 2016	2.89	5.69	
Post-Retrofit	February 2017	0.85	0.18	0.62
	March 2017	0.85	0.15	
	April 2017	1.37	0.35	

Reduction: 66% - 92%

Table 8: Summary of Burner Fan Motor Weather-Normalized Electrical Consumption

3.4 Retrofit Economics and Recommendations

Seasonal efficiency was used to quantify energy and carbon emissions savings for the two demonstration sites. Table 3 shows a summary of the demonstration site construction costs, energy costs savings, and payback. It must be noted that the construction costs are significantly higher than would be expected for a typical retrofit project. These higher costs are in part due to state of the art of equipment that was donated by the manufacturer Preferred Utilities. Contractor labor costs are also higher due to the scrutiny and more involved construction and commissioning oversight provided by SWA and Preferred Utilities.

	Central Park West (2 x 150 Hp Boilers)	Seapark East (2 x 200 Hp Boilers)
Materials - Preferred Utilities	$64,494	$64,494
Materials – Danfoss	-	$1,702
Installation Labor – Contractor	$34,440	$16,331
Total Construction Cost	**$98,934**	**$82,527**
Electricity Savings	-	$3,100
Heating Fuel Savings	$578*	$416*
Total Energy Cost Savings	**$578**	**$3,516**
Simple Payback	**171.2**	**23.5**

Table 9: Summary of Demonstration Site Costs, Savings, and Paybacks

*Fuel savings were 0.5% at Central Park West and 0.2% at Seapark East, combustion efficiency issues were included in savings analysis

A summary of anticipated costs, savings and payback for a typical project with two (2) 200 HP steam boilers is included in table 10 below. The electricity savings utilize a reduction in fan motor energy of 78%. The fuel cost savings utilize a seasonal efficiency increase of 1.8%. This figure is based on an average decrease in combustion losses of 1.2% (see table 5) as well as an average reduction in off cycle and purge losses of 1.2%, the total increase of 2.4% was de-rated by the uncertainty factor of 22.9% (see the uncertainty analysis section). The construction costs for a 'Typical Retrofit' includes a similar scope of work as executed at the demonstration sites. The figures for the typical retrofit include add on costs and incremental payback for purchasing new burners (as an end of useful life replacement) with linkageless controls.

The construction costs for the 'Low Cost Retrofit' is a reduction in the scope of work while ensuring that all the energy savings are still captured. The low cost option includes two servo motors (one for fuel and one for combustion air damper) and a VFD for the fan motor. The package includes modules that are installed into the existing panel (as opposed to installing a new panel). Boiler draft controls are not included in the package as this study shows they do not reduce off cycle losses, see section 3.8 further comments on draft control. The 'Low Cost Retrofit' scope of work and construction cost was developed by the Preferred Utilities in part based on the results of this research study. It must be noted that the 'Low Cost Retrofit' option needs to be proven out at a demonstration site and further evaluation is required to determine the pros and cons of this approach.

	Typical Retrofit – Two (2) 200 Hp Boilers		Low Cost Retrofit – Two (2) 200 Hp Boilers	
	Natural Gas	#2 Oil	Natural Gas	#2 Oil
Materials	$35,000	$35,000	$20,540	$20,540
Installation Labor	$25,000	$25,000	$10,000	$10,000
Total Construction Cost	**$60,000**	**$60,000**	**$30,540**	**$30,540**
Electricity Savings*	$3,000	$3,000	$3,000	$3,000
Heating Fuel Savings**	$3,675	$5,366	$3,675	$5,366
Total Energy Cost Savings	**$6,675**	**$8,366**	**$6,675**	**$8,366**
Simple Payback For Retrofit	**9.0**	**7.2**	**4.6**	**3.7**
Incremental Construction Cost for Adding Linkageless Control and VFDs to New Burners (2)	$10,000 - $20,000	$10,000 - $20,000	N/A	N/A
Incremental Simple Payback For New Burners	2 – 3 years	1 – 3 years	N/A	N/A
*Electric savings calculations use an average reduction of 78% and electricity utility costs of $0.17/kWh **1.8% increase in seasonal efficiency, natural gas costs of $0.97/therm and #2 oil costs of $1.97/gallon				

Table 10: Summary of Costs, Savings, and Paybacks for a Typical Property

The following is a summary of qualitative benefits of linkageless burners as well as the problems that were observed during the study and can be expected for a typical retrofit project.

Non Energy Benefits:

- Improved burner turndown which results in more consistent operating pressure which in turn can improve distribution system balancing and building occupant comfort. Some sample data for pre- and post- retrofit steam pressure is shown in section 5.3.1.
- Improved monitoring of critical boiler parameters with more specific fault detection.
- Ability to send burner data to building management systems.
- Ability to monitor remotely and upload data to the cloud.
- Ability to switch fuels (gas to oil or vice versa) without making adjustments or retuning

Disadvantages:

- Nuisance lockouts / alarms – a more sophisticated control system monitors more burner points which can sometimes lead to more alarm and lockout issues. Some lockouts/alarms experienced were related to low water cutoff and gas train valve malfunctions. However, once initial issues were resolved, lockouts/alarms tapered off.
- Learning curve for building super / operator.
- Service contractors have a limited number of mechanics that are up to speed on linkageless controls.
- Service contractor need to have spare parts such as servo motors on hand for emergency service.

A summary of the recommendations for linkageless burner technology includes the following:

- In most cases, retrofitting a burner with linkageless controls before end of useful life (EUL) has an extended payback of 7 – 9 years. However, there is a lower cost retrofit package coming to market that may reduce the payback to 3 – 5 years (*Note: the 'lower cost' retrofit package requires further evaluation*). In cases where large steam boilers run year round, such as in buildings with absorption chillers, the economics will be more favorable.
- Adding linkageless controls to a new burner at time of replacement has an incremental construction cost of $5,000 - $10,000. For all boilers above 100 Hp, the incremental payback for adding linkageless controls to a new burner is less than 5 years. SWA recommends linkageless controls on all new multifamily boilers above 100 hp output (4,200 MBH input). Commercial buildings typically have lower operating hours so the payback will reflect this.
- Linkageless burner controls enable the installation of VFDs for the burner motors, and VFDs were observed to result in burner electric savings of 66% - 92%. SWA recommends including VFDs as part of the linkageless controls system on all new burner motors above 5 Hp. VFDs also allow for soft start, which extends the useful life of the motors.

3.5 Energy and Green House Gas Savings

The tables below show the energy savings and greenhouse gas (GHG) emissions based on the seasonal efficiency improvements. The utility bills for the demonstration sites were analyzed and weather normalized, but it was not possible to break out the energy savings from the utility consumption. The savings observed are relatively low and as such the figures are in the noise of the building energy consumption.

	Central Park West	**Seapark East**
Annual Heating Fuel Savings* (therms)	438	429
Annual Electricity Savings* (kWh)	-	20,695
Annual GHG Reduction (CO_2e metric tons)	2.33	8.13

Table 11: Heating Fuel, Electricity, and Greenhouse Gas savings.
*Fuel savings percentage are the same as Table 9, electric savings calculations use an average reduction of 78% for the burner electrical consumption

Fuel Type (unit)	CO2e (metric ton/unit)
Natural Gas (therm)	0.00532
No. 2 Oil (gallon)	0.010271
Electricity (kWh)	0.0002826

Table 12: Greenhouse Gas coefficients by Fuel Type

(NYSERDA, "New York State Greenhouse Gas Inventory: 1990 – 2014")

3.5.1 Project Savings Scaled Up for New York City

The heating fuel, electricity, and greenhouse gas annual savings were scaled up for the potential NYC market. The analysis was conducted on 70% of the NYC Local Law 87 (LL87) official covered building's list which represents the approximate number of large (above 50,000 square feet) buildings with high mass steam boiler plants.

To scale up the burner fan electrical savings for VFDs, the average $\frac{Burner\ Fan\ kW}{squarefeet}$ was calculated from the burner electrical data collected at the demonstration sites. This value was then applied to each building on the LL87 list. Scaled up total annual electrical consumption was then calculated by using $\frac{Burner\ Runtime\ (hr)}{HDD}$ which is a weather-normalized metric obtained from the demonstration site data and a 10 year average HDD. The total annual electrical consumption was finally multiplied by a 78% reduction (average savings measured at Seapark East) to yield total kWh savings by installing VFDs on the burner motors. The results are summarized in the table below:

Annual Energy Savings (kWh)	Annual Energy Cost Savings*	Annual Greenhouse Gas Savings (metric tons)
71,567,150	$12,166,415	20,225

Table 13: NYC Electrical and Greenhouse Gas Savings

*Electricity utility costs $0.17/kWh

Scaled up heating fuel savings were projected in ranges to account for different fuel types. An average energy use intensity of 50 $\frac{kbtu}{squarefoot}$ was used, based on the Mayor's Office of Sustainability's "New York City's Energy and Water Use Report". A 1.8% heating fuel savings was then applied to the annual heating energy, the resulting fuel savings is shown below along with energy cost and greenhouse gas savings. Fuel type breakdowns are based on Local Law 87 data analysis, in which 85% of buildings are estimated to be on Natural Gas or Dual Fuel, and 15% on Oil.

Fuel Type	Annual Energy Savings (kBtu)	Annual Energy Cost Savings*	Annual Greenhouse Gas Savings (metric tons)*
Natural Gas	1,301,448,795	$12,624,053	69,237
Oil	233,080,804	$3,327,312	17,348

Table 14: NYC Fuel Gas/Oil and Greenhouse Gas Savings

*Based on natural gas costs of $0.97/therm and #2 oil costs of $1.97/gallon and GHG emission coefficients found in table 12, Oil types were not broken out and were assumed to be No. 2.

3.6 Boiler Cycling, Turndown and Steam Pressure

The linkageless control enables contractors to digitally dial in burner parameters. This finer degree of control, along with the ability to fire below the light off position, allows turndown to be optimized. The table below shows that on average the turndown increased due to the ease and accuracy of tuning capability. Both the low and high fire points were expanded, which results in a higher degree of steam pressure control and less boiler cycling. Detailed results for the gas meter clocking and turndown tuning can be found in the appendix.

The graphs in figures 17 and 18 show that boiler cycling was for the most part reduced during the post-retrofit period. This is a result of the increased turndown ratio, more specifically the decrease in low fire rate input. Reduced cycling decreases purge losses, although efficiency gains are minimal as shown in section 3.2. Less cycling also reduces wear and tear on the burner components leading to extended useful lifetimes.

	Rated Nameplate Turndown	Pre- Retrofit Turndown	Post Retrofit Turndown
295 CPW Boiler #1	3.1	2.9	4.6
295 CPW Boiler #2	3.1	3.4	4.4
Seapark Boiler #1	4	2.5	4.7
Seapark Boiler #2	4	6*	4.6

Table 15: Burner Turndown Results

*O&M issue -low fire was ~40% below rated value which resulted in high levels of carbon monoxide.

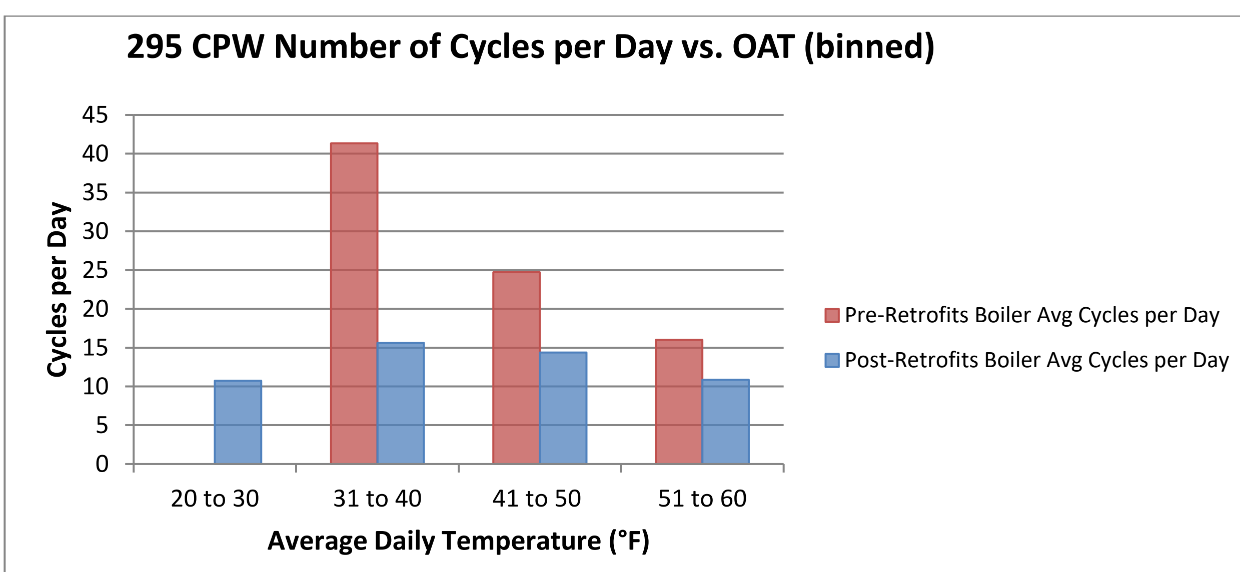


Figure 17: 295 CPW Pre- and Post-Retrofit Boiler Cycles

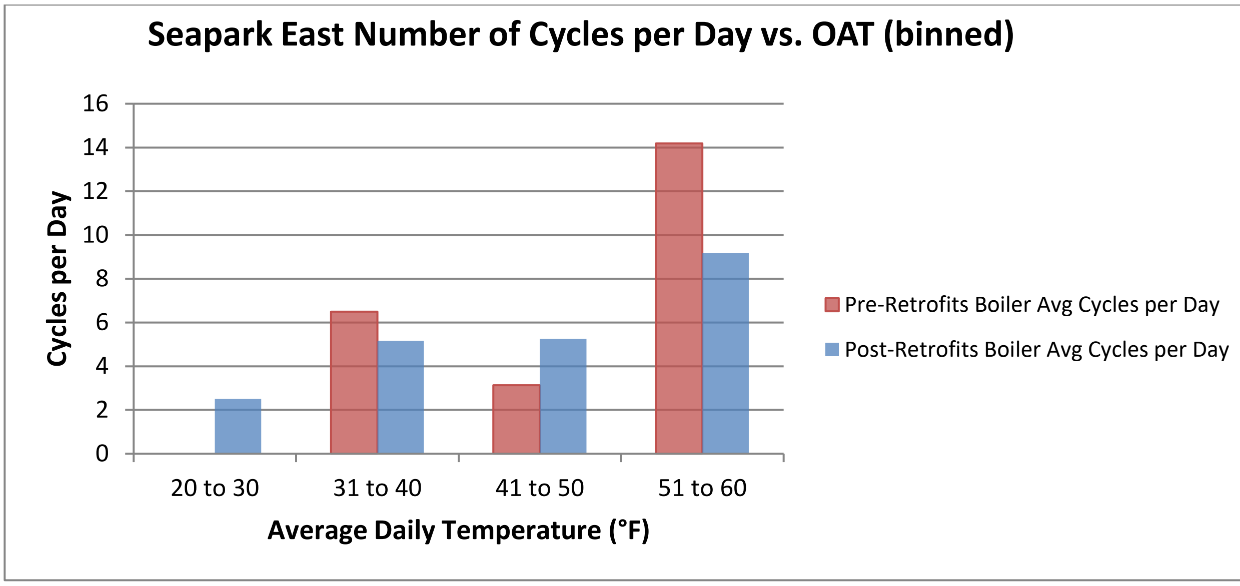


Figure 18: Seapark Pre- and Post-Retrofit Boiler Cycles

Higher burner turndown and reduced cycling also results in improved steam pressure control. Improved steam pressure control has benefits for distribution system balancing and building occupant comfort. The following graphs show steam pressure over a number of boiler cycles; the sample pre- and post- retrofit cycles have similar HDD values. For the post- retrofit period, steam pressure was observed to be consistent with less peaks / spikes. For 295 CPW, the heating control cycles the boilers on/off based on average apartment temperature, which results in much shorter cycle lengths than at Seapark East. The Seapark East heating controls run the boilers almost continuously to supply steam to the heating hot water heat exchangers. Both buildings show less fluctuation in steam pressure during the post- retrofit period. The decrease in low fire input allows the boiler to maintain pressure and heat output during lower heating loads.

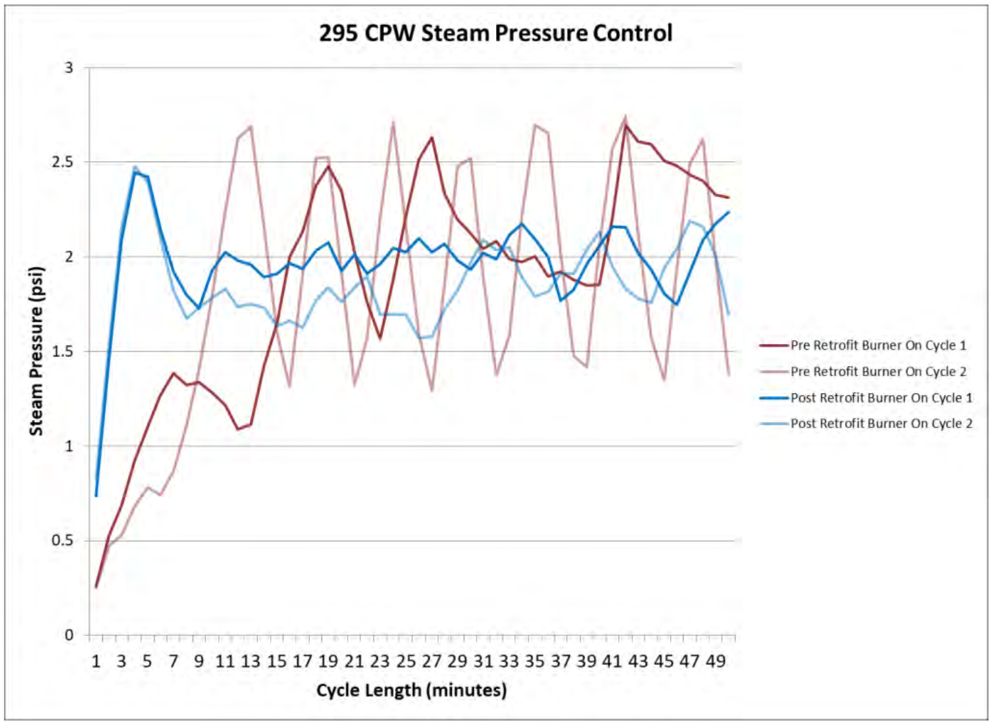


Figure 19: 295 CPW Pre- and Post-Retrofit Steam Pressure

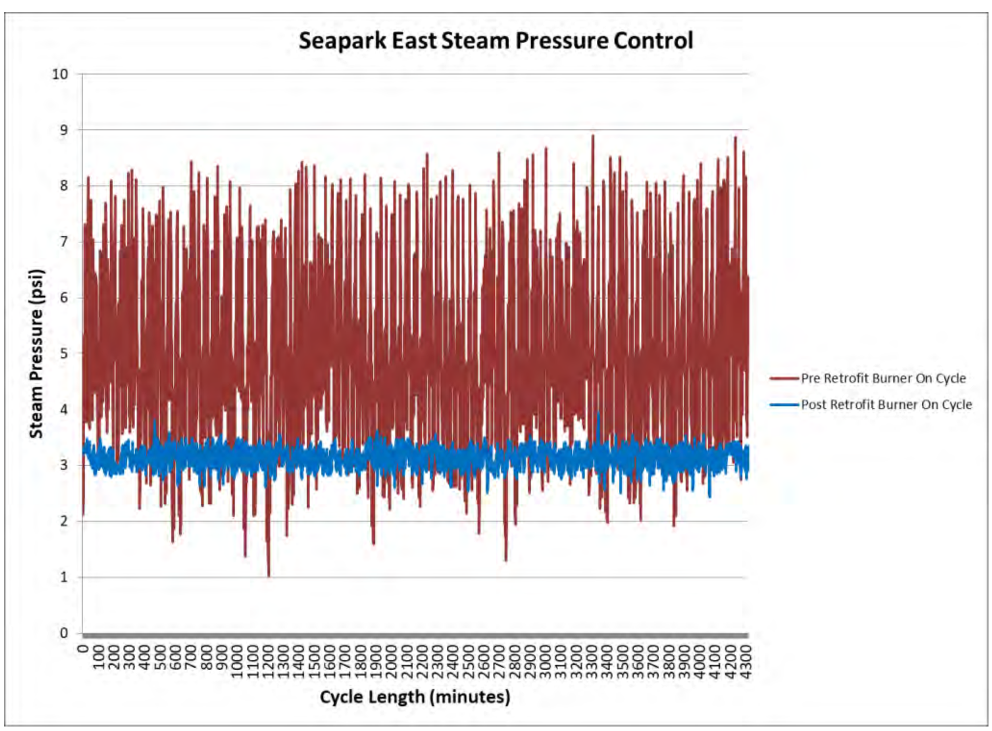


Figure 20: Seapark Pre- and Post-Retrofit Steam Pressure,

Note: The boiler's pressure settings were not altered during the analysis period. The reduction in steam pressure may be the result of faulty control panel sensor

3.7 Uncertainty Analysis

Where available, uncertainties were taken from the equipment technical specifications and are presented below. In the case of the gas meter readings and duct blaster test, uncertainties were estimated. The uncertainties of the measured variables are independent, the total uncertainty was approximated using fractional uncertainties.

$$U_x = \sqrt{\sum (\frac{\delta x}{|x_i|})^2}$$

- $\frac{\delta x}{|x_i|}$: Fractional uncertainty
- δx: Uncertainty in measured value
- $|x_i|$: Measured value

Instrument (measurement)	Uncertainty	Typical Value
Onset 12-bit Smart Sensor (OAT & Boiler Room Temperature)	± 0.36 °F from 32 to 122 °F	40°F / 75°F
Testo 350 Combustion Analyzer (Flue Temperature)	± 32.7 °F from -148 to 392 | ± 33.8 °F rest	250°F
The Energy Conservatory Manometer (Pressure)	± 1 %	-0.2 in. w.c.
Veris Pressure Transducer (Pressure)	± 1 %	-0.2 in. w.c.
Duct Blaster Test (Off-cycle CFM)	7.5%	50 CFM

Table 16: Instrumental Uncertainties

The following table is a summary of the propagation of the fractional uncertainties in each of the calculated values.

Measurement	Net Fractional Uncertainty	Range of Typical Value ± Net Fractional Uncertainty
Gas Meter Readings	10%	250 therms ± 25therms
Combustion Loss	11.5 %	15% ± 1.73%
Off-cycle Loss	13.8 %	1% ± .14%
Purge Loss	10.0 %	1% ± .1%
Seasonal Loss	22.9 %	17% ± 3.90%

Table 17: Net fractional Uncertainties of Calculated efficiencies

3.8 Limitations of the Study

The data gathered is displayed in this paper with a level of transparency, in hopes of providing meaningful and research based information. However, it was and is important to scrutinize the level of accuracy in each step of the data collection and analysis process. The following are shortcomings and difficulties that were dealt with during the study.

Building Sample Set:

Although the demonstration sites were selected to represent the vast majority of NYC buildings with high mass steam intermediate sized boiler plants, the study was limited to two buildings and a total of four boilers. It was cost prohibitive to include additional demonstration sites; however, additional data points may have shown a wider range for seasonal efficiency and savings. A follow up study could potentially include a high level utility analysis of a larger sample set of buildings to evaluate linkageless burner controls. However, if savings are in the same range as this study, it would not be possible to verify savings on a utility bill level.

Firm Rate Dual-Fuel Boilers versus Interruptible Rate Dual-Fuel Boilers

It was noted earlier in the report that fixed position linkages make it difficult to tune a burner for optimal efficiency for both natural gas and oil in dual-fuel burner applications. Both of the demonstration sites were dual-fuel systems on firm gas rates meaning that although the burner is capable of burning oil, they only fire on oil if the natural gas grid goes offline. As such, these burners are likely only fired on oil at city inspections. They are tuned to optimize efficiency on natural gas as oil operation only happens when a service technician is present. Interruptible rate dual-fuel burners typically fire on oil when the outdoor temperature drops below 15°F. This typically happens for a handful days out of the year in NYC when service technicians are busy with emergency calls. These burners have to be setup to burn oil and gas safely; the linkage setup typically compromises the combustion efficiency to ensure safe combustion for oil and gas. Linkageless burners are setup with independent fuel curves for oil and gas so efficiency does not need to be compromised for safe combustion. Switching fuels without retuning can be problematic for linkage burners, there are no such issues with linkageless systems as separate fuel curves for oil and gas are programmed into the controls. It is likely that interruptible rate dual-fuel boilers have lower baseline combustion efficiencies which in turn would result in higher savings for linkageless burner controls.

Unintended Construction and Exterior Component Issues

As with any retrofit project, unintended problems arise. Both sites experienced issues with faulty gas train valves; these valves were not part of the retrofit scope of work. The faulty valves resulted in non-optimal combustion efficiency. One of the burners at 295 Central Park West was not operating at optimal levels for part of the post- retrofit period. At Seapark East, one of the burners was set to manual low fire for part of the post- retrofit period due to issues with the gas train valve. The data was screened for low stack temperatures and abnormal oxygen readings. To address these issues, any data that was deemed to be flawed / bad was eliminated from the analysis.

Lack of Daily Gas Readings:

Daily gas readings were taken by the participating property's superintendents, by visually observing the boilers' gas meters. The superintendents were instructed to take readings at 8am before morning rounds. There may be a slight variance in the times that readings were taken but for the most part readings were taken in the early morning. In addition, there are some gaps in the gas meter readings where superintendents were absent or missed a reading. The cost of installing individual boiler gas meters was cost prohibitive, therefore manual daily gas readings was the only feasible option.

Data Time Stamps Misaligned:

Data was obtained through various sources of measurements and were collected via two major systems, the Hobo remote monitoring station and Testo combustion analyzer. The time stamps of some data sets did not agree with others. For example the burner fan electricity data would show that the burner is on, however the flue temperature and $\%O_2$ indicated otherwise. Purge times were accounted for, yet some data sets were still not aligned. Misalignments approximately ranged from 0-10 minutes. Corrections were made to the calculations and as such this issue had little to no effect on the final results of the study.

Testo Ambient Air Temperature Measurements:

Ambient air or combustion air temperature is one of the inputs for the equation that the Testo analyzers use to calculate combustion efficiency. During the monitoring periods, the Testo units were stored in cabinets in the boiler room to prevent damage to the equipment. The ambient air sensors are located on the Testo units, meaning that ambient temperature was measured within the storage cabinets. Due to heat gain from the Testos and laptop equipment, the temperature in the storage cabinets was slightly higher than the ambient air temperature of the boiler room. SWA reviewed the combustion calculations for the elevated ambient air temperatures observed. This issue resulted in a margin of error of less than 1% for combustion efficiency readings.

Insufficient Flue Gas Condensate Removal For Testo Equipment:

Initially, the only form of flue gas condensate removal was from the Testo 350 combustion analyzer's internal system. This was not a sufficient means of condensate removal, so an external gas chiller and peristaltic pump were installed in the flue gas line. This solved the issue for the majority of the study;

however the chiller and pump system failed once at Central Park West, causing the oxygen sensors in the Testo 350 to also fail. The chiller and pump system were replaced, and the oxygen sensors in both participating sites were replaced as the end of useful lifetime was approaching. The systems' down time caused several weeks of data to be excluded from the study. However, the Testo 350s were calibrated on a bi-weekly basis and the data was screened for errors / bad data due to problems with bad sensors.

Pitot Tube Issues:

Initially, the off-cycle volumetric air flow in the flue, and corresponding heat loss, were to be calculated from the Testo 350's direct measurements via a pitot tube. However, the off-cycle air flow was too low for the pitot tube to accurately measure, therefore the pitot tube was repurposed as a pressure sensor and off-cycle air flow was calculated as described in the off cycle loss section.

Draft Control:

This study did not analyze the effects of draft control on combustion control. Rather, the effect of draft control on off cycle air flow and heat loss was measured. The results show that during the off cycle, draft control had little to no effect on heat loss through the boiler and up the flue. A follow up study could evaluate the benefits of draft control during combustion and its impact on turndown.

Oxygen Trim Not Analyzed:

The implementation scope did not include oxygen trim. Therefore this study did not analyze the effects of oxygen trim. It may be assumed that the O2 trim could enable the burner to decrease oxygen content and excess air in flue gases which in turn increase combustion efficiency. However this was not assessed, nor was the accuracy or reliability of the systems scrutinized.

4. Retrofit Installation - Best Practice Guidelines

Contractors and manufacturers were interviewed at various stages during the retrofit process at both demonstration sites to solicit feedback on identified issues, potential solutions and options to improve the retrofit process. This feedback and data was compiled and utilized with SWA's industry knowledge to derive best practice approaches for the retrofit approach. The following is a summary of the best practice guidelines for executing the linkageless burner retrofits:

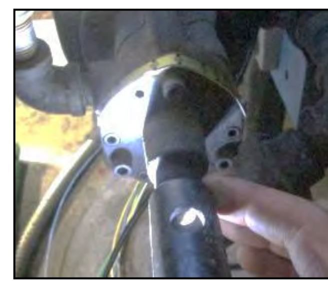
- *Managing Building Owner / Management Expectations* – In most cases, the linkageless system will be a much more sophisticated system than the existing burner control system. As such the new system will likely monitor more components of the boiler and burner system. If there are pre-existing issues with a component, the new control system will detect the issue and may shutdown / lockout the burner on safety. As a result, safety and operational lockouts may increase with a more sophisticated control system.
- *Evaluation of Existing Conditions and Boiler Room Preparation* – The boiler room should be surveyed for any pre-existing issues that may cause issues for a linkageless system. The following are some considerations that should be evaluated and or remedied before any retrofit work takes place: boiler room flooding and drainage, leaks from overhead steam / hot water piping, existing draft controls, gas train fuel valve issues and any general operational issues with the existing boiler and burner. In addition, the contractor / vendor should take detailed measurements of the burner dimensions and clearances to ensure that the correct parts are manufactured and ordered.
- *Adjustable Slot Brackets* – When mounting the motors for fuel valves, air dampers and draft controls, utilize adjustable slot brackets. These types of brackets will allow the shafts and motors connections to line up with relative ease. The adjustable slot brackets should be supplied by the manufacturer as part of the job parts order. Use thread locking fluid to ensure that the brackets do not move after installation.

- *Fuel Valve and Air Damper Position Indicators* – All fuel valves and air dampers should include an indicator arrow or notches to indicate the approx. position of the valve / damper. This is very helpful for field technicians for setup and troubleshooting.
- *Burner Differential Pressure Switch* - If a variable frequency drive (VFD) is to be installed as part of the retrofit work, the burner differential pressure switch should be upgraded as the existing sensor is not likely to be sensitive enough when the burner is operating on low fire.

- *Draft Control Setup and Control Piping Location* –Install the draft control pressure sensing line in the boiler smoke box, and set it to 0 or slightly negative (<-0.09 in w.c.). Most draft control installations in NYC have the sensing line located in the boiler furnace, which does not account for differing pressure losses across the boiler as the burner firing rate modulates.

- *Burner Combustion Air Damper Position* – It is critical to setup the burner so that the combustion air damper is completely shut when the boiler is off. M&V results show that off-cycle air flow and heat loss through the boiler chamber is primarily driven by the combustion air damper position.

- *Notch for Oil Pin Stamp* – During New York City Department of Environmental Protection (DEP) inspections, the inspector needs to view the oil pin stamp. This can be achieved by including a hole or notch in the oil metering pump shaft / connector so there is a window to view the stamp.



- *Contractor Training and Technology Issues* – There is a need to provide more ‘hands on’ or field training to burner mechanics on the linkageless controls. Contractors need to get more comfortable with setting and tuning a burner with a laptop as opposed to just wrenches. This technology barrier will become less challenging with more widespread adoption of linkageless burners.
- *Superintendent and Building Manager Training* – The contractor that performed the retrofit work should be retained for service and emergency calls. However, the superintendent and/or building manager should also be trained on the new linkageless system so they understand how the new control system functions. At a minimum, building personal should know how to reset the system when there is a lockout and should know how to view alarms / error codes.
- *Manuals and Wiring Diagrams* - All relevant manuals should be located in the boiler room, the new control wiring diagram should be posted on the burner panel door for all future troubleshooting and maintenance.
- *Manufacturer / Vendor Support* – The linkageless system manufacturer should provide technical support during the construction and commissioning process. Ideally, a manufacturer’s representative should be present in the field for the construction kick off and the system setup and commissioning.

5. Appendix:

5.1 Monthly Efficiency and Data Captured

The following tables summarizes the amount of monthly data captured.

5.1.1 Central Park West

Central Park West	Year	Month	Percent of HDD Captured	HDD Captured	Average Monthly Combustion Efficiency	Average Monthly Seasonal Efficiency
Pre-Retrofit	2016	March	59%	308	83.59%	81.44%
	2016	April	55%	211	84.43%	82.42%
	2016	May	40%	64	85.98%	82.82%
	2016	June	0%	0	86.84%	81.41%
Post-Retrofit	2016	December	20%	153	84.46%	83.49%
	2017	January	63%	496	84.37%	83.28%
	2017	February	71%	444	84.49%	83.14%
	2017	March	19%	141	84.21%	82.65%
	2017	April	24%	64	84.38%	82.87%

5.1.2 Seapark East

Seapark East	Year	Month	Percent of HDD Captured	HDD Captured	Average Monthly Combustion Efficiency	Average Monthly Seasonal Efficiency
Pre-Retrofit	2016	March	49%	257	86.57%	86.03%
	2016	April	88%	336	85.10%	83.98%
	2016	May	35%	57	85.87%	82.62%
Post-Retrofit	2017	January	11%	84	84.49%	82.50%
	2017	February	18%	111	82.01%	-*
	2017	March	4%	30	84.87%	83.82%
	2017	April	0%	0	85.82	-*

*No daily natural gas metering available for these data sets

5.2 Turndown Ratings

5.2.1 Central Park West

Nameplate Ratings		
Firing Rate	Rated Input (MBH)	Turndown
Low	2,100	3.1
High	6,550	

Boiler 1

Pre-Retrofit			*Post- Retrofit*		
Firing Rate	Measured Input (MBH)	Turndown	Firing Rate	Measured Input (MBH)	Turndown
Low	1,600	2.9	Low	1,161	4.6
Medium	4,400				
High	4,700		High	5,377	

Boiler 2

Pre-Retrofit			*Post- Retrofit*		
Firing Rate	Measured Input (MBH)	Turndown	Firing Rate	Measured Input (MBH)	Turndown
Low	1,500	3.4	Low	1,350	4.4
Medium	4,200				
High	5,100		High	5,934	

5.2.2 Seapark East

Nameplate Ratings		
Firing Rate	Rated Input (MBH)	Turndown
Low	2,100	4
High	8,440	

Boiler 1

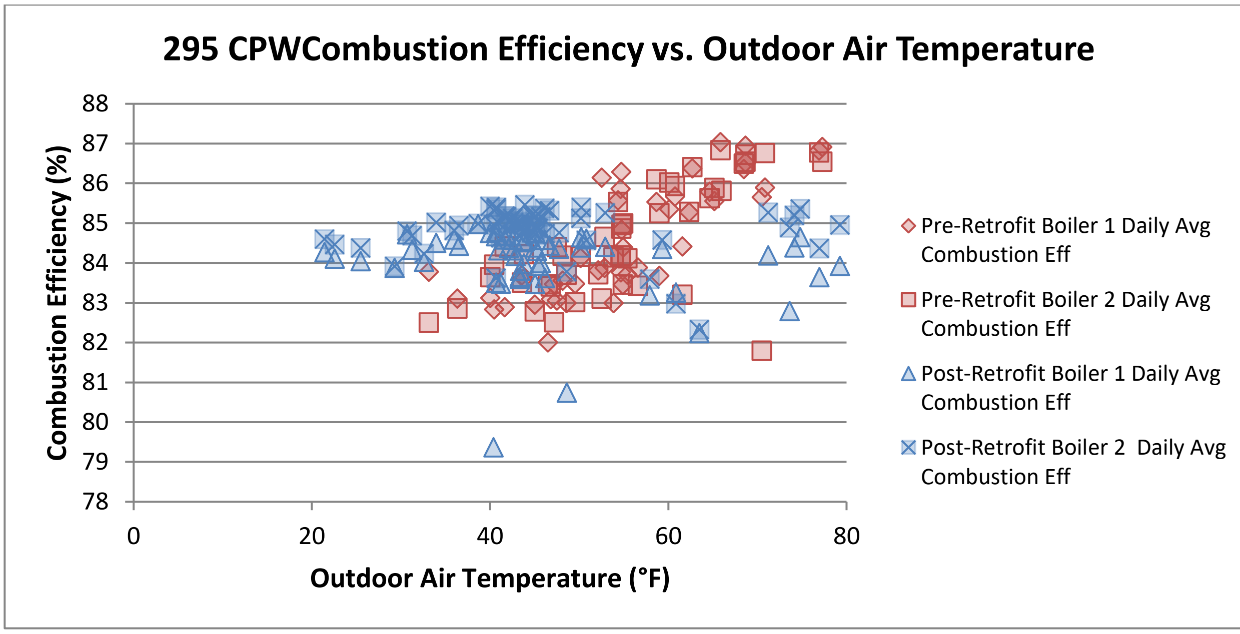
Pre-Retrofit			*Post- Retrofit*		
Firing Rate	Measured Input (MBH)	Turndown	Firing Rate	Measured Input (MBH)	Turndown
Low	3,000	2.5	Low	1,353	4.7
Medium	6,200				
High	7,400		High	6,400	

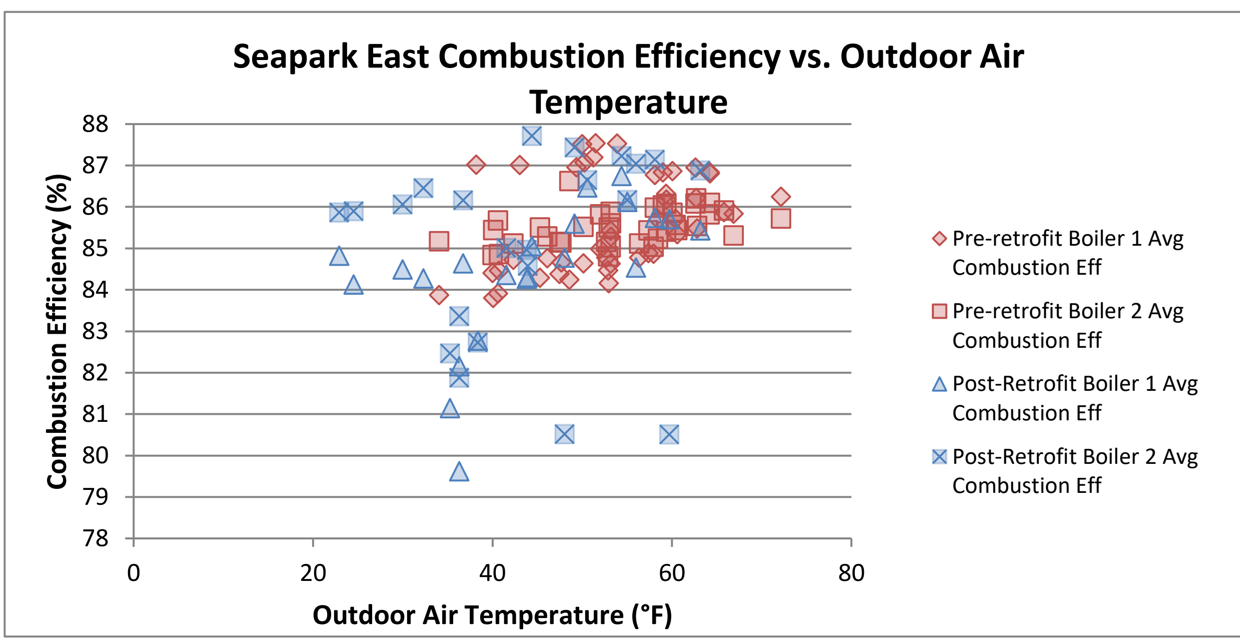
Boiler 2

Pre-Retrofit			*Post- Retrofit*		
Firing Rate	Measured Input (MBH)	Turndown	Firing Rate	Measured Input (MBH)	Turndown
Low	1,200	6	Low	1,395	4.6
Medium	6,200				
High	7,200		High	6,428	

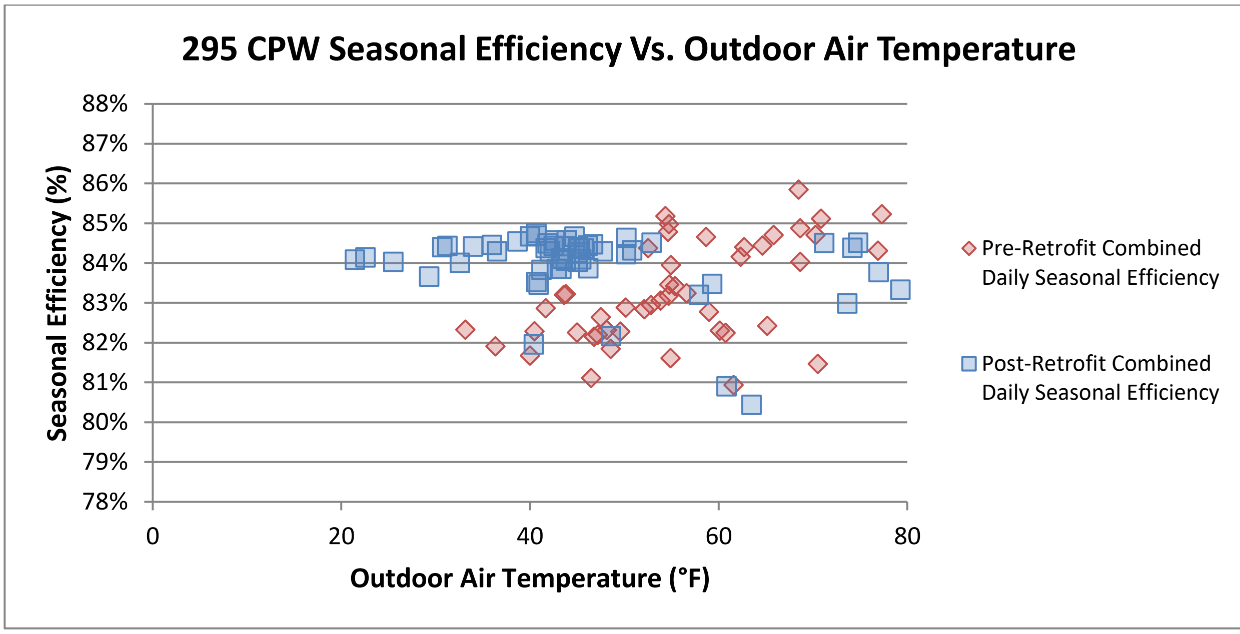
5.3 Additional Graphs

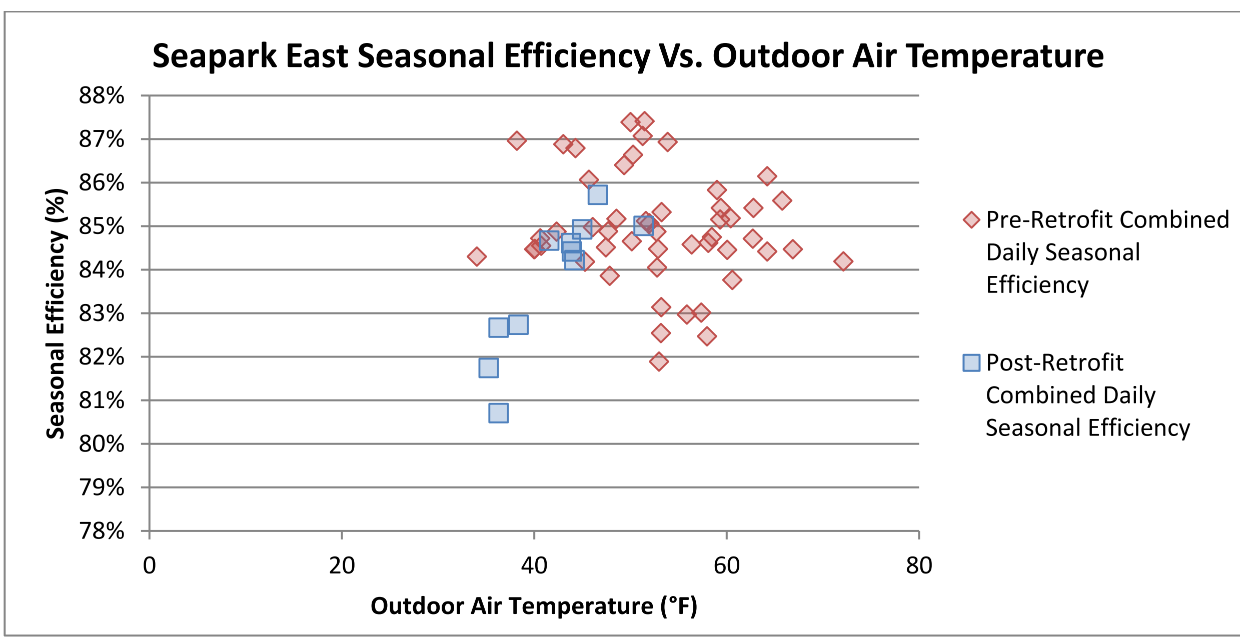
5.3.1 Combustion Efficiency vs. Outdoor Air Temperature



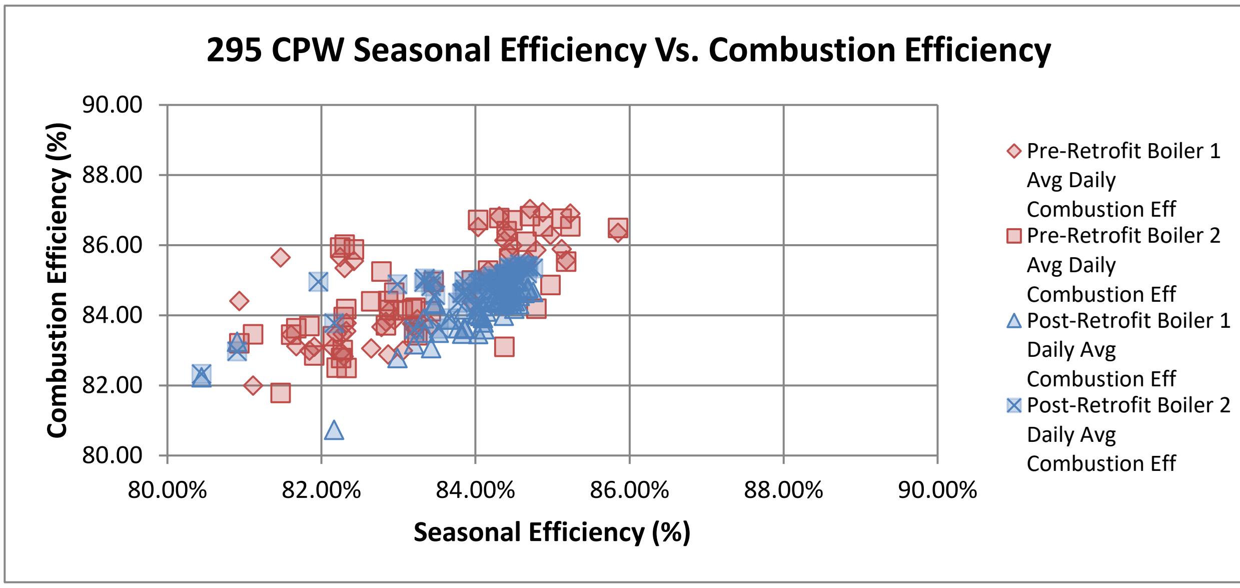


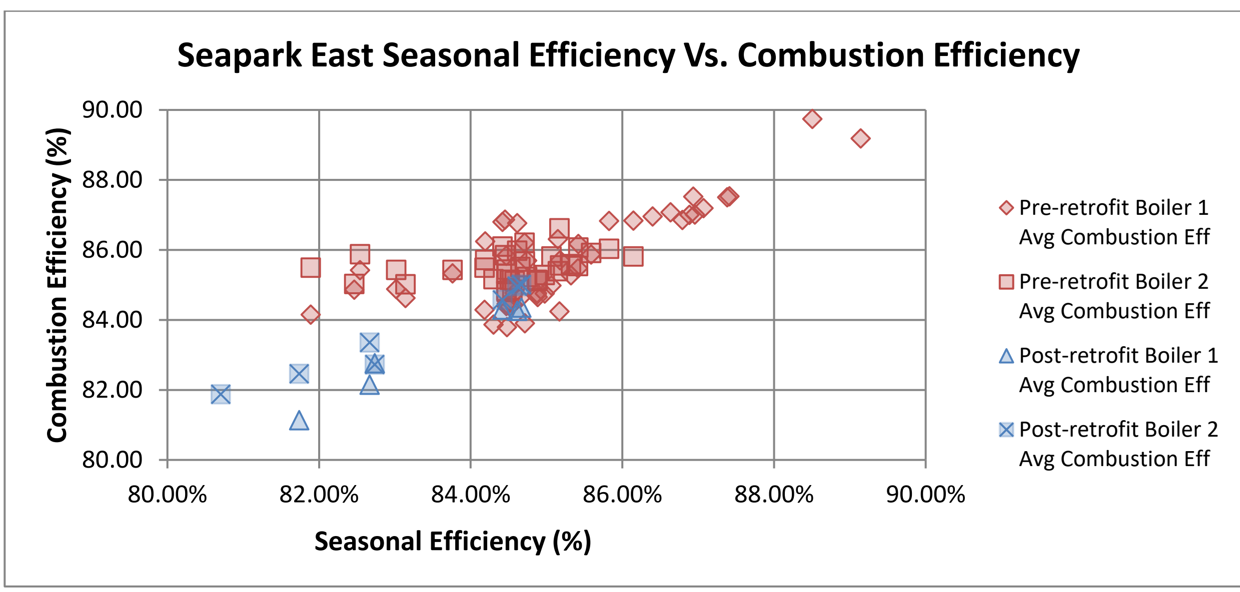
5.3.2 Seasonal Efficiency vs. Outdoor Air Temperature



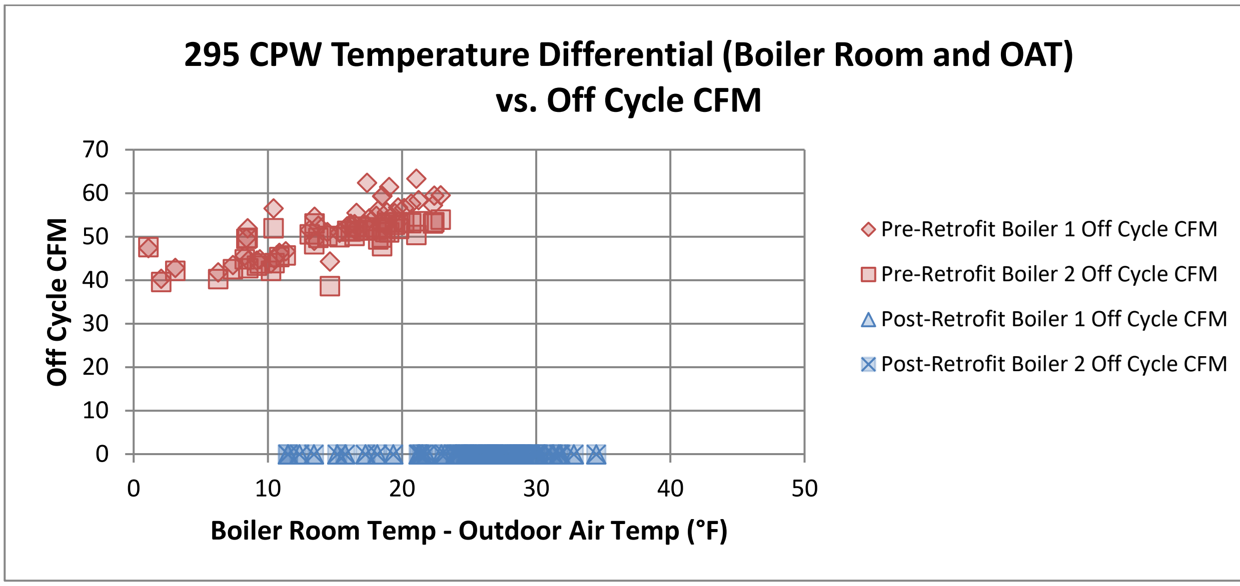


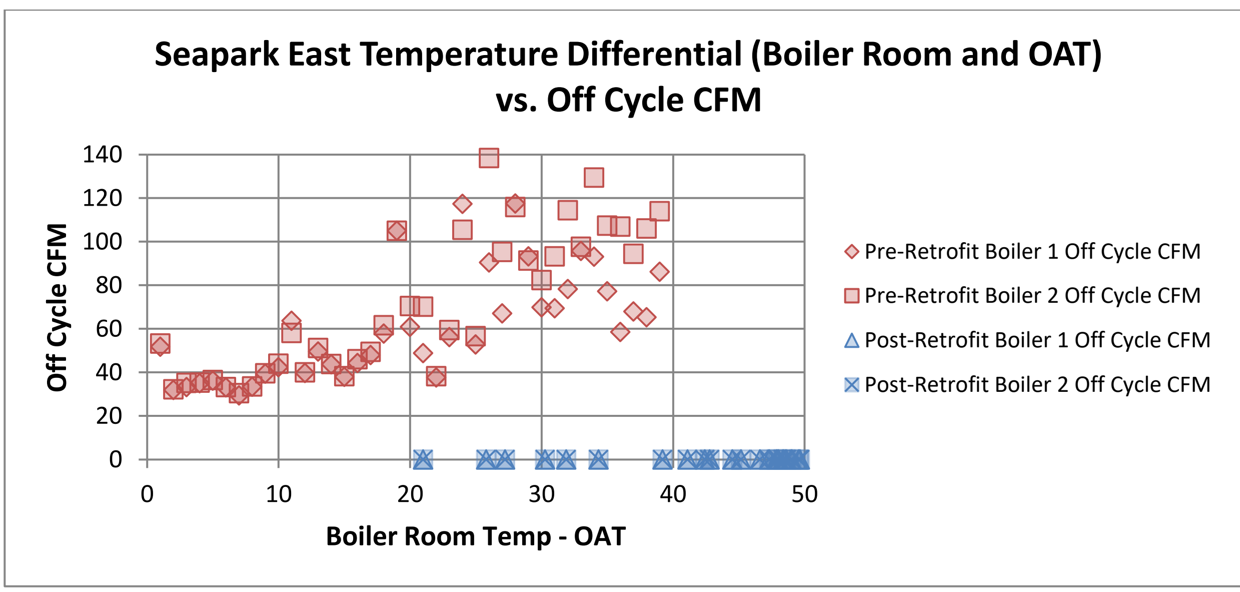
5.3.3 Seasonal Efficiency vs. Combustion Efficiency



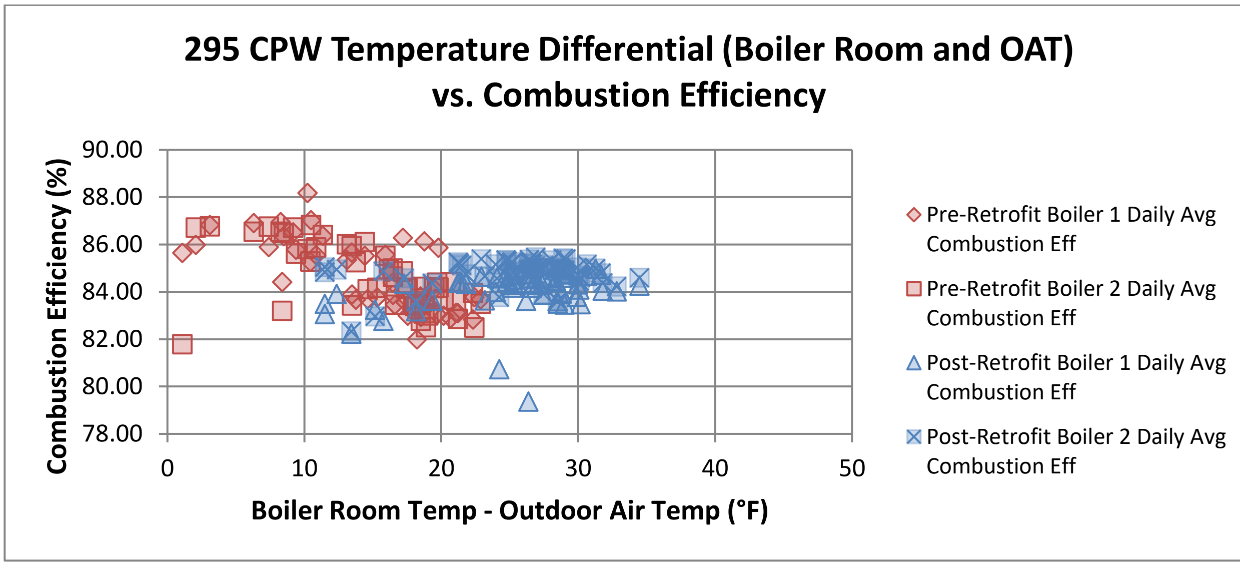


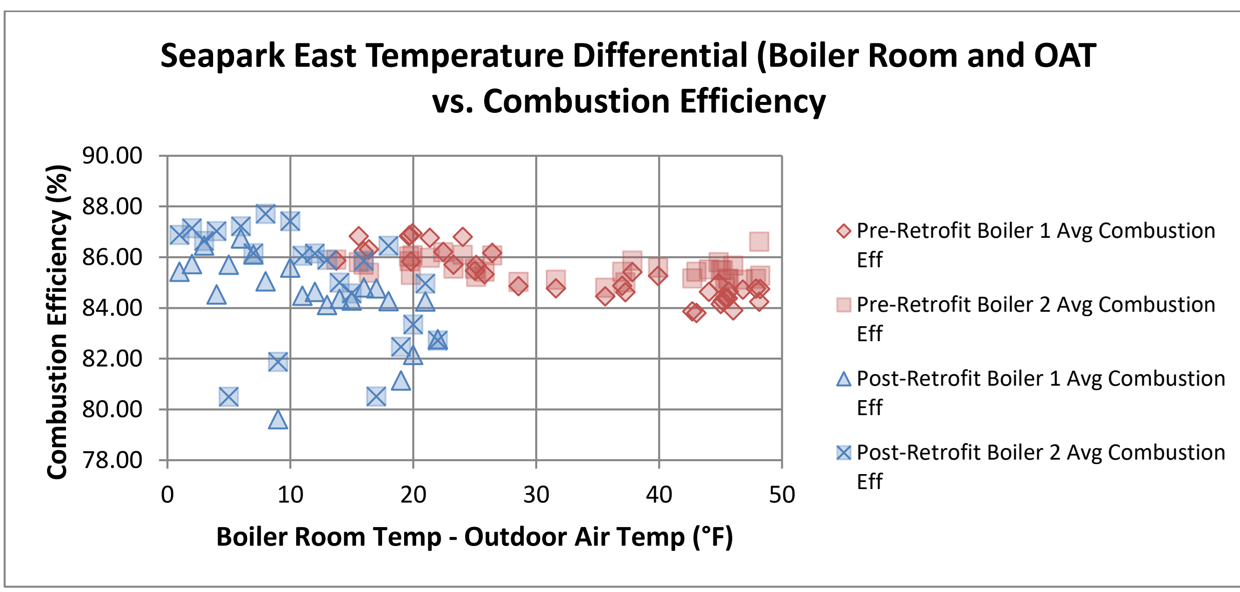
5.3.4 Temperature Differential (Boiler Room minus Outdoor Air Temperature) vs. Off Cycle Flue Air Flow (CFM)





5.3.5 Temperature Differential (Boiler Room minus Outdoor Air Temperature) vs. Combustion Efficiency





5.4 Combustion Efficiency Equation

Calculation Formulae (German)

Flue gas heat loss

$$qA = \left[(FT - AT)\left[\frac{A2}{(21 - O_2)} + B\right]\right] - XK$$

FT: Flue gas temperature
AT: Ambient air temperature
A2/B: Fuel-specific factors (see Table)
21: Oxygen level in air
O_2: Measured O_2 value (rounded to the nearest whole number)
XK: Proportional coefficient which expresses qA as a minus value when the dew point is not reached. Necessary for measurements on condensing burners. If the dew point temperature is not undershot XK = 0.

$$qA = f \times \frac{(FT - AT)}{CO_2}$$

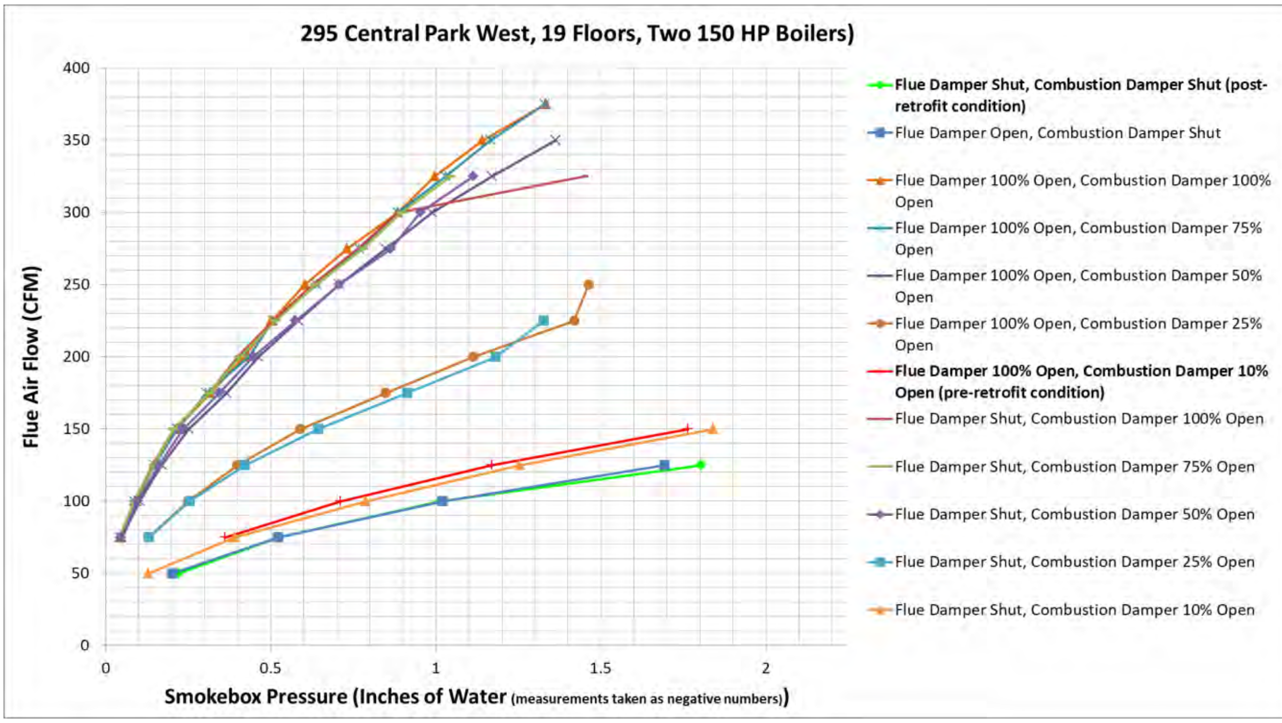
Siegert formula to calculate flue gas loss. It is used when the fuel-specific factors A2 and B (cf. Table) are zero.

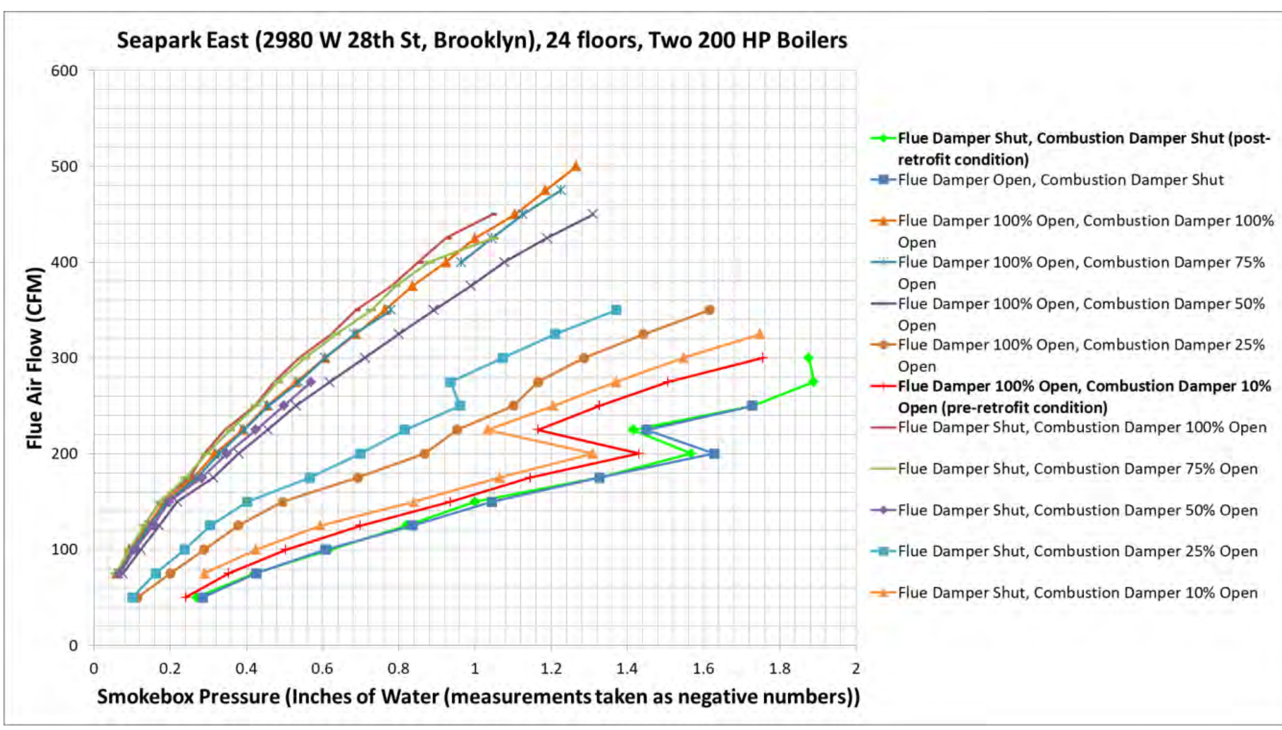
Fuel-specific factors

Table of fuel-specific factors

Fuel	A2	B	f	CO_{2max}
Fuel oil	0.68	0.007	-	15.4
Natural gas	0.65	0.009	-	11.9
LPG	0.63	0.008	-	13.9
Coke, Wood	0	0	0.74	20.0
Briquette	0	0	0.75	19.3
Bituminous coal	0	0	0.90	19.2
Anthracite	0	0	0.60	18.5
Coke-oven gas	0.6	0.011	-	-
Town gas	0.63	0.011	-	11.6
Test gas	0	0	-	13.0

5.5 Off-cycle Smokebox Pressure vs. Flue Air Flow Chart





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