Technical Assistance Study

Vacuum Steam Heating

ID Number(s): RIS-87-14-0110

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Date: 10/17/2014
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I. Contents

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III. Introduction

Keith Miller with National Grid (NGrid) requested engineering services from RISE Engineering. The intent of this study is to quantify the savings potential and market applicability of a new residential steam distribution system which operates under vacuum to deliver heat.

RISE Engineering conducted multiple site visits to perform a series of measurements in order to determine the overall system efficiency changes through different operating modes. These visits were performed at major system changes to download data from the monitors before each new test began.

IV. Executive Summary

Igor Zhadanovsky, PhD., the President of Applied Engineering Consulting, contacted Keith Miller of National Grid to request that his method to steam distribution be assessed for energy savings. Through this process, RISE Engineering was requested to perform measurement and verification of the energy savings potential of the vacuum distribution system approach. Based upon the collected data, the vacuum system retrofit produced favorable energy savings as a percentage of on-site fuel consumption. This technology could be installed at facilities which currently utilize single pipe steam to heat or those new construction facilities which are being designed with single pipe steam.

V. Facility Overview

The property that was utilized is a two story colonial that serves as both a day care and living quarters. Each floor has its own steam boiler and distribution system which are controlled by programmable thermostats. The first floor (noted as Unit #38), the day care, was not monitored in this study although it was stated that the thermostat was maintained at a constant setting. The top floor, Igor's home (Unit #36), was the focal point of the evaluation.

The residency is the 2nd floor of 1910 colonial, and is 1,150 square feet in floor area. Eight (8) radiators were utilized to heat the space. To ensure consistency between testing scenarios, two (2) of the cast iron radiators were disconnected from the system so that both the VSH and the single pipe steam system used the same number of radiators. The home's insulation level is low with most walls having no insulation. Fourteen (14) out of seventeen (17) windows are new, with the three (3) old windows being attached to a screened porch (each of which having storm windows). A forced air system in the attic space provides cooling only.

Radiator Location	Steam Delivery Order
Kitchen	1
Bedroom #1	2
Dining Room	3
Bedroom #2	4
Office	5
Living Room	6

A basic floor plan of Unit #36 is shown below. This lays out the various rooms, original and new radiators, and the space thermostat. The order in which the radiators receive steam is chronologically noted and shown in the table to the right.

VI. Vacuum Steam Heating

a. Technology

Residential homes constructed in the early 1900s with steam systems generally utilize one-pipe (SPS) or two-pipe steam distribution. In the scenario at Unit #36 (single pipe steam), gravity returns condensate back to the boiler through steam piping in a counter-flow manner[1]. The single pipe steam radiators are all high-mass cast iron units with air vents. These vents allow air within the system to purge during the "warm-up" cycle while preventing valuable steam from escaping. While this system is very easy to install, only one set of pipes, it generally lacks the maintenance necessary to keep it running properly.

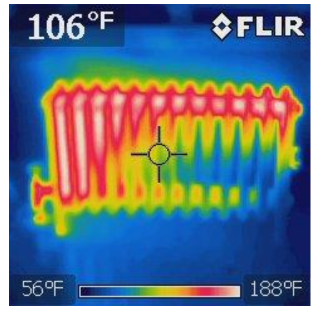


Figure 1: Single Pipe Steam Radiator (High mass cast iron)

Vacuum heating technology has been successfully utilized in both residential and commercial applications. Systems generally operate between 5 to 10 inches of mercury vacuum. The specific application being studied utilizes a deeper vacuum and modern plumbing / distribution replacement to further increase savings potential.

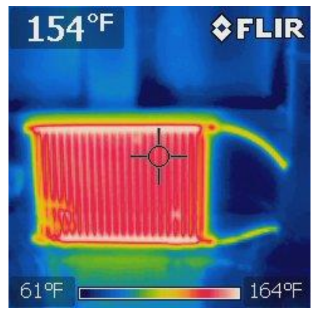


Figure 2: Vacuum Steam Heating system radiator (Low mass steam)

Modifying a standard single pipe steam system to a Vacuum Steam Heating system reduces operating temperatures while maintaining a high differential pressure across the system. In this specific scenario the single pipe steam system was abandoned in place. Tests were conducted in back-to-back weeks utilizing various scenarios to quantify the potential efficiency gain of switching to the VSH system. The VSH system utilized a supply and return hose to each radiator. The distribution system did not use a metal pipe but rather copper tubing and temperature-resistant clear plastic tubing. The VSH distribution system was attached to new low mass hydronic radiators. A vacuum pump maintained the vacuum in the system to between 20 and 24 inches of mercury vacuum.

Common practice within the industry generally calls for complete steam to hot water conversions. While this may be optimal for efficiency, costs to do so generally prohibit a customer from moving forward. The VHS may be a feasible alternative to obtain those savings.

[1] Two-pipe systems utilize a separate pipe to return condensate back to the boiler.

b. Analysis Methodology and Results

To quantify efficiency gains between the VSH system and the single pipe steam system a number of data monitors supplied both by RISE Engineering and Applied Engineering Consulting were utilized to track and trend the operational parameters of the various test scenarios. The monitors recorded data in increments of as little as 10 second intervals and up to 15 min intervals. Pulse meters were utilized to monitor the vacuum pump and the gas meter. A list of RISE Engineering's installed meters is as below.

Sensor #	Model	Use Description
1	Fyrite Tech Analyzer Model 60	Used to determine the combustion efficiency of the base case boiler
2	Flir Systems i7	Infrared camera utilized to document the heat output of the radiators
3	HOBO U12-011 Temp/RH	Used to monitor the basement temperature
4	HOBO UX100-011 Temp/RH	Used to monitor the temperature at the control thermostat
5	HOBO UA-002-64 Pendant Temperature/Light, 64K	Outdoor air and ambient solar conditions
6	HOBO UX120-017 4-Channel Pulse Input	Data recorded to measure time gaps in On/Off pulses from the CSV-A8
7	HOBO CSV-A8 AC Current Switch	The current switch which monitored run time on the vacuum pump

The meters that were deployed by Applied Engineering Consulting included the following.

Sensor #	Model	Use Description
1	Pulse Meter	Recorded Pulse output from Gas meter to record fuel consumption
2	Presure Sensor	Measure the Vacuum in the system
3 - 7	Temperature Sensors	Condensate return, Kitchen, Bedroom 1, Bedroom 2, Dining Room, Living Room, Office

The data from these meters was imported into a spreadsheet calculation to determine the savings for the following scenarios.

System Comparison
Old Boiler - Single Pipe Steam
Old Boiler - Vacuum System
New Boiler - Single Pipe Steam
New Boiler - Vacuum System
Old Boiler - Single Pipe Steam
New Boiler - Single Pipe Steam
Old Boiler - Vacuum System
New Boiler - Vacuum System
New Boiler - Vacuum System
New Boiler - Balanced Vacuum
Old Boiler - Single Pipe Steam
New Boiler - Balanced Vacuum

The first steps in determining the energy impact of the VSH system were to generate plot and trend lines from relevant data that would potentially impact the consumption of the facility. The two major independent variables for this project were the outdoor ambient conditions and the amount of potential solar heat gain. These two variables were identified as the independent variables because the thermostat was set to a specific load profile and was monitored to ensure that it held those conditions.

A plot of the outdoor air temperature vs. the fuel consumed by the boiler to heat the apartment is shown below.

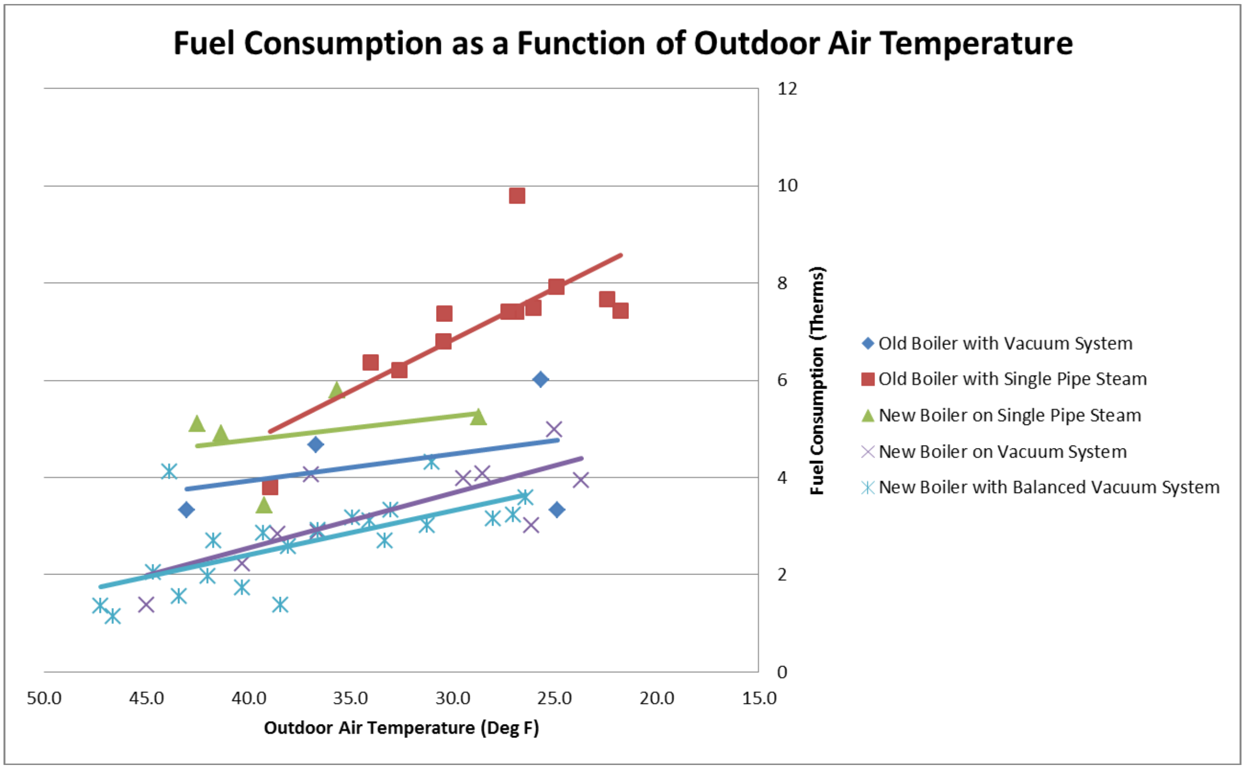


Figure 3: Fuel consumption as a function of outdoor air temperature per day

This graph (Figure 3) shows a direct relationship between the outdoor air temperature and fuel consumption of the facility. Note that the various tests took place across similar weather conditions despite taking multiple weeks to complete. Each data set represents its own test with the least efficient (Old Boiler with Single Pipe Steam (Red Squares)) being highest up the scale. Conversely, the most efficient test that was performed is lowest on the graph (New Boiler with the Balanced VSH System).

The second independent variable, the solar heat gain or in this case the lumens of light recorded by the light sensor, is plotted against the fuel consumption to determine the effect of solar heat gains on the property.

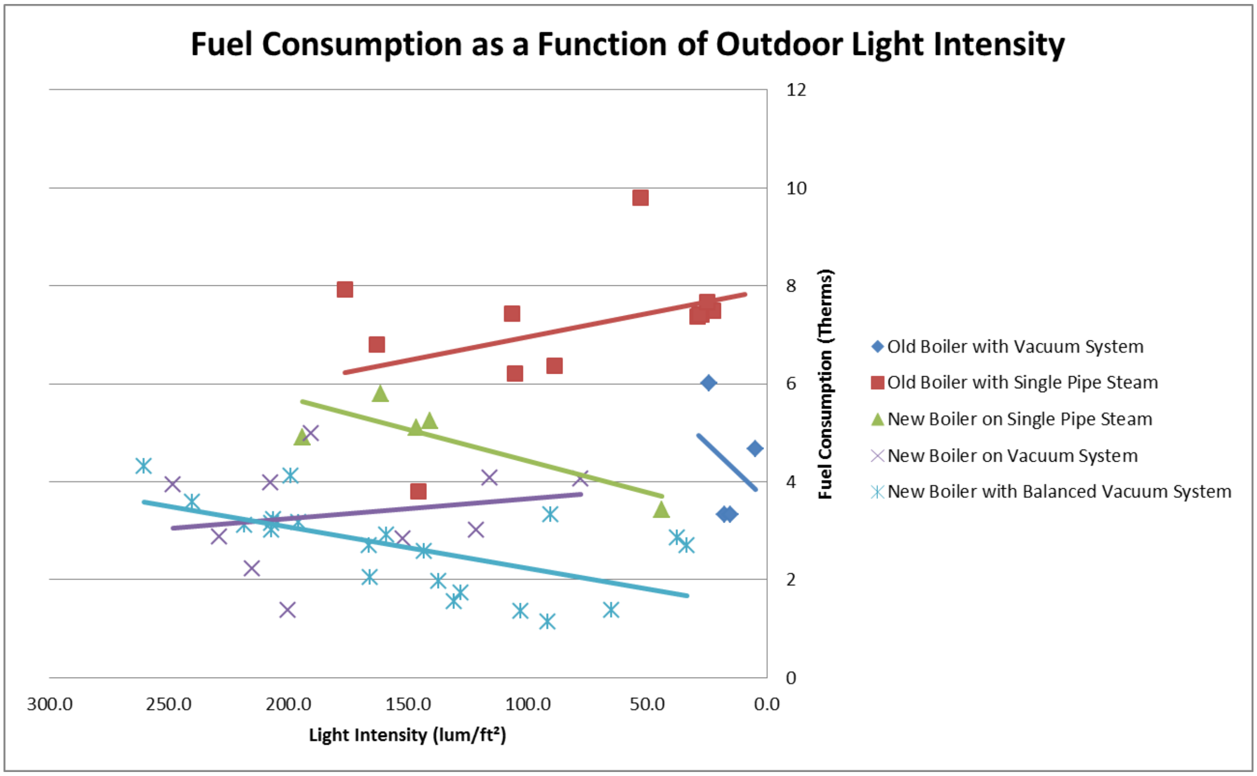


Figure 4: Fuel consumption as a function of outdoor light intensity per day

Figure 4 shows that the outdoor light intensity does not have the same linear effect on the fuel consumption as the outdoor air temperature (Figure 3) does. We can make this correlation because on days that have significantly different light intensities the fuel consumption can remain constant because the outdoor temperature was the same.

Since there is such a strong linear relationship between the fuel consumption and outdoor air temperature, a linear regression analysis was performed on the couplet of information to develop an equation for each test set. These equations were utilized to quantify average predicted daily fuel consumption values across a bin data set of Boston, MA compiled from the most recent TMY3 data[2].

[2] BinMaker® PRO Version 3.0.2 – Climatic Design Data © licensed from ASHRAE

daily average temperature as a predictor for heating consumption							
Mid-pts	Min DB (F)	Max DB (F)	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
			(Therms)	(Therms)	(Therms)	(Therms)	(Therms)
107.5	105	110	-9.49	0.17	4.82	-5.12	-3.75
102.5	100	105	-8.43	0.45	4.82	-4.55	-3.29
97.5	95	100	-7.38	0.73	4.81	-3.98	-2.84
92.5	90	95	-6.33	1.01	4.80	-3.42	-2.38
87.5	85	90	-5.28	1.28	4.79	-2.85	-1.92
82.5	80	85	-4.22	1.56	4.79	-2.28	-1.47
77.5	75	80	-3.17	1.84	4.78	-1.71	-1.01
72.5	70	75	-2.12	2.12	4.77	-1.14	-0.56
67.5	65	70	-1.06	2.40	4.77	-0.58	-0.10
62.5	60	65	0.00	2.67	4.76	0.00	0.36
57.5	55	60	1.04	2.95	4.75	0.56	0.81
52.5	50	55	2.09	3.23	4.74	1.13	1.27
47.5	45	50	3.15	3.51	4.74	1.70	1.73
42.5	40	45	4.20	3.79	4.73	2.26	2.18
37.5	35	40	5.25	4.06	4.72	2.83	2.64
32.5	30	35	6.31	4.34	4.72	3.40	3.10
27.5	25	30	7.36	4.62	4.71	3.97	3.55
22.5	20	25	8.41	4.90	4.70	4.54	4.01
17.5	15	20	9.46	5.17	4.69	5.10	4.46
12.5	10	15	10.52	5.45	4.69	5.67	4.92
7.5	5	10	11.57	5.73	4.68	6.24	5.38
2.5	0	5	12.62	6.01	4.67	6.81	5.83
-2.5	-5	0	13.68	6.29	4.67	7.38	6.29
-7.5	-10	-5	14.73	6.56	4.66	7.94	6.75

Figure 5: Midpoints of 5 degree temperature bins to predict average daily fuel consumption

Figure 5 shows us the average predicted fuel consumption at the midpoints for 5 degree temperature bin data. The data above the midpoint temperature of 62.5°F is grayed out as the heating system should be operating above 65°F outdoor air temperature. The cells below negative 2.5°F are grayed out because there were no hours recorded in the TMY3 bin data for Boston, MA that met those conditions.

Once the daily average consumption values were determined for the midpoint conditions a generic heating profile for a building of 1,150 square feet was utilized to determine that there were approximately 4,271 heating hours over the course of a TMY3 year. Based on that information, annual fuel consumption for heating the facility was generated.

Yearly heating therm consumption based upon daily average temperature and heating consumption								
Mid-pts	Min DB (F)	Max DB (F)	Assumed Heating Hours	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
			(Hours)	(Therms)	(Therms)	(Therms)	(Therms)	(Therms)
72.5	70	75	0	0.00	0.00	0.00	0.00	0.00
67.5	65	70	0	0.00	0.00	0.00	0.00	0.00
62.5	60	65	0	0.00	0.00	0.00	0.00	0.00
57.5	55	60	83	3.60	10.21	16.43	1.93	2.81
52.5	50	55	227	19.81	30.55	44.87	10.66	12.01
47.5	45	50	428	56.13	62.55	84.47	30.23	30.78
42.5	40	45	714	124.97	112.61	140.70	67.34	64.93
37.5	35	40	956	209.26	161.85	188.11	112.79	105.12
32.5	30	35	655	172.11	118.47	128.69	92.78	84.48
27.5	25	30	551	168.95	106.04	108.09	91.09	81.54
22.5	20	25	344	120.57	70.19	67.38	65.01	57.45
17.5	15	20	234	92.28	50.45	45.76	49.76	43.53
12.5	10	15	37	16.21	8.41	7.23	8.74	7.59
7.5	5	10	38	18.32	9.07	7.41	9.88	8.51
2.5	0	5	4	2.10	1.00	0.78	1.13	0.97
-2.5	-5	0	0	0.00	0.00	0.00	0.00	0.00
-7.5	-10	-5	0	0.00	0.00	0.00	0.00	0.00
Totals			4,271	1,004.34	741.40	839.92	541.35	499.74

Figure 6: TMY3 bin hours are used to predict yearly fuel consumption for heating

Figure 6 breaks down the predicted fuel consumption of each heating system based upon its midpoint temperature estimated and the hours in that temperature band. As the test data showed there is a significant improvement between the base case existing single pipe steam and very old steam boiler and the VSH system and a new higher efficiency steam boiler. Again cells above the 62.5°F midpoint and below the 2.5°F midpoint were not relevant to the study as there are either no heating hours in the temperature bands or the heating system should be off. There is one negative value in this chart; this value is carried over from the linear regression that was performed to develop the consumption equations. Since a boiler cannot generate natural gas it was not included in the calculation.

The savings for each test case is show below.

System Comparison	Predicted Consumption (Therms)	Percent Savings
Old Boiler - Single Pipe Steam	1,004	
Old Boiler - Vacuum System	741	26.2%
New Boiler - Single Pipe Steam	840	
New Boiler - Vacuum System	541	35.5%
Old Boiler - Single Pipe Steam	1,004	
New Boiler - Single Pipe Steam	840	16.4%
Old Boiler - Vacuum System	741	
New Boiler - Vacuum System	541	27.0%
New Boiler - Vacuum System	541	
New Boiler - Balanced Vacuum	500	7.7%
Old Boiler - Single Pipe Steam	1,004	
New Boiler - Balanced Vacuum	500	50.2%

Figure 7: Study Results showing percent savings between test cases

Figure 7 shows the percent savings based upon the analysis methodology described above. The savings range from 7.7% up to 50.2% depending on what type of a system change the facility undergoes. In many cases facilities will likely either utilize the “Old Boiler – Single Pipe Steam vs. Old Boiler – Vacuum System” comparison which in this specific test showed 26.2% savings.

In conjunction with the fuel savings associated with the VSH system installation there is a small electric penalty for the run hours of the vacuum pump. The pump was monitored for 29 days to record its change of state (pump on/pump off) to determine its total run time per day. Over the course of the 29 days it averaged 1:59.54 hours of run time. Extrapolating the run time out over the course of the 178 day heating season (as per the TMY3 midpoint heating hours) the vacuum pump will consume 163.58 kWh of electricity. The cost to run this pump is approximately $24.54 per year[3].

[3] $0.15 / kWh = “all-in” electric cost

VII. Explanation of Energy Savings

The predicted energy savings varies widely based on the system installed. As each scenario is independent from one another, a number of factors contribute to a reduction in the quantity of natural gas consumed by the boiler and measured at the meter. The following section of the study may be used as verification of energy savings and dissemination of such factors.

Savings were separated into the following categories for each of the scenarios reviewed

- Combustion Efficiency
- Boiler Standby Losses
- Off-cycle Losses
- Air removal

Other considerations in the categories above include:

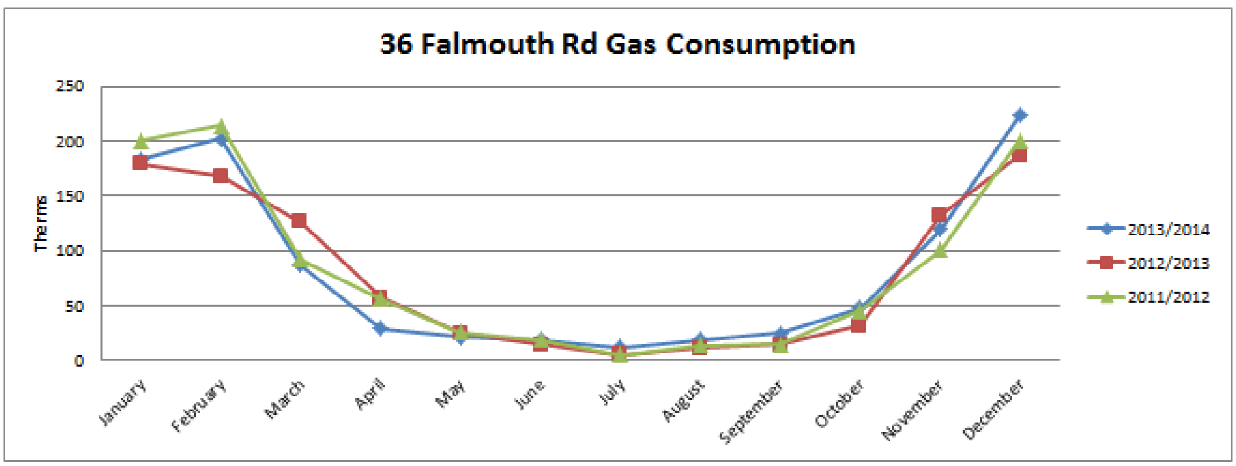
- Piping Losses
- Cycling
- Condensate Return

A general summary / breakout of energy savings is shown below. While not exact, energy savings seen at the meter are related to those derived using monitored data points.

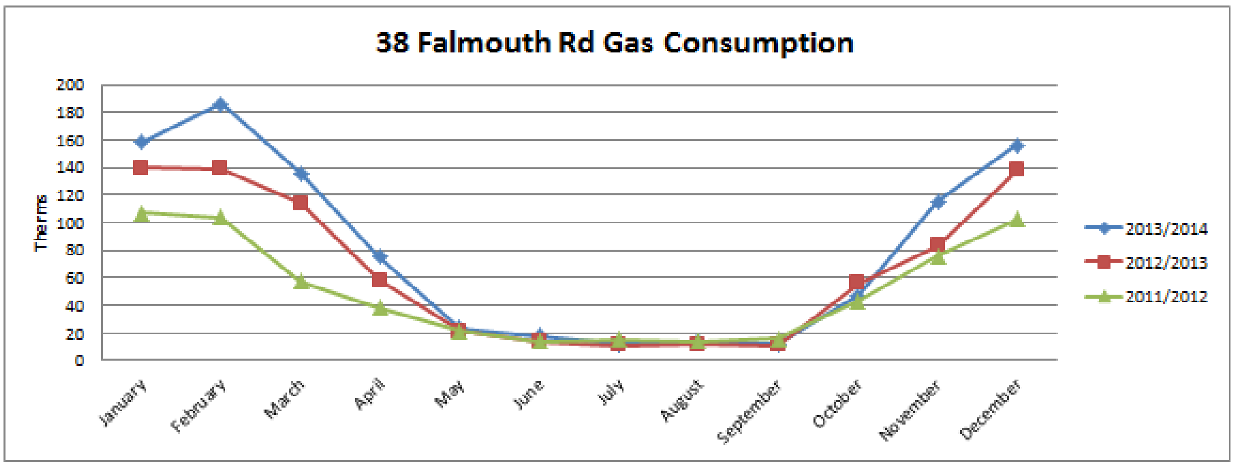
System Comparison	Derived from Fuel Metering		Quantified Using Data from Loggers				
	Predicted Consumption (Therms)	Percent Savings	Combustion Efficiency	Boiler Standby Losses	Off-cycle losses	Energy to Remove Air / Warm up pipes	Estimated Total Savings
Old Boiler - Single Pipe Steam	1,004.34	0%	0%	0%	0%	0%	0%
Old Boiler - Vacuum System	741.40	26%	2%	0%	14%	13%	29%
New Boiler - Single Pipe Steam	839.92	16%	16%	1%	-6%	3%	13%
New Boiler - Vacuum System	541.35	46%	16%	1%	20%	8%	45%
New Boiler - Balanced Vacuum System	499.74	50%	16%	1%	27%	6%	50%
Base	1,004.34	0%	0%	0%	0%	0%	0%

As the space being monitored is the second story of a residentially constructed building, any modifications to temperature set-points or occupancy conditions in the unit below could have a direct effect on the heat load of the evaluated unit. The fuel consumed by the boiler supplying heat to Unit #38 and other specific parameters were not monitored as part of this study. Historic fuel consumption for each of the units is shown below.

Account number	5084225481									
Address	36 Falmouth Rd, Newton MA									
Year	2013/2014			2012/2013			2011/2012			30 yr DD
Month	Date	Therms	DD	Date	Therms	DD	Date	Therms	DD	
January	2/1/2014	183	1,159	2/1/2013	179	1,033	2/1/2012	200	951	1,104
February	3/1/2014	202	1,007	3/1/2013	168	944	3/1/2012	214	801	951
March	4/1/2014	87	977	4/1/2013	126	841	4/1/2012	92	572	815
April	5/1/2014	29	502	5/1/2013	57	480	5/1/2012	56	366	503
May	6/1/2014	21	210	6/1/2013	25	221	6/1/2012	26	173	233
June	7/1/2014	19	28	7/1/2013	15	26	7/1/2012	19	76	48
July	8/1/2013	12	2	8/1/2012	5	0	8/1/2011	5	0	4
August	9/1/2013	19	0	9/1/2012	11	0	9/1/2011	14	0	8
September	10/1/2013	25	88	10/1/2012	15	73	10/1/2011	15	44	84
October	11/1/2013	48	266	11/1/2012	32	265	11/1/2011	45	252	344
November	12/1/2013	119	667	12/1/2012	132	676	12/1/2011	101	431	604
December	1/1/2014	223	972	1/1/2013	187	816	1/1/2012	200	770	932
Annual		987	5,878	Annual	952	5,375	Annual	987	4,436	5,630



Account number	5084225541									
Address	38 Falmouth Rd, Newton MA									
Year	2013/2014			2012/2013			2011/2012			30 yr DD
Month	Date	Therms	DD	Date	Therms	DD	Date	Therms	DD	
January	2/1/2014	158	1,159	2/1/2013	140	1,033	2/1/2012	107	951	1,104
February	3/1/2014	186	1,007	3/1/2013	139	944	3/1/2012	104	801	951
March	4/1/2014	136	977	4/1/2013	114	841	4/1/2012	57	572	815
April	5/1/2014	75	502	5/1/2013	58	480	5/1/2012	38	366	503
May	6/1/2014	23	210	6/1/2013	21	221	6/1/2012	21	173	233
June	7/1/2014	18	28	7/1/2013	14	26	7/1/2012	14	76	48
July	8/1/2013	12	2	8/1/2012	11	0	8/1/2011	15	0	4
August	9/1/2013	14	0	9/1/2012	12	0	9/1/2011	14	0	8
September	10/1/2013	12	88	10/1/2012	11	73	10/1/2011	16	44	84
October	11/1/2013	47	266	11/1/2012	56	265	11/1/2011	43	252	344
November	12/1/2013	115	667	12/1/2012	83	676	12/1/2011	76	431	604
December	1/1/2014	156	972	1/1/2013	138	816	1/1/2012	102	770	932
Annual		952	5,878	Annual	797	5,375	Annual	607	4,436	5,630



Normalized Gas Consumption - Unit #38											
Base			2013/2014			2012/2013			2011/2012		
Month	Days	Base Load	Heating	DD	Normalized	Heating	DD	Normalized	Heating	DD	Normalized
January	31	14	144	1159	137.4	126	1033	134.9	93	951	108.2
February	28	12	174	1007	163.9	127	944	127.5	92	801	108.7
March	31	14	122	977	101.9	100	841	97.1	43	572	61.5
April	30	13	62	502	61.8	45	480	46.8	25	366	33.9
May	31	14	9	210	10.2	7	221	7.6	7	173	9.7
June	30	15	0	28	0.0	0	26	0.0	0	76	0.0
July	31	13	0	2	0.0	0	0	0.0	0	0	0.0
August	31	13	0	0	0.0	0	0	0.0	0	0	0.0
September	30	13	0	88	0.0	0	73	0.0	0	44	0.0
October	31	14	33	266	42.9	42	265	54.8	29	252	39.9
November	30	13	102	667	92.0	70	676	62.2	63	431	87.8
December	31	14	142	972	136.3	124	816	141.8	88	770	106.7
Annual	365	163	788	5878	746	641	5375	673	440	4436	556

Normalized gas consumption associated with heating Unit #38 is depicted above. It should be noted that the site consumed approximately 11% more gas during 2013/2014 than in 2012/2013 when normalized for local weather conditions. This could be due to differences in temperature set-points at the thermostat or due to less heat being delivered indirectly from the steam system supplying Unit #36.

As part of this evaluation, the existing antiquated steam boiler was replaced with a new Peerless natural gas fired atmospheric cast iron sectional steam boiler. This four (4) section residential boiler features a spark ignition and a gross heating capacity of 147,000 BTU/hr. The original (approximately 100 years old) American Radiator Company boiler, as seen in the picture below on the left, had been retrofit with a Janitrol atmospheric natural gas conversion burner with a net input rating of 325,000 BTU/hr.

AHRI CERTIFIED	Series 63™												
Model Number	Input, MBH	Heating Capacity[3], MBH		Net Ratings[1]			Standing Pilot AFUE[3]		Spark Ignition AFUE[3]		Water Content		Approx. Shipping Weight, lb
		Water	Steam	Steam, sqft	Steam, MBH	Water, MBH	Water, %	Steam, %	Water, %	Steam, %	Water, gal	Steam, gal	
63-04	177	148	147	458	110	129	82.1	81	83.4	82.4	15.6	10.8	576

1 Net Ratings are based on DOE Heating Capacity less an allowance for normal piping and pickup as determined by the Testing and Rating Standard for Low Pressure Cast Iron Heating Boilers of the Hydronics Institute. Water ratings are based on a piping and pickup factor of 1.15. Steam ratings are based on a piping and pickup factor of 1.33. Consult PB Heat before selecting a boiler for gravity hot water installations or for installations having unusual piping and pickup requirements such as exposed piping, night set-back, etc. Ratings shown are for elevations up to 2,000 feet. For elevations above 2,000 feet, ratings should be reduced at the rate of 4% for each 1,000 feet above sea level.

2 Minimum Natural Gas Inlet Pressure exceptions: 63-04 STDG 5.3"; 63-06 STDG 5.5"; 63-06 SPRK 5.3".

3 Heating Capacity and Annual Fuel Utilization Efficiency (AFUE) ratings are based on U.S. Government tests. Before purchasing this appliance, read important information about its estimated annual energy consumption or energy efficiency rating that is available from your retailer.

a. Combustion Efficiency

Combustion Efficiency is a measure of how effectively the heat content of a fuel is transferred into usable heat. The stack temperature and flue gas oxygen (or carbon dioxide) concentrations are primary indicators of combustion efficiency.[4]

Installation of the new steam boiler is expected to have a large increase in the combustion efficiency of the overall system. The existing / original steam boiler was spot tested by RISE Engineering using a hand-held combustion analyzer displaying % oxygen, stack gas temperature and boiler efficiency. The analyzer displayed the following results while on single-pipe steam:

Combustion Efficiency Readings: SPS on 2/12/14			
Excess O2	14.5%	14.3%	14.4%
Stack Temperature (F)	450	495	504
Ambient Air Temperature (F)	41.7	43.3	
Net Stack Temperature (F)	408.3	451.7	
Combustion Efficiency	64.0%	64.0%	63.6%

The stack temperature for all systems was measured using 10 second increment data provided by Igor. Data was provided for each monitored day. An average temperature was developed for each day during times when the boiler system was determined to be operating. Combustion air was supplied to the burner from the ambient basement air. Average daily basement temperatures are utilized as the combustion air temperature.

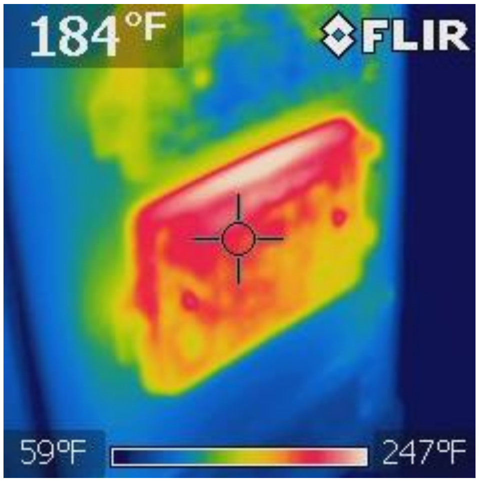
Excess %O2 in the stack was not measured on an incremental basis. The average excess %O2 for the existing boiler is approximately 14% based on spot measurements. The new boiler is predicted to be capable of firing at 10% excess O2 based on manufacturer's specifications. Excess O2 levels are kept the same between SPS and VSH when the using the same boiler as modifications were not made to the burner. Given this information and average flue gas and combustion air temperatures, the combustion efficiency for each of the heating scenarios is shown below. Available heat was calculated using the US Department of Energy's Process Heating Assessment and Survey Tool (PHAST) Version 3.0. There are slight combustion efficiency gains when switching between SPS and VSH (given the same boiler) due to a reduction in the overall net stack temperature.

Heating Scenario	Average Indoor Temperature (Deg F)	Average Stack Temperature (across all hours) - Deg. F	Average FGT when Blr On - Deg. F	Max. Stack Temperature	Average Basement Temperature	Excess O2:	Available Heat (% of HHV)	% Fuel Savings
Old Boiler Single Pipe Steam	65.96	197.83	477.10	515.93	63.24	14%	69.80%	0.0%
Old Boiler with Vac. System	65.78	167.64	451.19	505.89	62.97	14%	71.27%	2.1%
New Boiler Single Pipe Steam	66.51	200.39	326.71	361.24	60.38	10%	82.94%	15.8%
New Boiler Vac. System	66.11	144.40	316.86	360.09	59.04	10%	83.29%	16.2%
New Boiler Balanced Vac. System	66.25	129.39	320.76	362.23	59.86	10%	83.16%	16.1%

The % fuel savings all assume that the SPS with the original boiler is the "base" scenario.

[4] Advanced Manufacturing Office, Energy Efficiency and Renewable Energy, U.S. Department of Energy

b. Boiler Standby Losses



Boilers experience heat loss due to the boiler giving off heat by radiation and convection to the surroundings. This occurs because the temperate of the boiler jacket is greater than the air. The amount of jacket loss is determined largely by the surface area, surface temperature, and ambient temperature. [5]While the calculation to quantify the exact losses due to radiation and convection is complex, an acceptable approximation is considered to be 1.5% - 2% of the input rate.[6]

This percentage does not change with the load on the boiler so an oversized unit will have a greater reduction in performance efficiency.[7] With this in mind, it is apparent that the new boiler should have energy savings from a reduction in the input as well as it having a smaller surface area. It is also evident that the original boiler is currently oversized which would attribute more energy savings from reducing jacket losses to the new boiler. Additionally, the systems operating on a vacuum should also have energy savings because the temperature at which the water boils is reduced. This would reduce the surface temperature of the boiler, thus reducing jacket losses further.

As seen in the thermal image above, the original boiler's door is poorly insulated and transferring valuable energy to the ambient space. The average external temperature of the original steam boiler was measured at 113 °F versus 72 °F with the new boiler.

For the purpose of this analysis, 1.5% of the net input is assumed to be equivalent to the standby losses. No additional savings are attributed to scenarios in which the VSH is employed.

Boiler	Old	New
Input	325,000.00	177,000.00
Standby Loss	1.5%	1.5%
Standby Loss	4,875.00	2,655.00
% savings	0%	0.68%

The new boiler is estimated to save 0.68% of the base fuel consumption when compared to the original boiler.

[5] India. Bureau of Energy Efficiency, *Energy Performance of Boilers* http://beeindia.in/energy_managers_auditors/documents/guide_books/4Ch1.pdf (August 2014)
[6] Steve Dotty, *Commercial Energy Auditing Reference Handbook* (Lilburn: Fairmont Press, 2011), 347.
[7] Canada. Natural Resources Canada, *Radiation, Convection, and Other Losses* http://www.nrcan.gc.ca/energy/efficiency/industry/technical-info/tools/boilers/5429 (August 2014)

c. Off-cycle Losses

Just as the various scenarios experienced a reduction in energy during operating (firing) conditions, the system also saves energy while the burner is not firing. Energy lost up the boiler flue during off-cycle conditions was quantified for each of the five (5) tested conditions. The draft was greatly affected between the SPS and VSH due to the large reduction in average stack temperature. A summary of savings is presented below.

Stack Draft Effect	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
Volumetric Air Flow Requirements for Combustion - CFM	53.6	53.6	29.2	29.2	29.2
Stack Diameter (feet)	0.6	0.6	0.6	0.6	0.6
Stack Area (square feet)	0.3	0.3	0.3	0.3	0.3
Stack Height (ft)	30.0	30.0	30.0	30.0	30.0
Gravitation Acceleration (ft/s^2)	32.2	32.2	32.2	32.2	32.2
Discharge coefficient C	0.65	0.65	0.65	0.65	0.65
Average Stack Temperature (Degree F)	197.8	167.6	200.4	144.4	129.4
Average Stack Temperature (Degree R)	657.5	627.3	660.1	604.1	589.1
Average Outside Air Temperature During Run Hours (Degree F)	66.0	65.8	66.5	66.1	66.3
Average Outside Air Temperature During Run Hours (Degree R)	525.6	525.5	526.2	525.8	525.9
Average Combustion Air Temperature (Deg F)	63.2	63.0	60.4	59.0	59.9
Q (Stack Effect Draft Flow Rate) ft^3/s	3.4	3.1	3.4	2.7	2.5
Q (Stack Effect Draft Flow Rate) cfm	205.2	184.6	206.3	164.9	150.0
Off-cycle hours / year (Hrs On - FLRH)	2130.0	2210.9	1964.5	2133.2	2156.7
cubic feet / year of air required for combustion	6,844,698	7,104,681	3,438,073	3,733,293	3,774,437
cubic feet / year of combustion air due to stack draft effect	26,220,529	24,489,081	24,319,412	21,109,678	19,408,765
Btu / yr required for combustion air	16,582,153	13,386,402	8,664,721	5,736,206	4,723,892
Btu / yr required for combustion air due to stack draft effect	63,522,576	46,141,508	61,290,419	32,435,022	24,291,018
Losses per year due to stack effect (btu/yr)	46,940,422	32,755,106	52,625,698	26,698,817	19,567,126
Savings %	0.0%	14.1%	-5.7%	20.2%	27.3%

The pictures below show the original steam boiler flue on the left and newly installed steam boiler and stack on the right.

d. Air Removal

Each heating cycle has a "warm-up" time associated with it. As the distribution system was converted from single pipe steam to the vacuum system there is a significant difference in the duration of the preliminary cycle. In all cases, the radiators operating as an SPS system took much longer to receive steam and get up to temperature.

As vented air and water vapor will technically transfer to the space within the building's shell, only stack energy lost attributed to increased run time was determined to be "energy savings." A breakout of these savings may be seen in the following six (6) tables. Each of the radiators had their preliminary heating cycle characteristic measured for each of the five (5) testing scenarios.

Upon review, it is evident that radiators connected to the SPS system take much longer to get up to temperature. The table below shows the average time the boiler needed to fire before the radiators started to get warmer than the ambient conditions. It is believed that most of the savings related to the warm up time is directly related to the elimination of the air vents.

Average Heat-up Time (Hours)					
Radiator	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
Living Room	0.62	0.15	0.46	0.13	0.21
Kitchen	0.35	0.14	0.24	0.12	0.19
Bedroom #1	0.41	0.16	0.31	0.13	0.21
Bedroom #2	0.48	0.17	0.33	0.13	0.20
Office	0.50	0.18	0.38	0.15	0.23
Dining Room	0.47	0.15	0.44	0.13	0.21

The following pages break out the energy savings associated with each radiator. Predicted % fuel savings are solely based on the fuel attributed to warming up that specific radiator.

Living Room	Old Boiler – Single Pipe Steam	Old Boiler – Vacuum System	New Boiler - Single Pipe Steam	New Boiler – Vacuum System	New Boiler – Balanced Vacuum System
Date Used	2/8/2014	1/29/2014	2/25/2014	3/6/2014	3/16/2014
Start Time	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End Time	4:31:30 AM	12:45:17 AM	4:13:21 AM	1:22:56 AM	4:29:15 AM
Average start up time (hrs)	1.07	0.34	0.54	0.23	0.33
Counter Start	2	0	0	0	0
Counter End	85	28	31	21	20
Counter Delta	83	28	31	21	20
Therms	1.494	0.504	0.558	0.378	0.36
Average OA Temp	26.9	24.9	28.7	23.7	34.0
Average Indoor Temp	65.96	65.78	66.51	66.11	66.25
	39.07	40.91	37.80	42.41	32.21
Heat up Time for LR	Air Vents				
Start	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End	4:04:30 AM	12:33:37 AM	4:08:21 AM	1:17:06 AM	4:21:35 AM
Total Time	0.62	0.15	0.46	0.13	0.21
Start Temp	17.3	16.5	17.1	16.3	16.2
End Temp	26.7	25.1	24.6	23.9	25.2
Delta Temp	9.4	8.6	7.5	7.6	9.0
Estimated Startup Savings (time based)	0%	44%	15%	46%	39%
Heat to space	69.8%	71.3%	82.9%	83.3%	83.2%
% fuel savings - annual	0.0%	12.6%	2.6%	7.7%	6.5%

Kitchen	Old Boiler – Single Pipe Steam	Old Boiler – Vacuum System	New Boiler - Single Pipe Steam	New Boiler – Vacuum System	New Boiler – Balanced Vacuum System
Date Used	2/8/2014	1/29/2014	2/25/2014	3/6/2014	3/16/2014
Start Time	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End Time	4:31:30 AM	12:45:17 AM	4:13:21 AM	1:22:56 AM	4:29:15 AM
Average start up time (hrs)	1.07	0.34	0.54	0.23	0.33
Counter Start	2	0	0	0	0
Counter End	85	28	31	21	20
Counter Delta	83	28	31	21	20
Therms	1.494	0.504	0.558	0.378	0.36
Average OA Temp	26.9	24.9	28.7	23.7	34.0
Average Indoor Temp	65.96	65.78	66.51	66.11	66.25
	39.07	40.91	37.80	42.41	32.21
Heat up Time for Kitchen	Air Vents				
Start	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End	3:48:40 AM	12:33:17 AM	3:55:41 AM	1:16:36 AM	4:20:55 AM
Total Time	0.35	0.14	0.24	0.12	0.19
Start Temp	19.3	18.9	19.6	18.1	18.6
End Temp	22.0	23.0	21.3	24.0	19.1
Delta Temp	2.7	4.1	1.7	5.8	0.5
Estimated Startup Savings	0%	20%	10%	22%	15%
Heat to space	69.8%	71.3%	82.9%	83.3%	83.2%
% fuel savings - annual	0.0%	5.7%	1.7%	3.7%	2.5%

Bedroom #1	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
Date Used	2/8/2014	1/29/2014	2/25/2014	3/6/2014	3/16/2014
Start Time	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End Time	4:31:30 AM	12:45:17 AM	4:13:21 AM	1:22:56 AM	4:29:15 AM
Average start up time (hrs)	1.07	0.34	0.54	0.23	0.33
Counter Start	2	0	0	0	0
Counter End	85	28	31	21	20
Counter Delta	83	28	31	21	20
Therms	1.494	0.504	0.558	0.378	0.36
Average OA Temp	26.9	24.9	28.7	23.7	34.0
Average Indoor Temp	65.96	65.78	66.51	66.11	66.25
	39.07	40.91	37.80	42.41	32.21
Heat up Time for BR1	Air Vents				
Start	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End	3:52:00 AM	12:34:07 AM	3:59:21 AM	1:17:06 AM	4:21:45 AM
Total Time	0.41	0.16	0.31	0.13	0.21
Start Temp	15.3	5.3	15.1	13.9	12.3
End Temp	20.3	11.5	24.1	22.7	18.5
Delta Temp	5.0	6.2	9.0	8.8	6.1
Estimated Startup Savings	0%	24%	10%	26%	19%
Heat to space	69.8%	71.3%	82.9%	83.3%	83.2%
% fuel savings - annual	0.0%	6.8%	1.6%	4.4%	3.2%

Bedroom #2	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
Date Used	2/8/2014	1/29/2014	2/25/2014	3/6/2014	3/16/2014
Start Time	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End Time	4:31:30 AM	12:45:17 AM	4:13:21 AM	1:22:56 AM	4:29:15 AM
Average start up time (hrs)	1.07	0.34	0.54	0.23	0.33
Counter Start	2	0	0	0	0
Counter End	85	28	31	21	20
Counter Delta	83	28	31	21	20
Therms	1.494	0.504	0.558	0.378	0.36
Average OA Temp	26.9	24.9	28.7	23.7	34.0
Average Indoor Temp	65.96	65.78	66.51	66.11	66.25
	39.07	40.91	37.80	42.41	32.21
Heat up Time for BR2	Air Vents				
Start	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End	3:56:10 AM	12:34:47 AM	4:00:31 AM	1:17:06 AM	4:21:25 AM
Total Time	0.48	0.17	0.33	0.13	0.20
Start Temp	17.9	18.5	18.6	16.3	17.1
End Temp	20.7	20.4	20.4	30.5	19.1
Delta Temp	2.8	1.9	1.8	14.1	2.0
Estimated Startup Savings	0%	29%	14%	33%	26%
Heat to space	69.8%	71.3%	82.9%	83.3%	83.2%
% fuel savings - annual	0.0%	8.4%	2.4%	5.5%	4.3%

Office	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
Date Used	2/8/2014	1/29/2014	2/25/2014	3/6/2014	3/16/2014
Start Time	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End Time	4:31:30 AM	12:45:17 AM	4:13:21 AM	1:22:56 AM	4:29:15 AM
Average start up time (hrs)	1.07	0.34	0.54	0.23	0.33
Counter Start	2	0	0	0	0
Counter End	85	28	31	21	20
Counter Delta	83	28	31	21	20
Therms	1.494	0.504	0.558	0.378	0.36
Average OA Temp	26.9	24.9	28.7	23.7	34.0
Average Indoor Temp	65.96	65.78	66.51	66.11	66.25
	39.07	40.91	37.80	42.41	32.21
Heat up Time for Office	Air Vents				
Start	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End	3:57:20 AM	12:35:47 AM	4:03:31 AM	1:18:16 AM	4:22:45 AM
Total Time	0.50	0.18	0.38	0.15	0.23
Start Temp	17.1	17.3	17.8	17.4	17.6
End Temp	33.2	21.0	32.2	20.0	19.7
Delta Temp	16.0	3.7	14.3	2.6	2.1
Estimated Startup Savings	0%	29%	11%	33%	26%
Heat to space	69.8%	71.3%	82.9%	83.3%	83.2%
% fuel savings - annual	0.0%	8.5%	2.0%	5.5%	4.3%

Dining Room	Old Boiler - Single Pipe Steam	Old Boiler - Vacuum System	New Boiler - Single Pipe Steam	New Boiler - Vacuum System	New Boiler - Balanced Vacuum System
Date Used	2/8/2014	1/29/2014	2/25/2014	3/6/2014	3/16/2014
Start Time	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End Time	4:31:30 AM	12:45:17 AM	4:13:21 AM	1:22:56 AM	4:29:15 AM
Average start up time (hrs)	1.07	0.34	0.54	0.23	0.33
Counter Start	2	0	0	0	0
Counter End	85	28	31	21	20
Counter Delta	83	28	31	21	20
Therms	1.494	0.504	0.558	0.378	0.36
Average OA Temp	26.9	24.9	28.7	23.7	34.0
Average Indoor Temp	65.96	65.78	66.51	66.11	66.25
	39.07	40.91	37.80	42.41	32.21
Heat up Time for Dining Room	Air Vents				
Start	3:27:30 AM	12:24:47 AM	3:41:01 AM	1:09:26 AM	4:09:15 AM
End	3:55:40 AM	12:33:57 AM	4:07:31 AM	1:17:06 AM	4:21:55 AM
Total Time	0.47	0.15	0.44	0.13	0.21
Start Temp	17.9	17.7	18.5	16.9	16.5
End Temp	58.5	20.3	27.0	33.5	22.5
Delta Temp	40.6	2.6	8.5	16.6	5.9
Estimated Startup Savings	0%	30%	3%	32%	24%
Heat to space	69.8%	71.3%	82.9%	83.3%	83.2%
% fuel savings - annual	0.0%	8.5%	0.4%	5.4%	4.1%

The air vents in single pipe steam (SPS) play a vital role in the operation of the heating system. Each radiator as well as the end of the main supply line has an air vent that performs three functions every cycle. When a cycle begins and steam begins to enter the system, the air vent must open in order to allow the air to be pushed out of the radiator by the steam. Once steam has filled the radiator, the air vent must close to prevent steam loss. Once the heating cycle ends, the air vent must then be opened to allow air back into the system. This is important to break the vacuum caused by condensing steam. If the vacuum isn't broken when the steam enters the system during the next heating cycle, water hammer can occur and may cause damage to the system. The air vents also perform the important function of closing if the radiators flood.[8]

Air vents are most likely to waste energy if they are clogged. Clogging occurs through use over time. Since the system is open to air, rust and mineral deposits build up in the system. When the system is venting, small flakes and particles can build up in the holes of the vent.[9] Over time, these deposits can clog up the air vents, reducing the venting capacity. This affects the efficiency because the time it takes for the air to be removed from the system is proportional to the time heat is emitted by the radiators. Therefore, all of the energy used by the boiler during the time attributed to the inefficiency of the venting would be considered wasted energy.

[8] Roy C.E. Ahlgren, "Low Pressure Steam Heating Systems," *Ashrae Journal* (January 1994): 54-70. ebscohost.com
[9] Dan Holohan, "Care and Feeding of Air Vents," http://www.oldhousejournal.com

VIII. Report Summary

The Vacuum Steam Heating system, as designed and implemented by Applied Engineering Consulting, appears to save a significant amount of natural gas with only a minor electric penalty. The savings range from as little as 7.7% savings up to 50.2% savings, depending on what the test scenario was. Based upon RISE Engineering's industry experience, a customer would most likely pursue the options which do not require steam boiler change out (retrofit). Using this scenario as a basis for savings a customer could expect, if upgrading from single pipe steam to the VSH system, between 20 to 28% fuel savings. The VSH system is theoretically infinitely scalable, with the only limiting factor being the size of the vacuum pump system required to hold the system at the required negative 24 inches of mercury.

Further testing, cost analysis, and code review should be performed to determine if the product is fully cost effective. In this test case, the customer did not use their existing high mass cast iron steam radiators for the vacuum system but rather low mass replacement units. While this is acceptable at the customer's residence, the capital cost to upgrade a facility with a completely new radiation system could be cost prohibitive. Beyond the potential cost issues, there was no testing performed to determine the efficiency gain by utilizing low mass radiators versus the high mass cast iron units.

There are alternatives to luxury steam radiators utilized in retrofit at a fraction of cost. Hot water panel radiators could potentially be utilized for vacuum heating after some modifications. Another valid option is cast aluminum steam radiators commonly used in Europe. Aluminum radiators' life span, warrantied to 10 years, can be exceeded significantly when operated under a vacuum.

If a customer decides to forgo replacement of their cast iron radiators their savings could be significantly different from the test data acquired here. Further, a building and plumbing code review would need to be performed to ensure that the methodologies utilized to operate the test system are code compliant.

If you have any questions with the material presented in this report please contact Jean-Paul Vandeputte at RISE Engineering by calling 800-843-3636 or by email at JPVandeputte@Thielsch.com.

Recommendations made in this report are based on engineering estimates and third party information. Costs and saving are not guaranteed. It is recommended that the customer obtain a proposal and firm price from a qualified contractor for recommended measures before making final decisions about a course of action. Any change in the measure, equipment size or efficiency may change or eliminate the estimated fuel savings.

IX. Appendices

a. Pulse Data to Therm Conversion

Applied Engineering Consulting installed a pulse recorder on the Elster gas meter. This pulse recorder would generate a pulse that was recorded into the data acquisition system. A pulse would be generated each time the magnetron in the pulse meter sensed that the gas meter had recorded 0.05 m^3 of natural gas had been consumed by the boiler. This was converted into therms to ensure that the pulse meter was recording data that would match what National Grid was billing the customer for gas consumed. The meter that National Grid was generating bills for served the entire apartment including the boiler and other gas equipment, while the secondary meter that was being monitored was an additional unit reading only consumption by the boiler. The National Grid bills can be seen below; in particular we are concerned about March 2014 (February 5^{th} through March 7^{th}).

View Customer Usage Premise No:- 508422548 - IGOR ZHADANOVSKY

Account Header | History | Usage | Applications |

Gas Usage Data

Bill Month and Year	Latest Meter Read Date	No Of Billing Days	Actual Therms
May 2014	May 07,2014	30	29
Apr 2014	Apr 07,2014	31	87
Mar 2014	Mar 07,2014	31	202
Feb 2014	Feb 04,2014	28	185
Oct 2013	Oct 04,2013	25	25
Sep 2013	Sep 09,2013	35	19
Aug 2013	Aug 05,2013	28	12
Jul 2013	Jul 08,2013	28	15
Jun 2013	Jun 10,2013	35	25

March's bill was for 202 therms of natural gas. Since the customer typically consumes around 25 therms of natural gas during the summer months (a base line consumption where the boiler should not be running) the heating only consumption for the March bill should be around 175 therms of natural gas. The pulse output data, which does not include 8 days, is shown below.

	Number of Clicks from daily summary sheets	Therms Consumed based on .05m3 per pulse Therms = ((Pluse count)*0.05m^3)*0.36 Therm/m^3	m^3 consumption based upon pulse data
1/29/2014	185		
1/30/2014	334	6.012	16.7
1/31/2014	0	0	0
2/1/2014	0	0	0
2/2/2014	185	3.33	9.25
2/3/2014	260	4.68	13
2/4/2014	0	0	0
2/5/2014		0	0
2/6/2014		0	0
2/7/2014	416	7.488	20.8
2/8/2014	412	7.416	20.6
2/9/2014	409	7.362	20.45
2/10/2014	412	7.416	20.6
2/11/2014	426	7.668	21.3
2/12/2014	413	7.434	20.65
2/13/2014		0	0
2/14/2014		0	0
2/15/2014	354	6.372	17.7
2/16/2014	378	6.804	18.9
2/17/2014	440	7.92	22
2/18/2014	544	9.792	27.2
2/19/2014	345	6.21	17.25
2/20/2014	211	3.798	10.55
2/21/2014		0	0
2/22/2014		0	0
2/23/2014		0	0
2/24/2014	191	3.438	9.55
2/25/2014	273	4.914	13.65
2/26/2014	284	5.112	14.2
2/27/2014	322	5.796	16.1
2/28/2014	291	5.238	14.55
3/1/2014		0	0
3/2/2014	226	4.068	11.3
3/3/2014	168	3.024	8.4
3/4/2014	277	4.986	13.85
3/5/2014	227	4.086	11.35
3/6/2014	219	3.942	10.95
3/7/2014	221	3.978	11.05
3/8/2014	124	2.232	6.2
3/9/2014	160	2.88	8
3/10/2014	158	2.844	7.9
3/11/2014	77	1.386	3.85
3/12/2014		0	0
3/13/2014	199	3.582	9.95
3/14/2014	240	4.32	12
3/15/2014	114	2.052	5.7
3/16/2014	173	3.114	8.65
3/17/2014	180	3.24	9
3/18/2014	167	3.006	8.35
3/19/2014	162	2.916	8.1
3/20/2014	87	1.566	4.35
3/21/2014	96	1.728	4.8
3/22/2014	110	1.98	5.5
3/23/2014	143	2.574	7.15
3/24/2014	175	3.15	8.75
3/25/2014	150	2.7	7.5
3/26/2014	185	3.33	9.25
3/27/2014	176	3.168	8.8
3/28/2014	76	1.368	3.8
3/29/2014	64	1.152	3.2
3/30/2014	150	2.7	7.5
3/31/2014	159	2.862	7.95
4/1/2014	229	4.122	11.45
4/2/2014	77	1.386	3.85

Less the 8 days that do not have data, the boiler consumed 134 therms of natural gas. When you utilize the average natural gas consumption per day to populate in the missing cells (Average = 5.83 Therms/Day) the total consumption by the boiler becomes 180 therms. Since 180 therms + 25 therms = 205 therms, RISE Engineering is led to believe that the pulse meter was recording data accurately, and that the correct conversion value from Pulse counts to actual consumption is $0.05m^3$ of natural gas.

b. Costing Information

The project costs are as show below. These costs were supplied by Applied Engineering Consulting.

Boiler		$3,000.00
installation		$1,850.00
	Subtotal	$4,850.00

Plumbing		
lines from basement to 2nd floor		$1,500.00
lines in basement		$800.00
	Subtotal	$2,300.00

Materials		
fittings		$800.00
tubing		$180.00
Insulation		$330.00
	Subtotal	$1,310.00

Radiators	$5,200.00
Controls	$474.00
Vacuum pump	$395.00

Total Project Cost	$14,529.00

The two major project types that could be seen for this type of installation is to either; convert an existing steam system to a VSH which would cost $9,679 (does not include cost of new boiler), or to convert an existing system to VSH and add a new boiler too $14,529. Utilizing the predicted savings from the report a simple pay back analysis was performed.

System Comparison	Predicted Consumption (Therms)	Cost of gas at $1.15/Therm	Savings ($)*	System Cost	Simple Payback (Years)
Old Boiler - Single Pipe Steam	1,004	$1,154.99	$189.08	$4,850.00	25.65
New Boiler - Single Pipe Steam	840	$965.91			
Old Boiler - Single Pipe Steam	1,004	$1,154.99	$277.84	$9,679.00	34.84
Old Boiler - Vacuum System	741	$852.61			
Old Boiler - Single Pipe Steam	1,004	$1,154.99	$507.90	$14,529.00	28.61
New Boiler - Vacuum System	541	$622.55			

*Penalty for increased electric consumption included

Based on the simple paybacks for this specific facility the projects would not pass a National Grid Benefit Cost Ratio (BCR) screening. A larger client could potentially generate the savings necessary to offset the project costs with their savings.

c. Daily outdoor average temperature

Hour of the Day	Average Temperature	Average Light Intensity (Lumens)	Fuel Consumption (Therms)	System
1/29/2014	24.9	17.6	3.33	Old Boiler with Vacuum System
1/30/2014	25.7	24.3	6.01	
1/31/2014	35.4	15.4		
2/1/2014	39.8	21.9		
2/2/2014	43.0	15.4	3.33	
2/3/2014	36.7	4.8	4.68	
2/4/2014	31.5	28.9		
2/5/2014	33.3	9.3		Old Boiler with Single Pipe Steam
2/6/2014	26.9	23.4		
2/7/2014	26.0	22.7	7.49	
2/8/2014	26.9	27.7	7.42	
2/9/2014	30.4	29.0	7.36	
2/10/2014	27.3	28.2	7.42	
2/11/2014	22.4	25.3	7.67	
2/12/2014	21.8	106.6	7.43	
2/13/2014	31.8	23.0		
2/14/2014	35.7	140.9		
2/15/2014	34.0	88.9	6.37	
2/16/2014	30.4	163.0	6.80	
2/17/2014	24.9	176.3	7.92	
2/18/2014	26.8	53.1	9.79	
2/19/2014	32.6	105.5	6.21	
2/20/2014	38.9	145.8	3.80	
2/21/2014	39.2	44.0		New Boiler on Single Pipe Steam
2/22/2014	41.3	194.4		
2/23/2014	42.5	146.5		
2/24/2014	35.7	161.8	3.44	
2/25/2014	28.7	141.1	4.91	
2/26/2014	26.3	139.1	5.11	
2/27/2014	25.0	154.3	5.80	
2/28/2014	22.1	211.1	5.24	
3/1/2014	27.7	191.5		

Hour of the Day	Average Temperature	Average Light Intensity (Lumens)	Fuel Consumption (Therms)	System
3/2/2014	36.9	77.9	4.068	New Boiler on Vacuum System
3/3/2014	26.1	121.5	3.024	
3/4/2014	25.0	190.8	4.986	
3/5/2014	28.5	116.1	4.086	
3/6/2014	23.7	248.6	3.942	
3/7/2014	29.4	207.8	3.978	
3/8/2014	40.3	215.3	2.232	
3/9/2014	36.6	229.0	2.88	
3/10/2014	38.5	152.2	2.844	
3/11/2014	45.0	200.5	1.386	
3/12/2014	43.2	79.9		
3/13/2014	26.4	240.2	3.582	New Boiler with Balanced Vacuum System
3/14/2014	31.0	260.5	4.32	
3/15/2014	44.7	165.9	2.052	
3/16/2014	34.0	218.4	3.114	
3/17/2014	27.0	206.5	3.24	
3/18/2014	31.3	207.4	3.006	
3/19/2014	36.6	159.3	2.916	
3/20/2014	43.4	130.9	1.566	
3/21/2014	40.3	128.2	1.728	
3/22/2014	42.0	137.5	1.98	
3/23/2014	38.1	143.4	2.574	
3/24/2014	28.0	207.4	3.15	
3/25/2014	33.3	166.2	2.7	
3/26/2014	33.0	90.7	3.33	
3/27/2014	34.9	195.9	3.168	
3/28/2014	47.2	102.9	1.368	
3/29/2014	46.6	91.9	1.152	
3/30/2014	41.7	33.5	2.7	
3/31/2014	39.3	37.6	2.862	
4/1/2014	43.9	199.2	4.122	
4/2/2014	38.4	64.9	1.386	

d. Daily indoor average temperature recorded at thermostat

Hour of the Day	Average Indoor Temperature (Deg F)	Fuel Consumption (Therms)	
1/29/2014	65.0	3.33	Old Boiler with Vacuum System
1/30/2014	65.7	6.01	
1/31/2014	65.4		
2/1/2014	66.1		
2/2/2014	66.1	3.33	
2/3/2014	66.3	4.68	
2/4/2014	65.0		
2/5/2014	66.1		Old Boiler with Single Pipe Steam
2/6/2014	66.4		
2/7/2014	66.2	7.49	
2/8/2014	66.0	7.42	
2/9/2014	65.9	7.36	
2/10/2014	66.0	7.42	
2/11/2014	66.0	7.67	
2/12/2014	65.5	7.43	
2/13/2014	66.0		
2/14/2014	66.4		
2/15/2014	66.2	6.37	
2/16/2014	66.0	6.80	
2/17/2014	No Data	7.92	
2/18/2014	No Data	9.79	
2/19/2014	No Data	6.21	
2/20/2014	No Data	3.80	
2/21/2014	No Data		New Boiler on Single Pipe Steam
2/22/2014	No Data		
2/23/2014	No Data		
2/24/2014	No Data	3.44	
2/25/2014	No Data	4.91	
2/26/2014	No Data	5.11	
2/27/2014	No Data	5.80	
2/28/2014	67.1	5.24	
3/1/2014	65.9		

Hour of the Day	Average Indoor Temperature (Deg F)	Fuel Consumption (Therms)	
3/2/2014	65.9	4.068	New Boiler on Vacuum System
3/3/2014	65.7	3.024	
3/4/2014	65.6	4.986	
3/5/2014	65.8	4.086	
3/6/2014	65.8	3.942	
3/7/2014	65.7	3.978	
3/8/2014	66.2	2.232	
3/9/2014	66.3	2.88	
3/10/2014	66.2	2.844	
3/11/2014	67.9	1.386	
3/12/2014	66.8		
3/13/2014	66.1	3.582	New Boiler with Balanced Vacuum System
3/14/2014	66.0	4.32	
3/15/2014	66.6	2.052	
3/16/2014	66.2	3.114	
3/17/2014	66.2	3.24	
3/18/2014	66.3	3.006	
3/19/2014	66.1	2.916	
3/20/2014	66.4	1.566	
3/21/2014	66.5	1.728	
3/22/2014	66.4	1.98	
3/23/2014	66.1	2.574	
3/24/2014	65.8	3.15	
3/25/2014	66.0	2.7	
3/26/2014	65.8	3.33	
3/27/2014	66.1	3.168	
3/28/2014	66.3	1.368	
3/29/2014	67.2	1.152	
3/30/2014	66.3	2.7	
3/31/2014	66.2	2.862	
4/1/2014	67.1	4.122	
4/2/2014	65.9	1.386	

e. Vacuum pump daily run time

Hour of the Day	Daily Run Time of Vacuum Pump (Hours)	Predicted Consumption of Vacuum Pump (kWh)	Fuel Consumption (Therms)	System
1/29/2014	0:00:00	0.000	3.33	Old Boiler with Vacuum System
1/30/2014	0:00:00	0.000	6.01	
1/31/2014	0:00:00	0.000		
2/1/2014	0:00:00	0.000		
2/2/2014	0:00:00	0.000	3.33	
2/3/2014	0:00:00	0.000	4.68	
2/4/2014	0:00:00	0.000		
2/5/2014	0:00:00	0.000		Old Boiler with Single Pipe Steam
2/6/2014	0:00:00	0.000		
2/7/2014	0:00:00	0.000	7.49	
2/8/2014	0:00:00	0.000	7.42	
2/9/2014	0:00:00	0.000	7.36	
2/10/2014	0:00:00	0.000	7.42	
2/11/2014	0:00:00	0.000	7.67	
2/12/2014	0:00:00	0.000	7.43	
2/13/2014	0:00:00	0.000		
2/14/2014	0:00:00	0.000		
2/15/2014	0:00:00	0.000	6.37	
2/16/2014	0:00:00	0.000	6.80	
2/17/2014	0:00:00	0.000	7.92	
2/18/2014	0:00:00	0.000	9.79	
2/19/2014	0:00:00	0.000	6.21	
2/20/2014	0:00:00	0.000	3.80	
2/21/2014	0:00:00	0.000		New Boiler on Single Pipe Steam
2/22/2014	0:00:00	0.000		
2/23/2014	0:00:00	0.000		
2/24/2014	0:00:00	0.000	3.44	
2/25/2014	0:00:00	0.000	4.91	
2/26/2014	0:00:00	0.000	5.11	
2/27/2014	0:00:00	0.000	5.80	
2/28/2014	0:00:00	0.000	5.24	
3/1/2014	0:00:00	0.000		

Hour of the Day	Daily Run Time of Vacuum Pump (Hours)	Predicted Consumption of Vacuum Pump (kWh)	Fuel Consumption (Therms)	System
3/2/2014	0:00:00	0.000	4.07	New Boiler on Vacuum System
3/3/2014	0:00:00	0.000	3.02	
3/4/2014	0:00:00	0.000	4.99	
3/5/2014	3:56:43	1.809	4.09	
3/6/2014	2:22:18	1.089	3.94	
3/7/2014	3:08:45	1.441	3.98	
3/8/2014	2:37:16	1.204	2.23	
3/9/2014	3:13:54	1.480	2.88	
3/10/2014	2:35:21	1.188	2.84	
3/11/2014	2:23:21	1.096	1.39	
3/12/2014	1:45:18	0.805		
3/13/2014	2:12:47	1.012	3.58	New Boiler with Balanced Vacuum System
3/14/2014	2:29:10	1.142	4.32	
3/15/2014	2:01:10	0.928	2.05	
3/16/2014	1:34:38	0.721	3.11	
3/17/2014	2:31:25	1.158	3.24	
3/18/2014	1:56:31	0.889	3.01	
3/19/2014	1:47:31	0.820	2.92	
3/20/2014	1:38:54	0.751	1.57	
3/21/2014	1:43:00	0.790	1.73	
3/22/2014	1:32:54	0.705	1.98	
3/23/2014	2:09:08	0.989	2.57	
3/24/2014	1:54:37	0.874	3.15	
3/25/2014	1:46:53	0.813	2.70	
3/26/2014	1:35:36	0.728	3.33	
3/27/2014	1:57:12	0.897	3.17	
3/28/2014	0:57:06	0.437	1.37	
3/29/2014	1:41:56	0.774	1.15	
3/30/2014	1:33:28	0.713	2.70	
3/31/2014	1:22:47	0.629	2.86	
4/1/2014	1:06:19	0.506	4.12	
4/2/2014	0:21:06	0.161	1.39	

f. TMY 3 midpoint data for heating for Boston, MA

				1	2	3	4	5	6	7	8	9	10	11	12
	Min DB	Max DB	Total	January	February	March	April	May	June	July	August	September	October	November	December
Mid-pts	(F)	(F)	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs	Hrs
107.5	105	110	0	0	0	0	0	0	0	0	0	0	0	0	0
102.5	100	105	0	0	0	0	0	0	0	0	0	0	0	0	0
97.5	95	100	0	0	0	0	0	0	0	0	0	0	0	0	0
92.5	90	95	0	0	0	0	0	0	0	0	0	0	0	0	0
87.5	85	90	0	0	0	0	0	0	0	0	0	0	0	0	0
82.5	80	85	0	0	0	0	0	0	0	0	0	0	0	0	0
77.5	75	80	0	0	0	0	0	0	0	0	0	0	0	0	0
72.5	70	75	0	0	0	0	0	0	0	0	0	0	0	0	0
67.5	65	70	0	0	0	0	0	0	0	0	0	0	0	0	0
62.5	60	65	0	0	0	0	0	0	0	0	0	0	0	0	0
57.5	55	60	83	3	0	11	27	0	0	0	0	0	0	26	16
52.5	50	55	227	14	0	30	83	0	0	0	0	0	0	70	30
47.5	45	50	428	4	11	57	155	0	0	0	0	0	0	130	71
42.5	40	45	714	38	81	89	251	0	0	0	0	0	0	169	86
37.5	35	40	956	101	165	241	122	0	0	0	0	0	0	161	166
32.5	30	35	655	143	135	176	31	0	0	0	0	0	0	79	91
27.5	25	30	551	208	99	77	18	0	0	0	0	0	0	34	115
22.5	20	25	344	142	81	30	0	0	0	0	0	0	0	13	78
17.5	15	20	234	76	87	29	0	0	0	0	0	0	0	13	29
12.5	10	15	37	15	9	0	0	0	0	0	0	0	0	0	13
7.5	5	10	38	0	4	0	0	0	0	0	0	0	0	0	34
2.5	0	5	4	0	0	0	0	0	0	0	0	0	0	0	4
-2.5	-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-7.5	-10	-5	0	0	0	0	0	0	0	0	0	0	0	0	0

g. Linear Regression data

Old Boiler with Vacuum System

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.381033098
R Square	0.145186222
Adjusted R Square	-0.282220667
Standard Error	1.454733238
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.718870413	0.718870413	0.339690879	0.618966902
Residual	2	4.232497587	2.116248794		
Total	3	4.951368			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.14698016	3.187876059	1.928236872	0.193629544	-7.569343467	19.86330379	-7.569343467	19.86330379
X Variable 1	-0.055568267	0.095342143	-0.58283006	0.618966902	-0.465792397	0.354655864	-0.465792397	0.354655864

Old Boiler with Single Pipe Steam

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.756392803
R Square	0.572130072
Adjusted R Square	0.529343079
Standard Error	0.949396042
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	12.05251956	12.05251956	13.37158876	0.004412973
Residual	10	9.01352844	0.901352844		
Total	11	21.066048			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	13.15000672	1.666246064	7.891995668	1.32611E-05	9.437379128	16.86263431	9.437379128	16.86263431
X Variable 1	-0.210575637	0.057585961	-3.65671831	0.004412973	-0.338885154	-0.08226612	-0.338885154	-0.08226612

New Boiler on Single Pipe Steam

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.047547508
R Square	0.002260766
Adjusted R Square	-0.330318979
Standard Error	1.015321892
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.007007567	0.007007567	0.006797665	0.939483451
Residual	3	3.092635633	1.030878544		
Total	4	3.0996432			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	4.668815589	2.835741892	1.646417681	0.198231627	-4.355780717	13.69341189	-4.355780717	13.69341189
X Variable 1	0.001429153	0.017334004	0.082447951	0.939483451	-0.053735385	0.056593691	-0.053735385	0.056593691

New Boiler on Vacuum System

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.78538362
R Square	0.616827431
Adjusted R Square	0.56893086
Standard Error	0.697878078
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6.272177905	6.272177905	12.87832128	0.007098531
Residual	8	3.896270495	0.487033812		
Total	9	10.1684484			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	7.091727974	1.067776625	6.641583837	0.000162217	4.629430661	9.554025286	4.629430661	9.554025286
X Variable 1	-0.113607256	0.031657487	-3.5886378	0.007098531	-0.186609553	-0.04060496	-0.186609553	-0.040604959

New Boiler with Balanced Vacuum System

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.65253133
R Square	0.425797136
Adjusted R Square	0.395575933
Standard Error	0.693893446
Observations	21

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6.783854964	6.783854964	14.08935082	0.001344955
Residual	19	9.148274178	0.481488115		
Total	20	15.93212914			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.061862013	0.916908624	6.611195329	2.51319E-06	4.142750207	7.980973819	4.142750207	7.980973819
X Variable 1	-0.091275858	0.024317025	-3.7535784	0.001344955	-0.142171976	-0.04037974	-0.142171976	-0.040379741