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Condensing Boilers Evaluation: Retrofit and New Construction Applications

Dylan Cutler

Jesse Dean

Jason Acosta

Dennis Jones

The Green Proving Ground program leverages GSA's real estate portfolio to evaluate innovative sustainable building technologies and practices. Findings are used to support the development of GSA performance specifications and inform decision-making within GSA, other federal agencies, and the real estate industry. The program aims to drive innovation in environmental performance in federal buildings and help lead market transformation through deployment of new technologies.

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For more information contact:

Energy and Environment Team
Facilities Management and Services Programs
Public Buildings Service - Rocky Mountain Region
U.S. General Services Administration
One Denver Federal Center
P.O. Box 25546 (8P2PM)
Denver, CO 80225-0546

Phone: (303)236 - 8000

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I. Executive Summary

A. Background

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) evaluated five condensing boiler plants on behalf of General Services Administration (GSA) Rocky Mountain Region (Region 8). Condensing boilers can increase the efficiency of a building's steady-state heating efficiency from 6% to 18% over standard boiler systems, depending on how the condensing boilers are designed, operated, and the efficiency of the existing boilers. GSA Region 8 has jurisdiction, custody, or control over approximately 615 federally owned and leased buildings throughout the region. Region 8 is generally a heating-dominated climate and the significant efficiency improvement available through correctly designed condensing boiler systems could achieve significant savings in operating costs and reduce energy consumption in buildings across the region.

This technology evaluation was carried out through observation, measurement, and verification (OM&V) of the performance of five different condensing boiler installations that had been deployed in various GSA buildings at the Denver Federal Center (DFC) in Lakewood, Colorado. The buildings evaluated were buildings: 25, 45, 54, 710a, and 810. The condensing boilers retrofits were completed in the summer of 2010. This report evaluates the design characteristics, operational efficiency, and life cycle cost effectiveness of the installations.

Nationwide, GSA owns and leases over 354 million square feet (ft^2) of space in 9,600 buildings[i]. This demonstration project was hosted by Region 8, yet it can serve to inform both the region and GSA nationwide on the appropriate use of condensing boiler installations. By evaluating the technical and economic feasibility of new ideas and technologies, such as energy efficient condensing boiler technology, GSA will be in a better position to select appropriate technology and drive innovation in environmental performance across the agency's portfolio.

GSA is a leader among federal agencies in aggressively pursuing energy efficiency opportunities for its facilities and installing renewable energy systems to heat and power these facilities. This is especially true in Region 8. The Energy Independence and Security Act of 2007 (EISA) established energy reduction goals for federal facilities, and mandated energy intensity reductions of 3% per fiscal year (FY) relative to a 2003 baseline.

B. What is the Technology?

Condensing boilers achieve higher efficiencies by condensing water vapor contained in flue gases. When natural gas is combusted in a boiler, approximately 90% of the energy contained in the fuel is converted into sensible heat (heat that causes a change in temperature) and approximately 10% is converted into latent heat (heat involved in phase change of a material). This latent heat is stored in the water vapor that is a byproduct of the combustion process.

In traditional boiler technology, the latent heat contained in the water vapor is allowed to escape in the flue gases. Condensing boilers reclaim that latent heat by condensing the water vapor and transferring that heat back into the return water. This process of condensing the water vapor can increase the steady-state efficiency of an average boiler from ≈80% to between 86% and 98% (depending on boiler operation)[ii]. For existing boilers, their operational efficiency will often be much lower than 80% due to pre- and post-purge during cycling and the high mass of older boilers. In 2001, the Consortium for Energy Efficiency produced a market analysis of condensing boilers[iii] that notes that condensing boilers achieve the high efficiencies discussed above and have high market penetration in Europe due to this, as well as other factors such as increased incentives and higher energy costs.

These potential efficiency gains can only be attained if the boiler is operating in "condensing" mode. Condensing mode is achieved when the temperature of the return water is below the dew point of the water vapor in the flue gas. For natural gas boilers in Denver's climate, the dew point is approximately 130°F. The dew point of the

water vapor in the exhaust is dependent on the altitude, temperature, and type of fuel. Generally, if the return water temperature is below approximately 130°F, the water vapor will start to condense and the system will achieve a higher efficiency. The lower the return water temperature, the more condensation occurs and higher efficiency is achieved. To reduce the return water temperature it is important to consider:

- The type of coils used in the system – higher delta T (ΔT) coils and coils designed to operate at lower supply water temperature will result in lower return water temperature.
- The piping design and valve selection – less bypass and mixing of supply and return water, as well as selection of two-way valves instead of three-way valves, will result in lower return water temperature. Two way control valves when combined with variable flow pumping will result in lower return water temperatures and less pumping energy use.
- Supply water temperature control – lowering the supply water temperature when the outdoor temperature is higher (outdoor air reset control) will still meet the building load, yet reduce return water temperature.

Condensing boilers offer the potential to reduce operating costs and save energy through the higher efficiencies attainable with the flue gas condensing technology. These savings are only realistically attained through appropriate system design and operation.

C. Study Design and Objectives

This study evaluates the performance of five separate condensing boiler installations at the DFC. The buildings evaluated were buildings: 25, 45, 54, 710a, and 810. Each of these buildings received a condensing boiler retrofit during the summer of 2010.

The objective of this demonstration is to:

- Evaluate the installed performance of the condensing boilers at the five buildings listed above.
- Identify best practices for condensing boiler installations.
- Develop a methodology for evaluating future designs and installations.
- Assess the economic performance of condensing boiler technology based on life cycle costing (LCC).
- Identify the potential to adopt condensing boilers within GSA region 8.

The overall goal of this report is to provide technical information and best practice guidance with regards to condensing boiler installation and operation. The field demonstrations will provide the necessary data to evaluate the technology's performance and will allow accurate comparison with non-condensing boilers, near-condensing boilers, and other available technologies.

The main parameters that will be evaluated in this study will be the installed performance of the boilers and the cost-effectiveness of the retrofits. The variable that has the largest single impact on the installed performance of the boilers is the configuration of the distributed heating system that the boiler is supplying. Therefore, the different heating systems in each building will be discussed and evaluated for effective pairing with the condensing boiler technology.

D. Project Results/Findings

Analysis of the utility bill data showed that all of the condensing boiler installations are realizing significant savings. These savings ranged from 16% to 41% reduction in energy use. This analysis included weather normalization to compare pre- and post-retrofit gas usage on equal grounds. The total estimated savings for the boiler projects was approximately 10,100 million British thermal units (MMBtus) in 2011.

The capital costs in this analysis were normalized to provide an economic assessment with typical installation costs (providing an average installed cost that was verified against available data sources, see pg. 46). The economic analysis was also completed for actual installation costs at the DFC, and can be viewed in the Utility Bill Analysis subsection located in the Results section (see pg. 24). The economic analysis demonstrated that all five of the projects had positive net present value (NPV) (using a 25-year lifetime) for the case where a boiler replacement was necessary. The standard replacement boiler in this analysis was assumed to be an 84% efficient, near-condensing boiler that would comply with federal mandates for energy efficient heating systems. Boiler replacements were necessary for four of the five installations. These four buildings all had existing boilers that were more than 20 years old. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) maintains a database on equipment lifetimes and the replacement age for boilers and suggests replacement after 18 to 25 years (depending on exact boiler type)[iv]. Building 810 was the only building that made the replacement specifically for improved efficiency. The high initial cost of condensing boilers made the technology not cost effective for the one case where a boiler replacement was not deemed necessary. The economic analysis for each building is shown in Table 1.

Table 1 – Calculated simple payback and NPV for the five sites for condensing boilers using normalized initial costs

Building	Initial Cost Replacement Boiler	Initial Cost Condensing Boiler	Energy Cost Savings	Simple Payback Period (Years)	Net Present Value
25	$629,084	$697,406	$15,326	4.46	$254,452
45	$183,836	$203,801	$6,361	3.14[1]	$114,001
54	$524,236	$581,171	$9,161	6.21	$136,004
710A	$122,557	$135,868	$2,344	5.68	$36,046
810	$629,084[2]	$697,406	$16,368	42.61	-$352,695

[1]The energy savings for building 45 are increased due to a steam to hot water conversion that occurred during the retrofit. This cost is not reflected in the normalized initial cost and results in an enhanced economic evaluation for that building.
[2]The replacement cost for building 810 is shown here, yet the economics shown are for efficiency upgrade (not an incremental cost analysis) due to the fact that building 810's boilers were not due for replacement.

One of the criteria set out in the objectives section was achieving condensing mode operation for greater than 20% of the annual operating hours. Analysis of the building automation system (BAS) trend data showed that only two of the five boiler plants achieved this goal during the monitored period. Figure 1 shows the percent of monitored hours that return water temperature was recorded in 10°F bins.
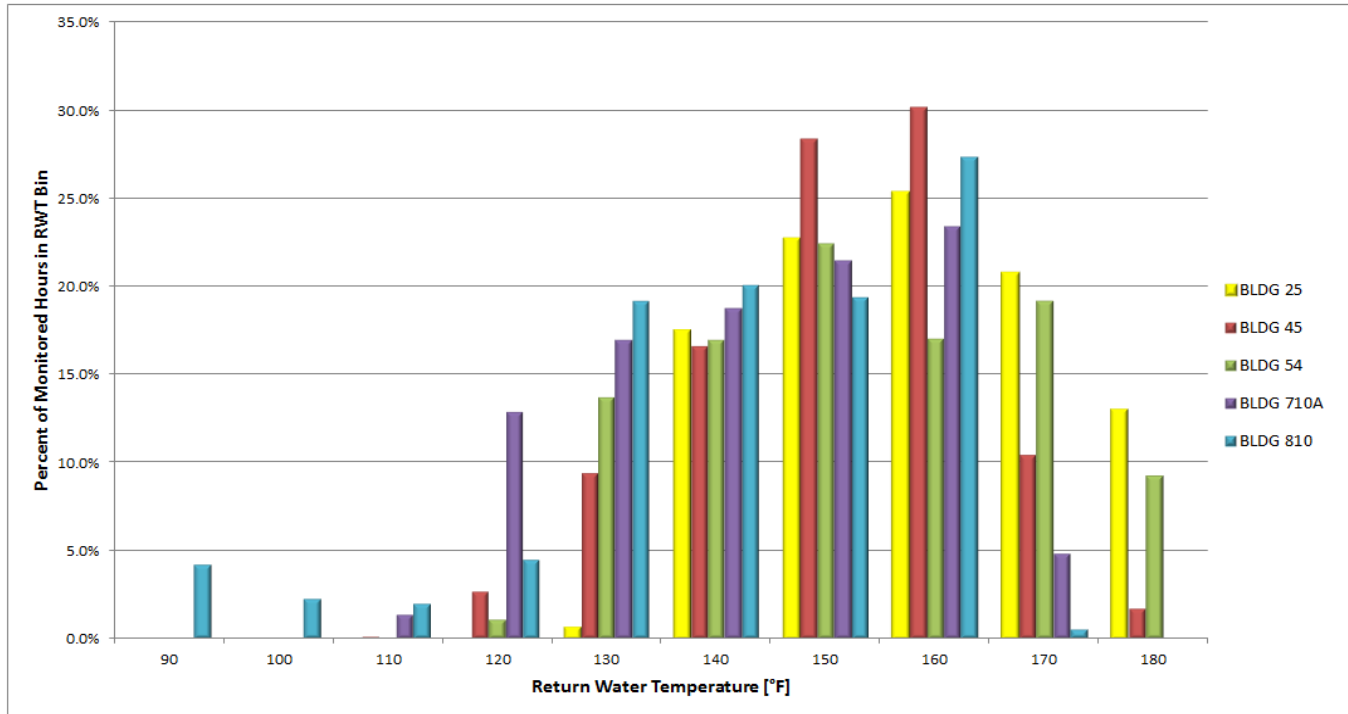
Figure 1 – Measured return water temperatures over monitoring period, separated into 10°F bins

The boilers' efficiencies are a function of the firing rate, as well as the return water temperature. The higher return water temperatures received by the boilers led to calculated annual thermal efficiencies ranging from 87% to 93% depending on the firing rate. When the boiler staging control sequence was taken into account (to determine approximate firing rate), it was estimated that those efficiencies were in the 88% to 90% range depending on the building.

These efficiencies could be improved if the return water temperature to the boilers was brought down further in to the condensing zone (less than 130°F) for a larger portion of the year. This could be achieved through retrofit of some of the hot water distribution systems, specifically the valving, piping, and coil design.

A cost/benefit analysis for retrofitting the hot water system in building 25 was conducted and demonstrated simple payback periods ranging from 11 to 33 years, depending on the actual return water temperature achieved by the retrofit. The analysis of retrofitting the hot water delivery system was only completed for building 25 due to the detailed information available on that building. In building 25, one potential solution to eliminating the problem of mixing supply and return water, which raises the temperature of the return water, would be to close the balancing valve on the air handler heating coil bypass leg and turn off the booster pumps. If the booster pumps need to operate to overcome the static pressure within the unit then the site can explore the option of installing a variable frequency drive (VFD) on each pump and modulating the booster pump flow rate based on hot water valve position. The installation costs associated with this estimate include the cost of a VFD on each booster pump, as well as the cost of a new control point.

This is a very building-specific type of analysis that should be investigated in other buildings and in proposed installations. Other low-cost or no-cost solutions are more aggressive outdoor air reset controls and valve adjustments on bypass piping.

E.   Conclusions

Condensing boilers are an effective technology for reducing the energy consumed for space heating if best practices are followed during installation. Condensing boilers should first be considered for retrofit in buildings that already return water temperatures below 130°F throughout much of the year. The building automation system (BAS) in many buildings can provide this information. In buildings where it is impossible or difficult to avoid return water temperatures above 130°F, high efficiency near-condensing boilers, with thermal efficiencies above 84%, may be more cost effective. It is important to note that basic steps, like a more aggressive outdoor air temperature reset and balancing of the three-way valves, should be taken into account before a conclusion can be made regarding the return water temperature. Comprehensive retrofits, including replacement of three-way valves with two-way valves and installation of VFDs on the pumps, should be considered during the evaluation process.

After two way valves have been installed and mixing has been eliminated the site should implement the most aggressive outside air reset schedule that they can for the given facility. The facilities analyzed in this study could have potentially implemented a more aggressive outside air reset that would have resulted in more hours in condensing mode. As an example, the supply water temperature could be reset from 170 °F (at or below 20 °F outside air temperature) down to 130 °F at or above 60 °F. The exact outdoor air reset formula will be specific to climate and building characteristics. In addition to optimizing the outdoor air reset schedule, mild climates can operate in condensing mode for a higher percentage of time than more extreme climates given the same system design and outside air reset.

The boiler plants installed at the DFC were installed correctly as modular systems with the proper controls to ensure that the boilers maintained a low firing rate throughout most of the year. The installation of outdoor air reset controls reduced the supply hot water temperature on warmer days, which in turn reduced the return water temperature to allow the boilers to operate in condensing mode more often. The installation of a condensate treatment system in the boilers at DFC reduces the environmental impact of the acidic condensate water.

Installing a modular condensing boiler plant alone does not guarantee savings beyond what near-condensing boilers can achieve. Near-condensing boilers are boilers that attain the highest efficiency possible without recapturing latent heat loss with condensing operation. Their steady-state efficiencies are between 85% and 88%. If the return hot water temperature never falls below 130°F, the threshold for condensing operation, the more expensive condensing boilers will only operate as efficiently as near-condensing boilers (typical cost premium for condensing boilers range from 10% to 15% more than near-condensing boilers).

Condensing boilers have the potential to reduce the cost and environmental impact of heating GSA's buildings throughout region 8. Typical candidates include, but are not limited to, buildings in moderate climates, buildings with low temperature heating systems (such as in-floor radiant heating), and buildings with hot water loops that can easily be retrofitted to avoid coil bypasses and three-way valves. Region 8 should consider condensing boilers during each boiler replacement, but a building-by-building analysis is necessary to determine the most cost effective boiler replacement in each building.

To ensure the maximum amount of savings is achieved from installation of condensing boilers, a review of the hot water distribution system must be undertaken with an aim of providing the lowest possible return water temperature to the boilers. Improvements can include the removal of bypasses and three- way valves, along with the installation of VFDs on pumps. This will reduce mixing and lower the return water temperature. Further improvements can include the installation of high ΔT coils in air handlers and variable air volume (VAV) boxes

that still can meet heating loads at lower supply water temperatures. The valving measures are generally lower cost solutions and should be addressed prior to coil retrofits. The calculated simple payback ranged from 11 to 33 years for installing VFDs on the small AHU booster pumps and closing the balancing valve in the by-pass loop for building 25 (depending on the assumed improvement in return water temperature). For this particular building the installed costs would not have been reduced if this was implemented when the boiler plant was installed since the modifications need to be made at the AHUs themselves.

Finally, it should be noted that after the writing of this report, the Federal Energy Management Program (FEMP) updated the minimum efficiency requirements associated with natural gas fired boilers to require 94% or greater thermal efficiency from these systems.[v] This essentially requires all federal agencies to install condensing boilers for all boiler replacements. This mandate makes the recommendations and best practices described in this report even more important; in order to obtain the high efficiency operation that is the motivation for such a mandate, it will be crucial to install these systems with the correct controls and hydronic configuration to ensure the maximum amount of operating time in condensing mode.

II.   Background

A.   Introduction

Heating energy use accounts for 26% of the total energy use in commercial buildings in the United States. It is the largest single energy end-use in buildings. Space heating in commercial buildings is provided by boilers in 32% of commercial buildings, making boilers the most common heating technology in the commercial sector.[vi] Installing condensing boilers will reduce onsite thermal energy use and help GSA move one step closer to achieving the energy use intensity reduction requirements that are mandated in EISA. This report will help provide guidance on how condensing boilers can contribute to significant reduction in the energy that space heating accounts for.

Condensing boiler technology has the capability of increasing the steady-state efficiency between 6% and 18% over traditional boiler technology. Steady-state efficiency is the efficiency of the boiler once it has reached normal, specified operating temperatures and does not include standby losses. The average gas-fired boiler in the United States in 2010 had a rated (steady state) efficiency of 80%.[vii] Older boilers can operate at a significantly lower efficiency. The efficiency of older equipment depends on its condition, as well as the mixture of combustion fuel in the boiler. Actual boiler efficiency can be determined with a combustion analyzer. Condensing boilers have a range of efficiencies, depending on the operating conditions, that span from approximately 86-98%. If appropriately installed and operated, condensing boiler technology offers GSA the ability to significantly reduce space heating energy consumption.

The main barriers to achieving these increased efficiencies are how the boilers are integrated with the hot water distribution system and how the boilers are operated. In new construction, condensing boilers are paired with hot water distributions systems with a large temperature differential from supply to return. These systems often have specific, high ΔT coils (40° to 50°F) that enable the required temperature differential for the boilers to operate in condensing mode for large portions of the year. Heated radiant floor, pool heating, and snow melt are other systems that allow boilers to operate in condensing mode. It can be difficult to achieve these types of operations in a retrofit scenario.

B.   Opportunity

The most common technology used for space heating in domestic commercial buildings are boilers (accounting for 32% of all heated floor area), followed by furnaces and packaged units (Table 2). The vast majority of boilers are traditional, natural gas fired boilers that generate hot water or steam. These boilers had an average rated efficiency of 80%, as of 2010. Condensing boilers have steady-state efficiencies that range from 86% to 98% depending on boiler operation. This presents a significant opportunity for GSA to reduce its energy consumption and reduce annual utility costs region wide. Due to the heating-dominated climate of Region 8 (which includes ASHRAE climate zones 5, 6, and 7), condensing boilers represent an even greater opportunity for this region if correctly deployed. Denver is located in climate zone 5. Climate zones 6 and 7 are colder than climate zone 5.

Table 2 - Type of heating equipment used in US commercial buildings, 2003 (CBECS)*

Heating Equipment	2003
Boilers	32%
Furnaces	30%
Packaged Heating Units	28%
Individual Space Heaters	19%
Heat Pumps	14%
District Heat	8%
Other	5%

* Heating and cooling equipment percentages of floor space total
more than 100% because equipment share floor space

Condensing boilers offer the potential to reduce operating costs and save energy through the higher efficiencies attainable with the technology. These savings are only realistically attained through appropriate system design and operation.

The technology evaluated at the five buildings that were monitored at the DFC were Cleaver Brooks Clear Fire Condensing boilers (CFC 2,500 MBH and CFC 1,500 MBH models). Similar boilers are currently available from other manufacturers and have been available in the marketplace for approximately 30 years. The first generation condensing boilers were manufactured in the early 1980s. These boilers generally had single-stage firing rates and lacked the modulating capabilities that the newer condensing boilers offer. The second generation of condensing boilers had fully modulating burners that offer improved efficiencies at lower firing rates and improved staging opportunities. These came into production in the early 1990s.[iv] Condensing boilers have been deployed to a limited extent across the United States and to a larger extent across Europe (where governmental standards or incentives and higher energy costs have encouraged more widespread adoption). As of 2001, condensing boilers represented approximately 2% of total boiler sales in the United States.[iii]

The low level of market penetration demonstrates a significant opportunity for increased deployment of this technology. GSA has already started to lead this effort and has deployed condensing boilers in many of its buildings in an attempt to reduce energy consumption and operating costs.

C.   Demonstration Project Locations

The five buildings selected for this study were chosen due to the fact that they had received condensing boiler retrofits during the summer and early fall of 2010 and were now fully operational. All five buildings are located at the DFC in Denver, CO. The five sites are: buildings 25, 45, 54, 710a, and 810. The retrofits in buildings 25, 45, and 54 all replaced boilers that were approximately 20 years old. Building 810 replaced boilers from 1998. Building 710a did not have data on the pre-existing boiler age, yet the low-rated efficiency listed (66%) implies an older vintage.

The buildings range in size from 37,000 ft^2 to 787,000 ft^2. They provide hot water to a wide variety of air-side systems, terminal units, and perimeter baseboard units. One of the retrofits (building 45), included a steam to hot water retrofit during the boiler switch over. The air handling unit types include hot deck/cold deck, constant volume (CV), and VAV. The wide variety in the distribution systems was important to the study in that it allowed for comparison across numerous types of retrofit applications. For more detailed descriptions of the individual buildings, refer to subsection IV-A. Facility Description (page 15).

This study was completed during the spring of 2012. The trend data acquired from the BAS system was collected from February 11 to April 16, 2012. The utility data was collected from October 2008 until October 2011. This range provided two years of utility data prior to the condensing boiler retrofits and one year of data post-retrofit.

III. Technology Description and Objectives

A. Technical Objectives

The ability to achieve the upper end of the potential efficiency improvement relies on appropriate system design and operation. It is the purpose of this report to study the operation of the five installations at the DFC, quantify the installed performance of those installations, and report on the actual savings achieved by these systems. The condensing boiler technology will be compared to both the pre-existing boilers and to near-condensing boilers. The operation and performance of the systems will be evaluated through:

- Fifteen minute trend data from the BAS, collected throughout the winter-early spring of 2012.
- Utility bill analysis - using regression analysis on pre- and post-retrofit utility data to quantify actual savings due to the boiler retrofits.

These two analysis methods will be used to evaluate actual and predicted annual efficiencies. Using these results, the actual energy savings will be quantified. Specifically, this study will evaluate the different types of heat distribution systems in the five different buildings at the DFC and will evaluate the effects that the different system characteristics, such as piping configuration and coil type, had on the condensing boiler operation and annual efficiency.

The report also will use the Condensing Boiler Design Model (CBDM), developed by Group 14 Engineering through a subcontract with NREL, to further support and verify the best practice recommendations on both new and retrofit condensing boiler installations.

Finally, this study will evaluate the economic viability of the technology and its applicability for widespread adoption across the GSA building portfolio. Table 3 lists some of the specific objectives, metrics, and success criteria defined for this study.

**Table 3 – Performance metrics developed at outset of study**

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Condensing Mode Operation	Percent of time operating in condensing mode	Supply Water Temperature (F) Return Water Temperature (F)	*Operating in condensing mode > 20% of the time*
Cost Effectiveness	Life cycle cost effectiveness	Installation costs relative to standard high efficiency boiler Natural gas rates for GSA facilities in each region	*Exceeds GSA's life cycle cost criteria for energy efficiency projects versus standard high efficiency boiler*
Qualitative Performance Objectives			
Operation and Maintenance (O&M) Costs	Heating, ventilating, and air conditioning (HVAC) maintenance costs per year	O&M costs of pre retrofit steam boiler O&M costs of pre retrofit hot water boiler	*Reduction in O&M costs relative to steam boiler and existing hot water boiler*

It is important to note that one of the main objectives of this report is to provide analysis and recommendations for appropriate integration with the hot water distribution system in the building. Appropriate integration will increase the percent of time spent in condensing mode and improve the cost-effectiveness of the installations.

B. Condensing Boiler Technology Description

Condensing boilers have been manufactured since the 1980s. The first generation boilers were typically single stage boilers, with the first fully modulating models coming into production in the mid-1990s.[viii] Condensing boilers are a fully mature technology that is in line with DOE/FEMP's TRL 9 classification.[ix] These systems have been deployed throughout the United States and the world and are currently supported with various state and utility incentives.

Condensing boilers achieve their higher efficiencies by condensing water vapor in the flue gases. When natural gas is combusted in a boiler, approximately 90% of the energy contained in the fuel is converted into sensible heat (heat that causes a change in temperature) and approximately 10% is converted into latent heat (heat involved in phase change). This latent heat is stored in the water vapor that is a byproduct of the combustion process. One can see from the simplified combustion equation for methane, the principal component of natural gas, that two molecules of water are produced for every molecule of methane combusted:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Heat}$$
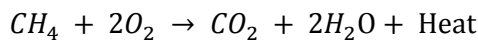
It takes energy to evaporate these water molecules into the flue gases. It is this latent energy contained in the water vapor that condensing boilers recapture.

In traditional boiler technologies, the latent heat contained in the water vapor is allowed to escape in the flue gases. Condensing boilers reclaim that latent heat by condensing the water vapor and transferring that heat back into the return water. According to the manufacturer of the boilers in this case study, this process of condensing the water vapor can increase the steady-state efficiency of the boiler from between 80% and 87% to between 88% and 98% (depending on boiler operation).[x]

These potential efficiency gains can only be attained if the boiler is operating in "condensing" mode. Condensing mode is achieved when the temperature of the return water is below the dew point of the water vapor in the flue gas. For natural gas the dew point is approximately 130°F. Therefore, if the return water temperature is below 130°F, the water vapor will start to condense and the system will achieve a higher efficiency. The lower the return water temperature, the more condensation occurs and higher efficiency is achieved.

The design characteristics of the condensing boiler plant and the hot water systems that the boiler plant serves affect both the operational efficiency and return water temperature of the boilers. The design characteristics of the boiler plant, piping system, heating system, and control system need to be documented and understood to accurately design and operate a condensing boiler plant.

Boiler Plant

Boiler Sizing – Condensing boilers operate at higher efficiencies at lower firing rates. Most condensing boilers can modulate to very low firing rates (≈10% of full fire), and achieve higher efficiency at these low rates. Appropriate sizing of boiler plants also limits cycling losses at low loads, further improving the overall efficiency of the plant. The first step in properly designing a condensing boiler plant is to design the system to include multiple smaller boilers to meet a given load, rather than using one or two large boilers to meet a given load. This will help achieve higher operating efficiencies and avoid excess initial cost by matching the capacity more closely to the building load.

Boiler Turndown Ratio – The turndown ratio of a boiler defines the range of firing rates at which a boiler can continuously operate. Below the minimum turndown ratio, the boiler will start short-cycling, introducing losses associated with pre- and post- burner purging. This impacts the part-load efficiency of the boiler; the higher the turn turndown ratio the better the part-load performance. For example a turn down ratio of 10:1 would allow for operation down to 10% of the rated output, where as a 5:1 turn down ratio would only allow for operation down to 20% of the rated output.

Boiler Minimum Water Flow – Some condensing boilers have a minimum water side flow rate at minimum and maximum firing rates, to protect the heat exchanger. This minimum flow rate can affect the sequencing of the boilers, the operation of the boiler plant, and ultimately the supply and return water temperatures. The lower the minimum flow rate the better the part-load performance of the plant.

Boiler Efficiency – The efficiency of a condensing boiler is a function of the hot water return temperature and the percent firing rate. The efficiency of the boiler increases at lower return water temperature and lower firing rates. Conventional boilers operate at lower efficiencies when firing rates are lower due to the increased amount of excess air in the exhaust and the high exhaust air temperature. Condensing boilers are able to operate at high efficiencies with increased amounts of excess air (at lower firing rates) due to the low exhaust air temperatures.

The increase in efficiency at low firing rates holds true until the boiler needs to operate below the low end of the turndown ratio. Efficiency then decreases significantly due to short-cycling. The part-load performance of the units needs to be understood and accounted for when selecting and sizing the boilers.

Piping and Pumping System

Primary versus Primary/Secondary – A primary hot water loop is designed with one water loop that circulates water through boilers and the heating coils within the facility. This loop can be CV or variable volume depending on the requirements of the boiler (Figure 2).
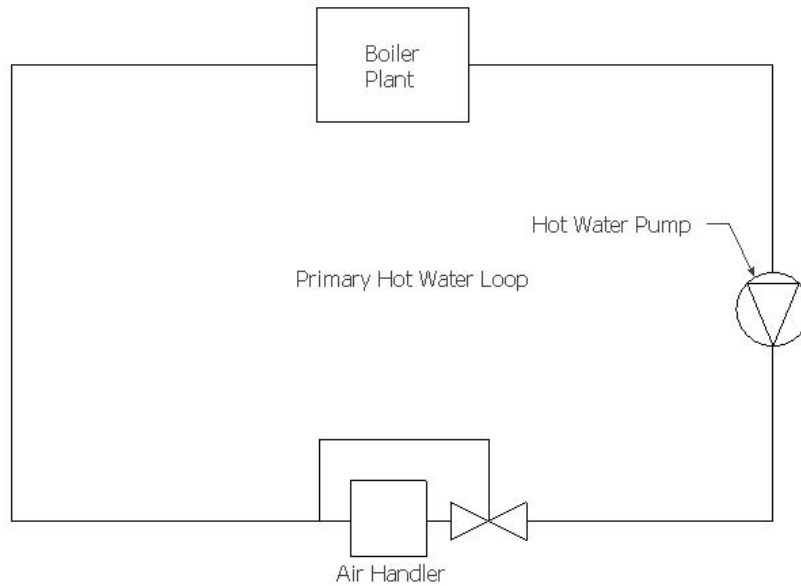
Figure 2 – Constant Volume Primary Hot Water Loop

A primary / secondary loop is typically set up with a CV primary loop and either a CV secondary loop or variable volume secondary loop that pulls hot water off of the main primary loop through the boiler plant and supplies water to the coils within the facility (Figure 3). In systems designed with distributed booster pumps, the small booster pump loops can serve as the secondary loop.
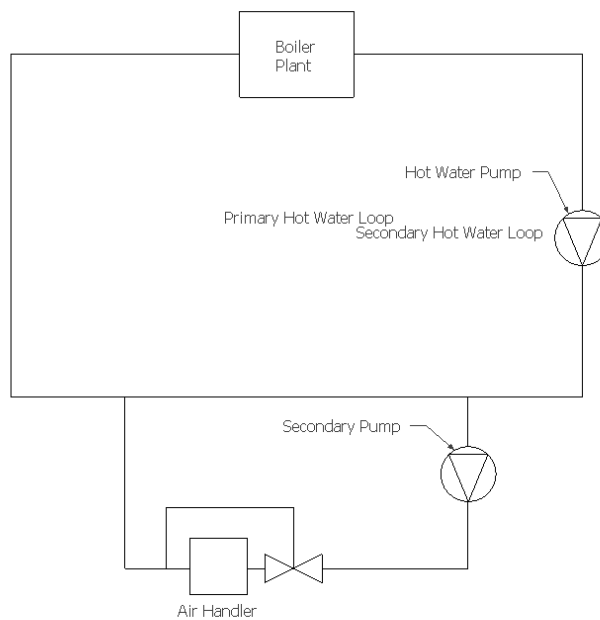

Figure 3 – Primary/Secondary Hot Water Loop

Secondary Flow Rate and Control Valve Selection – The flow rate through the heating coils is a function of the heating coil design and the loads at any given time. The flow rate through the entire system is a function of the piping and control valve design with additional water pumped and mixing if there is a three-way valve. Older facilities were designed with three-way control valves and CV water loops because engineers were encouraged to provide constant flow through the boiler, which is no longer necessary with modulating boilers. With this type of configuration, much of the supply water can bypass the coil (especially at lower loads). The bypass stream then mixes with the water leaving the coil, increasing the return water temperature. An image of a heating coil with a three-way control valve is provided below (Figure 4).
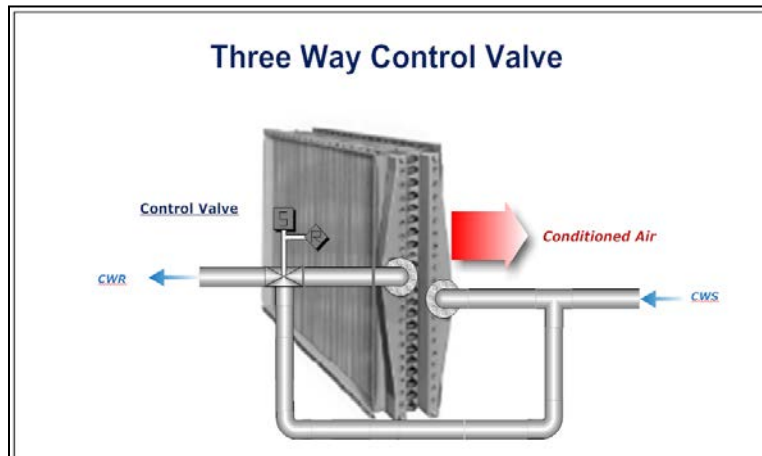
Figure 4 – Three Way Control Valve
Image Credit: Jesse Dean (NREL)

If the coils are designed with two way control valves, the water flow rate through the coils is modulated and the mixing problem is eliminated. This type of design requires the use of variable frequency drives on the pumps (Figure 5).
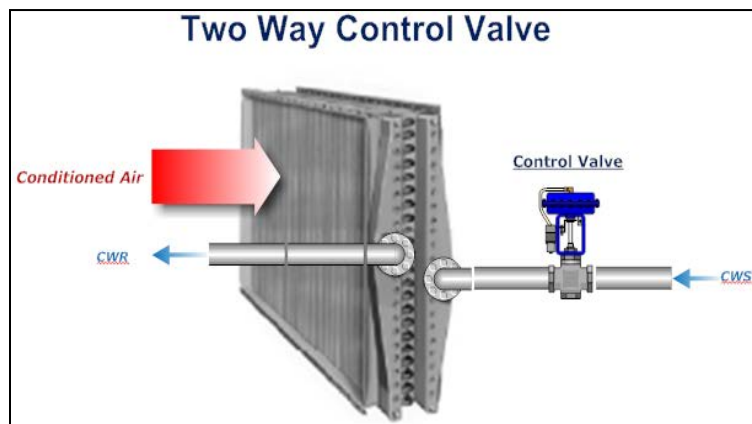

Figure 5 – Two Way Control Valve
Image Credit: Jesse Dean (NREL)

Some systems are designed with a bypass between the supply and return water at the main boiler plant that maintains a minimum flow rate through the plant. Other boilers have this included in an internal circulator. All of these factors need to be accounted for in the design phase.

Heating System and Heating Coil Design

Heating Coil Design ΔT – Most air handling unit and terminal unit heating coils are designed for a 20° or 30°F temperature drop across the coil. For example, a typical coil will be designed for 180°F supply water temperature and 150°F return water temperatures during peak conditions, which would prohibit the system from operating in condensing mode with a 180°F supply water temperature. Heating coils can be designed with higher ΔT's, on the order of 50 to 60°F, which allow for much cooler return water temperatures given a supply water temperature of 180°F. Ideally, the coil will be designed for a high ΔT and a lower supply water temperature. This extra step will ensure the water leaving the coil is below 130°F for a greater percentage of the time than a high ΔT coil alone.

Radiant/Convective Baseboard Heating Systems – Perimeter baseboard radiant heaters are designed to operate with higher supply water temperatures, on the order of 180°F. If a space is heated with primarily perimeter baseboard/radiators then the supply water temperature can be decreased by increasing the heater surface area on the baseboard/radiator system. If area increase is not feasible, the supply water temperature might need to remain high to properly heat the space.

Control Sequences

Boiler Staging – The boiler operation can be staged so that multiple boilers are on at a low firing rate instead of a single boiler operating at close to full capacity. For example, three boilers could be operating at 30% of capacity instead of a single boiler operating at 90%. The only caveat with this operation strategy is that it is important to not have the boilers on so low that short cycling occurs.

Outside Air or Load Based Reset – The supply water temperature can be reset based on the outside air temperature or the heating coil valve positions. The reduced supply water temperature allows for cooler return water temperatures and some type of supply water reset should be implemented to reduce the return water temperature.

Material Requirements

It is important to note that the acidic nature of the flue gas condensate requires highly corrosion-resistant materials to be used in condensing boiler heat exchanger and venting construction. Traditional boilers do not use the corrosion resistant material and therefore must ensure operation above the condensing temperature. This effectively puts a cap on the efficiency achievable with traditional boiler technology. It also must be noted that the corrosion resistant materials used in the condensing boilers come at a much higher cost. A condensate treatment system may be required to treat the acidic condensate before it enters the drain. All of the boiler installations at the DFC included condensate treatment. The increased cost for installation of this piece of equipment increases the installation costs compared to a standard boiler.

Condensing boilers offer the potential to reduce operating costs and save energy through the higher efficiencies attainable with the technology. These savings are only realistically attained through appropriate system design and operation.

IV.   Assessment

A.   Facility Description

The DFC buildings were evaluated through numerous site visits during the 2011-2012 heating season. DFC building managers and mechanical technicians provided access and information on the different buildings' HVAC systems. The site visits provided information on the boiler plants and HVAC systems within each facility. The following information was collected during the site visits:

- *Boiler Plant Design* – The number of boilers, boiler name plate capacity, and minimum water-side flow rate.
- *Pump and Piping Design* – The pump name plate data and variable frequency drive minimum set point data, as well as information on the primary/secondary configuration.
- *Air Handling Units, Terminal Units, and Baseboard Heaters* - The number and type of air handling units (AHUs). The heating coil ΔT, when this information was available, as well as control valve configuration and secondary pumping system information.
- *Controls* – The control sequence for the boiler plant and the heating loads on the boiler plant were noted and trended where applicable.

While it was not possible to evaluate every AHU and terminal unit in the building, representative units were evaluated and documented. The following building descriptions do not attempt to document every aspect of the heating system for each building; instead they provide an overview of the different types of systems, coils, and valving found in each building. These aspects of the heating system have a significant impact on the return water temperature, and, therefore, performance of the condensing boilers.

The following table gives a summary of the boilers, primary pumps, and coils/valving for each of the five buildings evaluated in this study. This is followed by an overview of each specific building.

Table 4 – Facility Boiler Plant and HVAC System Description

Building	25	45	54	710A	810
Number of boilers	6	3 (Plus 2 old backup steam boilers)	5 (Plus an old backup boiler)	2	6 (Plus an old backup boiler)
Max Output per boiler (MBH)	2,500	1,500 - new boilers, 1,339 - old boilers	2,500 - new boilers 10,400 - old boiler	1,500	2,500
Primary pumps, Rated Flow (GPM)	2 @ 480	3 @ 225	2,000	2 @ 40	3 @ 475
VFDs on Pumps	Yes	Yes	No	Yes	Yes
Air Handling Units	28 AHUs	6 AHUs	20 AHUs hot deck/ cold deck	-	30 AHUs - not all have heating coils
Control Valve Design	2 way valves with heating coil bypass	3 way valves	3 way or 2 way valves with bypass	-	3 way valves
Terminal Units	360 VAV boxes	8 Unit heaters	-	Terminal units	-
Control Valve Design	2 way valves	2 way valves	-	2 way valves	-
Baseboard Units	200 feet baseboard	1.2 MBH baseboards	-	-	300 ft. baseboard
Control Valve Design	2 way valves	2 way valves	-	-	2 way valves
Other	6 laboratory AHUs - 100% outdoor Air	4 Fan coil Units	7 additional AHUs	-	-
Control Valve Design	2 way valves with AHU bypass	2 way valves	3 way or 2 way valves with bypass	-	-

Building 25:

The National Enforcement Investigations Center occupies building 25 at the DFC and provides technical support for U.S. Environmental Protection Agency (EPA) enforcement and compliance assurance programs nationwide. The total facility area is 101,735 ft^2, with an estimated 137 EPA personnel occupying the facility. The interior space is a mixture of office space and laboratory space. The energy use within the facility is driven by the ventilation loads and energy requirements of the laboratories.[xi]

Building 25's entire HVAC system was upgraded in 2002, with the exception of the boilers, which were installed in 2010. A one line diagram of the boiler plant and associated HVAC system components is provided in the following graphic (Figure 6).
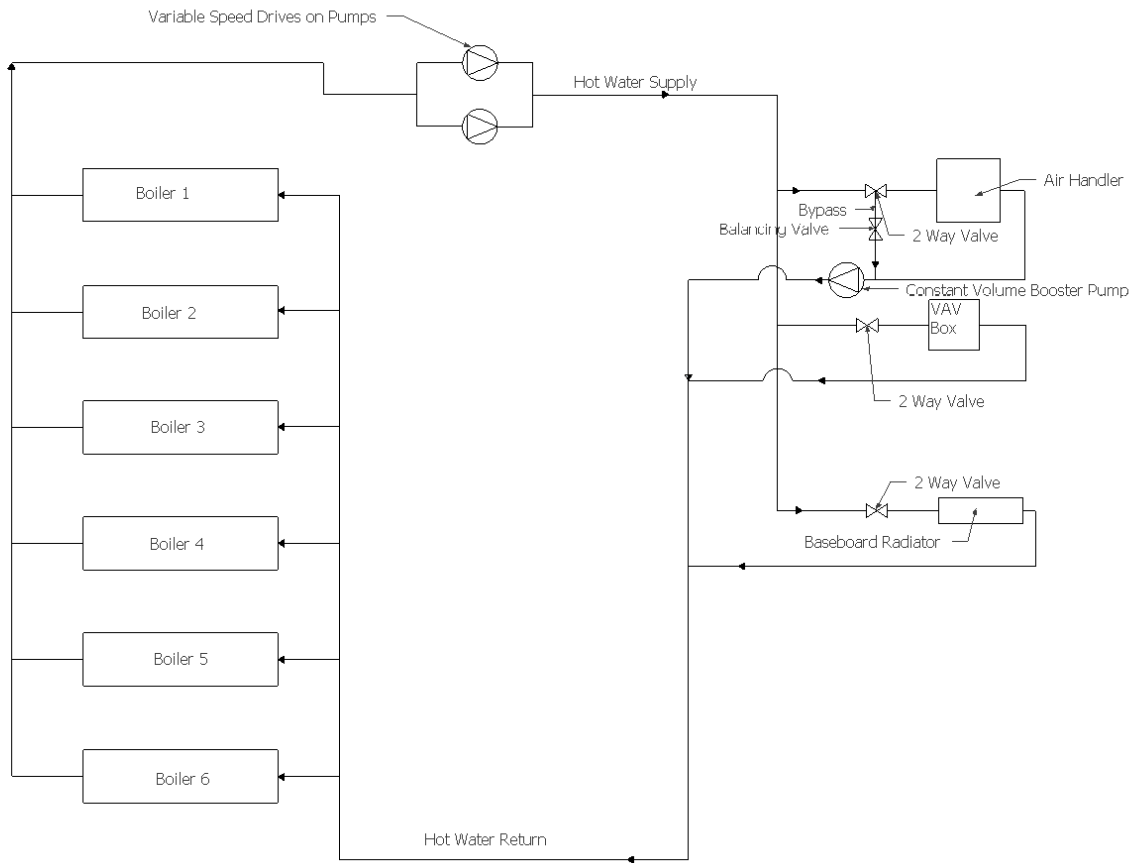
Figure 6 – EPA Building Heating System One Line Diagram

The six 2,500 MBH boilers provide hot water to AHUs, VAV box re-heat coils, and perimeter baseboard units. The plant is set up with a variable flow primary loop and two variable speed pumps. Each pump is rated at 480 gpm and only one pump operates at a time. The AHUs are the largest thermal heating load on the system and are set up with CV booster pumps, two-way control valves, and a hot water bypass at each AHU. The office AHUs are VAV and the six laboratory AHUs are 100% outdoor air units. Each lab is equipped with a phoenix valve that can reduce air flow to 50% during unoccupied hours. The VAV boxes have hot water reheat coils and there is approximately 200 ft. of baseboard radiators. The VAV box re-heat coils and baseboard heaters are connected to the variable flow primary loop and have two-way control valves.

The three main hydronic loops (AHUs, VAV reheat, and baseboards) are operated in parallel and mix return water before re-entering the boiler plant. The booster pumps in the AHUs are required to overcome the pressure drop in the coils, based on the fact that the system has been retrofitted over time and the additional AHUs that have been added to the system have increased the pressure drop through the system. The CV booster pumps and AHU bypass mix hot supply water with cooler return water, which has the effect of increasing the return water temperatures. The new boilers at the EPA building have an outdoor air lockout that shuts them off when the outside air temperature is above 72°F.

Building 45:

The boiler plant in building 45 contains three new 1500 MBH condensing boilers, as well as two old steam boilers. The old steam boilers act as a backup system and transfer the steam to hot water through a heat exchanger. This heating plant serves both building 45 ($\approx$78,000 ft^2) and building 46 ($\approx$21,400 ft^2). It is approximately 50% high bay and 50% office space. As part of the boiler retrofit, building 45 was converted from a steam to a hot water distribution system. The steam to hot water conversion was pursued both to improve heating system efficiency and to remove a potential health liability due to asbestos-encased piping systems in the old steam installation.

There are five to six "multizone" air handlers that are equipped with three-way valves. There are eight unit heaters that serve the high bay garage area. These unit heaters are rated at 180 MBH, 200°F entering water temperature, and 180°F return water temperature. Due to the high temperature requirements and low ΔT, these units are not ideal for a condensing boiler system. A small number of baseboard radiators provide heating as well. Four fan coil units are located in the garage that are controlled by two-way valves. Three primary pumps circulate hot water; each equipped with variable speed drives and rated at 225 gpm.
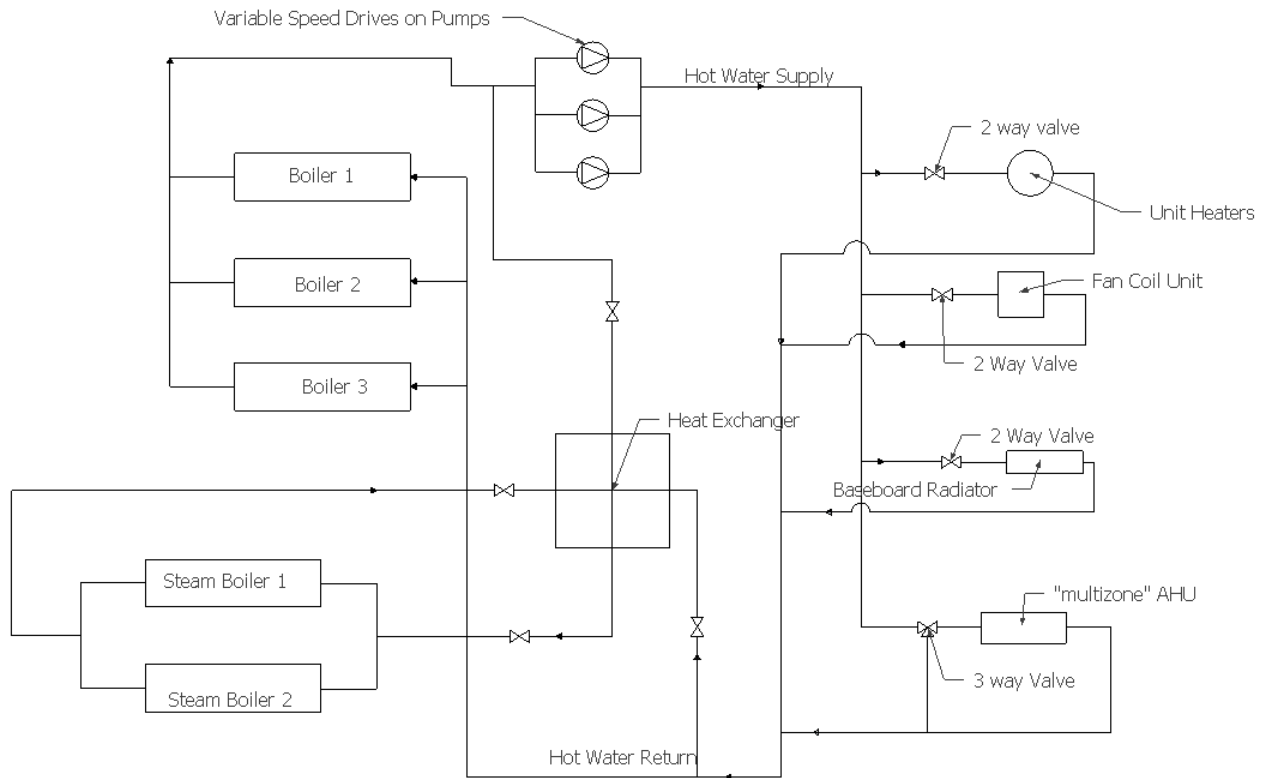

Figure 7– Building 45 Heating System One Line Diagram

Building 54

The boilers located in building 54 serve buildings 52, 53, and 55. Building 54 is a small facility with two main rooms, one room houses the condensing boiler plant, and the other serves as a small storage room. Five new condensing boilers were installed. Each boiler has a rated capacity of 2,500 MBH. One of the existing boilers was left in place to serve as a backup. The backup boiler has a rated capacity of 10,400 MBH and a steady state efficiency of 80%. The 2,000 gpm pumps are CV, which essentially prohibits the installation of two-way valves (it can still follow the pump curve, with reduced efficiency and unstable operation). Without any two-way valves, the return water temperature will be higher, as coil bypasses are necessary to prohibit increasing the pump head when the valves begin to close. There are approximately 27 AHUs served by the boilers, 20 of which are hot deck/cold deck units. In hot deck/cold deck units, air is separately heated and cooled and then mixed to achieve the desired temperature. This is most commonly a CV system design that results in significant mixing of supply water into the return water from the coils. All of the main air handler coils had small booster pumps to maintain a certain flow through the coil. All of the heating coils in the AHUs are equipped with three-way valves. A one-line diagram of the heating system is presented below (Figure 8).
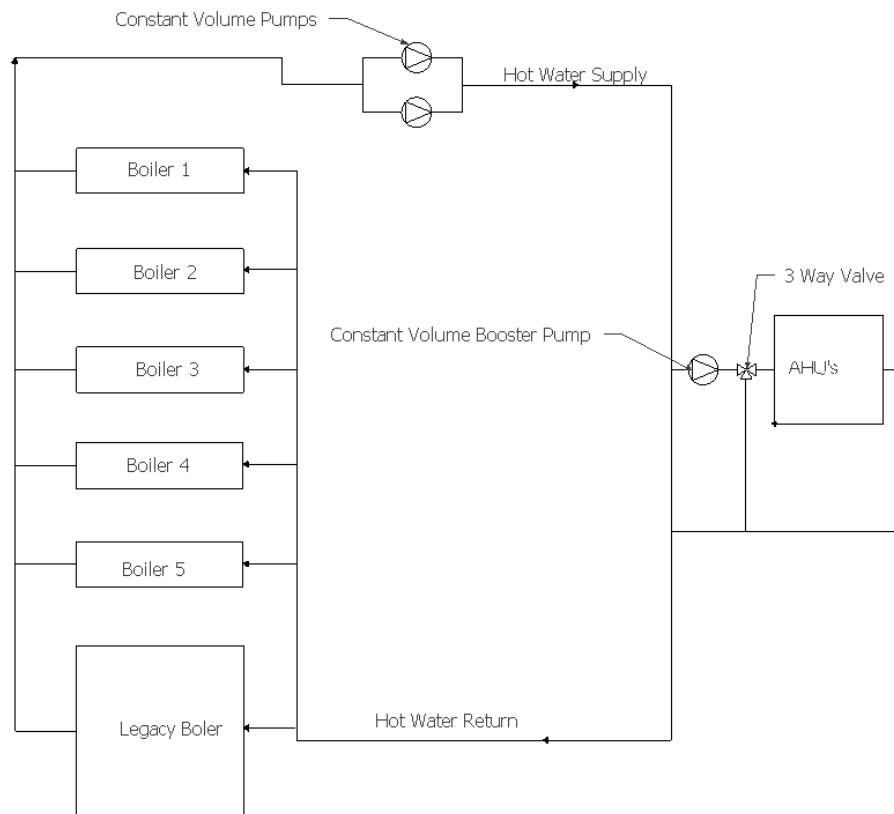

Figure 8 – Building 54 Heating System One Line Diagram

Building 710A

Building 710A's heating is served entirely by terminal units controlled by two-way valves. The building is approximately 37,000 ft^2 of office space. There is one central AHU that contains only a cooling coil, with the terminal units providing the reheat needed. Two-way control valves control the terminal reheat. Since all of the heating coils are controlled by two-way valves and all the hot water pumps are already equipped with variable speed drives, this facility is an ideal candidate for control adjustments that can lower the return water temperature without significant capital investment. There are two new condensing boilers that heat the entire building. Each of these boilers has a 1,500 MBH capacity. The primary hot water pumps consist of two 40 gpm pumps installed in parallel and equipped with variable speed drives. A one-line diagram of the heating system is presented below (Figure 9).
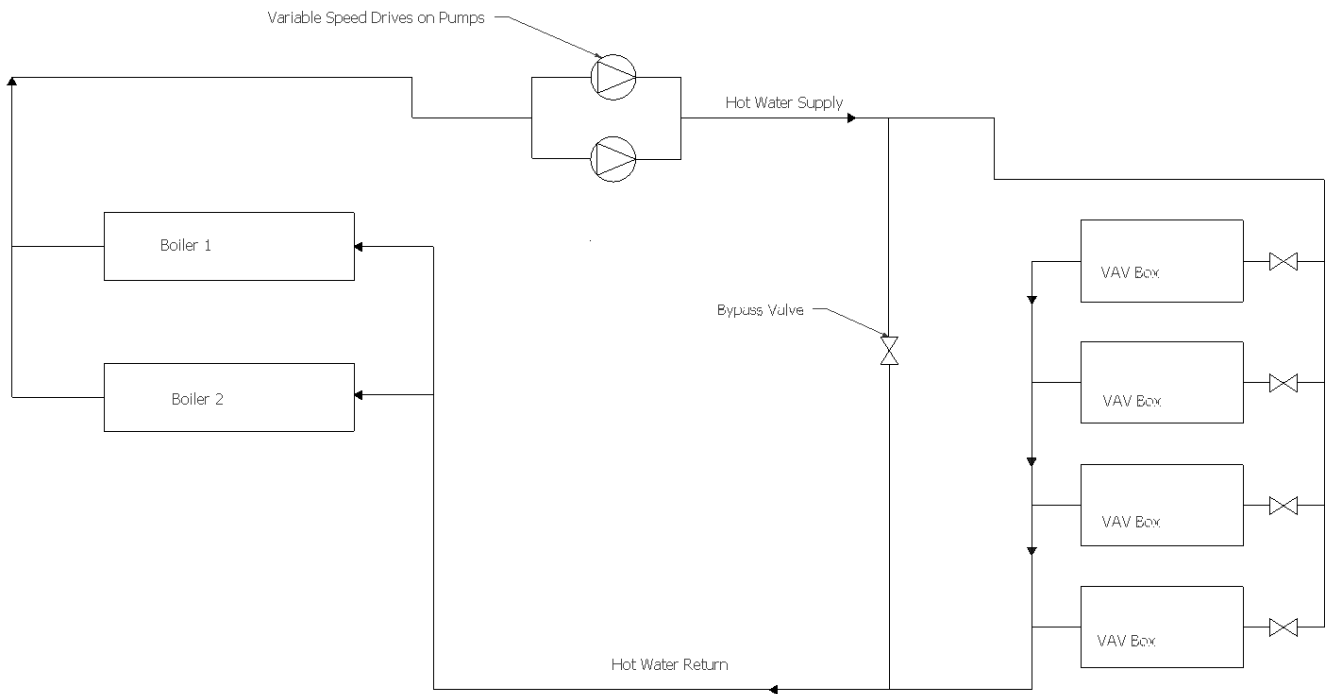

Figure 9 – Building 710A Heating System One Line Diagram

Building 810

Building 810 is approximately 787,000 ft^2 and contains six new condensing boilers (2,500 MBH each) as well as a large, older boiler. The building is half warehouse space and half offices. There are approximately 30 air handlers, although not all of them contain heating coils. They are hot deck/cold deck, constant volume systems. All of the heating coils in the air handlers have three-way valves. There are also approximately 70 unit heaters. The unit heaters are ceiling mounted fans that contain a hot water coil and are prevalent in high bay areas. There is also approximately 300 ft of baseboard heating in building 810. The baseboard radiators and the unit heaters require relatively hot entering water temperatures, which makes it difficult for the return water temperatures to be below the 130°F required for the boilers to operate in condensing mode. There are three primary hot water pumps rated at 475 gpm and equipped with variable speed drives. There are three CV booster pumps in the mechanical room and several more located throughout the building.

B. Technology Specification

The condensing boiler technology is a system of technologies, consisting of the boiler itself, the flue stack, and the condensate collection system. A schematic of the Cleaver Brooks boilers installed at the DFC is presented in Figure 10. There are many other manufacturers that supply condensing boilers that demonstrate similar performance. The salient characteristics of the condensing boiler are the stainless steel, high-efficiency heat exchangers and fully modulating burners. The flue stack must be manufactured of corrosion resistant material (such as AL294-C), instead of the traditional B-Vent due to the flue gases condensing in the stack. Condensing boilers also need a condensate collection system to deal with the acidic condensate in an environmentally safe manner. This is usually accomplished through a corrosion resistant collection system (often PVC) that feeds into a holding tank that contains some sort of neutralizing agent.
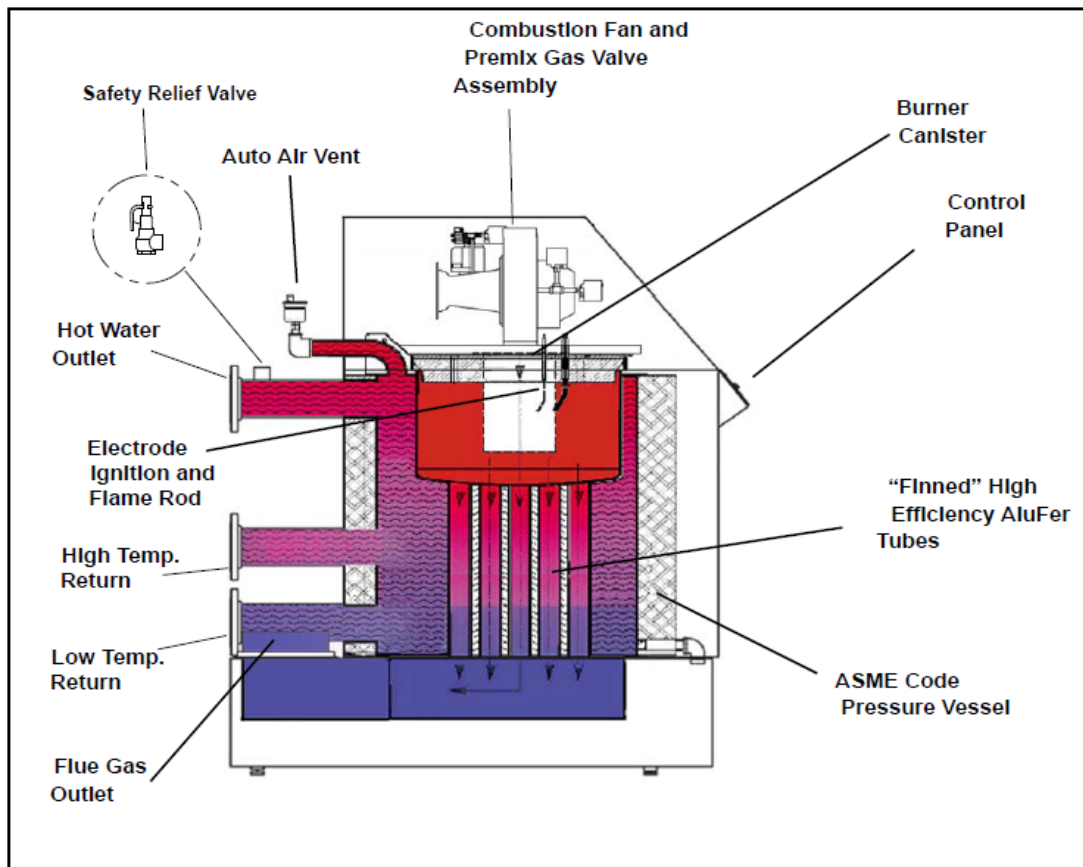
Figure 10 - Diagram of the Cleaver Brooks Clear Fire boiler
Image Credit: Cleaver Brooks

It should be noted that while the actual condensing boiler technology system ends here, the operation/performance of the technology depends on its integration with the building's heating system. The manner in which the system is integrated with the hot water distribution system will determine how efficiently the boilers operate and will impact both energy usage and cost savings. It is, therefore, recommended to specify not only the technology itself, but also how it should be integrated with the building's heating system.

C.   Technology Deployment

The existing boilers at the site consisted of natural gas fired boilers of the non-condensing type. In all of the buildings except for building 45, these boilers provided hot water to the building that was used in AHU heating coils, baseboard, and terminal units to provide heat to the building. In building 45, the existing system was a steam system. The existing boiler data is provided in Table 5, and was provided by GSA.

Table 5 - Existing boiler data

Building	Manufacturer	Model	Year Built	Max Input (MBH)	Min Input (MBH)	Max Output (MBH)	Min Output (MBH)	Rated Efficiency (Input/ Output)
25	York Shipley	SPLV-250-N	1990	10468 CFH		8369 CFH		80%
25	York Shipley	SPLV-250-N	1990	10468 CFH		8369 CFH		80%
25	Bryan	CL120-S-15-FDG	1990	900	450	720		80%
45	Bryan	RV350-S-15-FDG	1990	3110	1555	2488		80%
45	Bryan	RV350-S-15-FDG	1990	3110	1555	2488		80%
54	Bryan	RV250-W-FDG	1990	2125	1063	1700		80%
54	Bryan	RV250-W-FDG	1990	2125	1063	1700		80%
710A	Multitemp	MOP-1540		1540		1014		66%
710A	Multitemp	MOP-1540		1540		1014		66%
810	Bryan	RW850-W-FDG	1998	8500	3386	6800	2709	80%
810	Bryan	RW1050-W-FDG	1998	10500	3888	8400	3111	80%

The condensing boilers were deployed in each of the five buildings evaluated during the summer-fall of 2010. This consisted of removing the existing boiler(s) and installing the condensing boilers in the existing boiler room. The boilers were all installed in parallel, allowing for staging of the boilers as required by the load. This implies that a single boiler can be on and receiving all of the flow or numerous boilers can be on with each receiving a portion of the flow. This enables staging of the boilers as programmed into the controller. It also allows for equal runtime of the different boilers with appropriate sequencing.

In all cases except for building 54, the new pumps were matched with variable frequency drives (VFDs) to enable variable flow to the hydronic loop. When matched with the appropriate heating system, this allows for reduced flow at lower loads, reducing pump power consumption and maintaining a larger temperature differential between supply and return. The pumps also were installed in parallel.

In general, the boiler retrofit did not include any retrofit to the rest of the HVAC system. There was no swap out of coils or changeover from CV systems to VAV systems. Whatever system was in place in each building was left, and was simply supplied by the condensing boilers in place of the old boilers. The one exception to this was

building 45. In building 45, the entire heating system was switched over from steam to hot water at the same time as the boiler retrofit.

D.   Test Plan

The testing plan consisted of evaluating the performance of the condensing boilers through the use of BAS trend data, utility bills, and site assessments.

Utility data was provided by GSA for the period October 2008 through September 2011. This provided approximately two years of pre-retrofit data, and one year of post-retrofit data. These data were normalized to outside air temperatures to provide accurate comparison between pre and post-retrofit data.

The 15 minute trend data was gathered from the BAS from February 7, 2012 through April 15, 2012. These data were provided to NREL by the head of advanced metering at the DFC. This data was provided in weekly installments for each building under observation. These data were then compiled and processed using Python scripts that reformatted the data into comma separated files that allowed for efficient data analysis. Python is an open source programming language that provides efficient data processing capabilities.

Finally, each building was evaluated during site visits to the DFC campus. These sites visits provided name plate data on all of the relevant HVAC systems within the buildings.

E.   Instrumentation Plan

The BAS points that were monitored for each building consisted of: outdoor air temperature [°F], supply water temperature [°F], return water temperature [°F], pump enabled [ON/OFF], VFD speed [%], and coil position for the first two and last two coils in the hydronic loop [%]. In some cases the coil position points were not available (either due to pneumatic control or lack of direct digital control (DDC) data). In other cases, the VFD speed was not provided. All of these points were recorded every 15 minutes for the two-month data collection period. The exact data points collected are listed in Table 6.

Table 6 - Monitored Points for the each building

Building	OAT	SWT	RWT	Pump Enabled	Pump Speed	Coil Position
25	✔	✔	✔	✔	✔	✔
45	✔	✔	✔	✔	✔	
54	✔	✔	✔			
710A	✔	✔	✔	✔	✔	
810	✔	✔	✔	✔	✔ [1]	✔

1) Pump speed was registered at 80% for the entire montioring period

In building 54, pump status and speed were not recorded due to the fact that it still contained CV pumps. It is also worth noting that the pump speeds for all three pumps in building 810 were recorded as 80% for the entire period of observation and these three control points should be commissioned to correct the fault associated with the pump operating at the same flow rate. The pump speed should modulate based on the heating load and vary throughout the winter.

V. Results

The results section is broken up into three main sections. The first section describes the utility data analysis and results. The second section evaluates the BAS trend data that were collected and looks at predicted annual efficiencies, estimated from the data collection period. The last section evaluates results on how the different hot water distribution systems were interacting with the condensing boilers in terms of return water temperature and firing rates.

A. Utility Bill Analysis

Monthly natural gas consumption data were provided by Region 8 for the period October 2008 through September 2011. The condensing boiler retrofits occurred during late summer/early fall of 2010. Therefore, the utility data provided contains approximately two years of pre-retrofit data, and one year of post-retrofit data. The function and schedule of the buildings did not change over the period of the analysis.

To accurately quantify the savings due to the condensing boiler retrofit, it was necessary to normalize the utility data with respect to weather. Ideally, one would be able to compare the gas consumption between a winter month before the retrofit and a winter month after, yet a simple comparison is not accurate due to the fact that one month might have experienced warmer or colder weather than the other. Therefore a method called steady-state inverse modeling was used to compare the pre- and post-retrofit data. This method is described in detail in the 2009 ASHRAE Handbook – Fundamentals[xii], and an overview of the process is described below.

First, daily average outdoor dry-bulb temperature data were gathered from Weather Underground for the three year period for which the utility data was provided[xiii]. These data were used, along with the building's "balance temperature," to approximate the heating demand for that time period. "Balance temperature" is defined as the temperature below which active heating is required. A balance temperature is a building-specific temperature that is a function of the building's construction and internal loads. The heating demand for the building is then quantified in terms of heating-degree days using the outdoor air temperature and the building's balance temperature. Heating-degree days quantify how far and how often the outdoor temperature differs from the balance temperature of the building. Therefore, they quantify the heating demand on the building.

A linear regression was then performed on the correlation between heating-degree days and daily energy use. An example regression is shown in Figure 11, the rest of the figures are included in Appendix A. This was done twice for each individual building, once for the pre-retrofit gas consumption and once for the post-retrofit gas consumption. It can be seen that the regressions had very high R^2 values across all of the five buildings, with all but one regression having R^2 between 94% and 99% (other value at 86%).

These two correlations describe how much natural gas was used by the building before and after the condensing boiler retrofit for any given outdoor air temperature. This makes it possible to compare the gas consumption on an equal basis regardless of the weather data for that specific year.
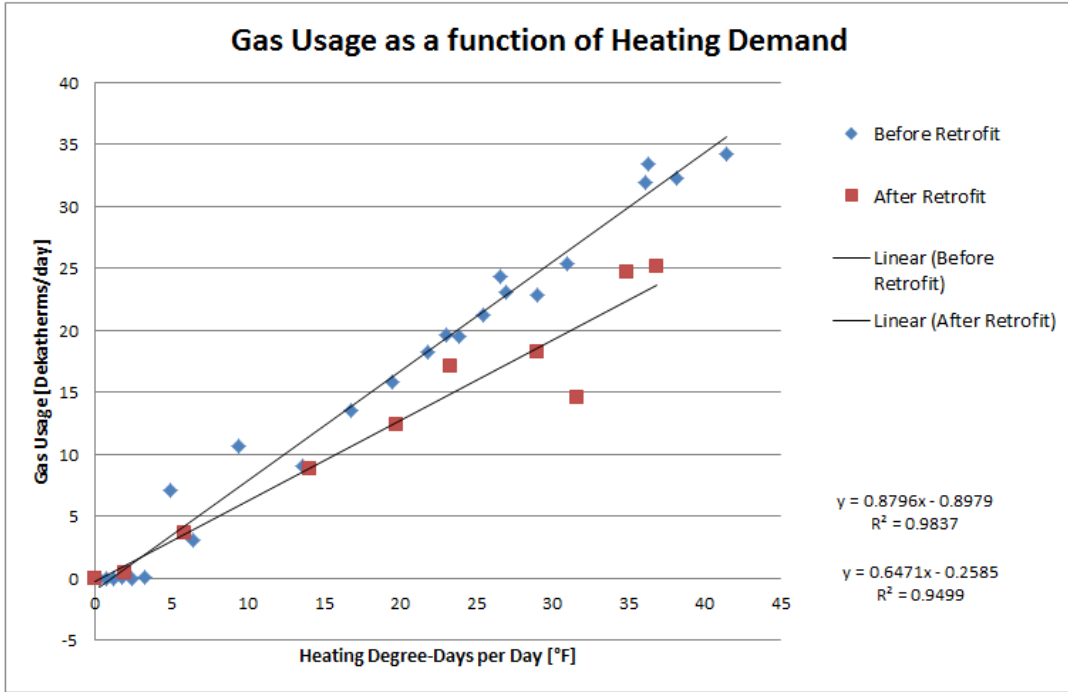
Figure 11 – Regression on gas usage as a function of heating degree-days (Building 45)

The pre- and post-correlations were used to estimate the annual savings due to the boiler retrofits. The energy savings are presented in Figure 12. The first pair of bars for each building are the actual gas consumption values for 2009 and 2011 (pre- and post-retrofit), and the blue, second set of bars is the weather normalized gas consumption for the same year.
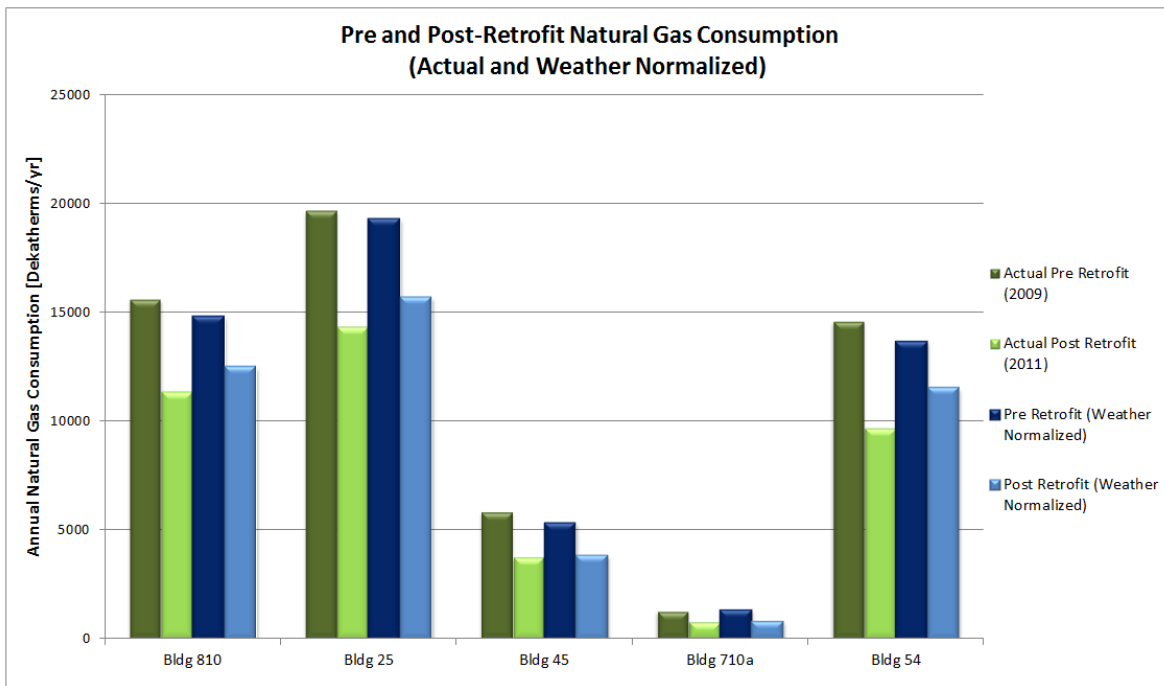

Figure 12 – Natural gas savings from condensing boilers (actual and weather normalized savings)

The estimated annual cost savings are presented in Table 7. These cost savings are again based on the weather normalized savings for 2011. The assumed utility rate for this example is the average natural gas rate for January to September 2011. That average cost was calculated at $7.10/Dekatherm. Changes in natural gas rates will affect the estimated savings and resulting paybacks. This is shown in Figure 13 .

Table 7 – Estimated savings for 2011 for each observed building

Building	Year	Estimated Savings	Percent Savings
Bldg 25	2011	$25,544	19%
Bldg 45	2011	$10,602	28%
Bldg 54	2011	$15,269	16%
Bldg 710A	2011	$3,906	41%
Bldg 810	2011	$16,368	16%

The total estimated energy savings from the utility data analysis that was performed was 100,097 therms of natural gas, and $71,690 of annual utility bill savings.

The estimated savings are larger than what would be expected from a change in steady-state efficiency alone. This can be attributed to the switch from the old "high mass" boilers, which require more energy to heat the boiler to the operating temperature. Condensing boilers are "low mass" systems that contain less water and lower mass heat exchangers, which can reduce cycling losses. In the case of building 45, this retrofit also included a conversion from steam to hot water. This change to the hydronic system also would impact the monitored savings.

Table 17 shows the economic evaluation of replacing the existing boilers with condensing boilers for each of the five sites at the DFC. The initial costs used for the condensing boiler systems were based on the normalized cost of $48.18/MBH, established in this report.

Initial cost estimates were generated from a number of sources including capital cost values for the condensing projects provided by GSA. These values were combined with research from a full market-research effort to generate a $/MBH installed cost estimate for standard boilers, near-condensing and condensing boilers ($26.21/MBH for standard, $43.46/MBH for near-condensing, and $48.17/MBH for condensing). For discussion of the market research, refer to subsection VI.D: Market Potential within the GSA Portfolio.

Table 8 and Table 9 show the results of this economic analysis. Table 8 presents the economic analysis with the "average" installed cost generated from market research. Table 9 shows the same analysis with the actual installed costs of the DFC installations. The cost of the standard replacement boilers were estimated using the 86% efficient boiler costs from the market cost research performed for this report (see Table 15). The standard replacement boiler costs were used in calculating the incremental cost when a replacement is necessary; therefore it was necessary to use a system cost that would reflect the typical replacement option. It was assumed that GSA would replace older boilers with at least a near-condensing system in order to pursue energy reduction on-site and stay compliant with federal requirements. When calculating the incremental energy cost savings of the condensing boiler over the near-condensing replacement option, the calculated energy cost savings were multiplied by the ratio of the rated efficiency improvement ($\frac{(95-86)}{(95-80)}$ or 60% of the savings achieved

by the condensing boilers) to account for the incremental energy savings that would be achieved by the condensing option.

Table 8 – Calculated simple payback and net present value for the five sites for condensing boilers with normalized initial costs

Building	Initial Cost Replacement Boiler	Initial Cost Condensing Boiler	Replacement Necessary			Replacement Optional		
			Incremental Energy Cost Savings	Simple Payback Period (Years)	Net Present Value	Energy Cost Savings	Simple Payback Period (Years)	Net Present Value
25	$629,084	$697,406	$15,326	4.46	$254,452	$25,544	27.30	-$159,449
45	$183,836	$203,801	$6,361	3.14	$114,001	$10,602	19.22	$19,477
54	$524,236	$581,171	$9,161	6.21	$136,004	$15,269	38.06	-$259,606
710A	$122,557	$135,868	$2,344	5.68	$36,046	$3,906	34.78	-$53,607
810	$629,084	$697,406	$9,821	6.96	$138,504	$16,368	42.61	-$352,695

Table 9 – Calculated simple payback and net present value for the five sites for condensing boilers with actual initial costs

Building	Initial Cost Replacement Boiler	Initial Cost Condensing Boiler	Replacement Necessary			Replacement Optional		
			Incremental Energy Cost Savings	Simple Payback Period (Years)[1]	Net Present Value	Energy Cost Savings	Simple Payback Period (Years)	Net Present Value
25	$629,084	$618,057	$15,326	NA	$333,800	$25,544	24.2	-$80,100
45	$183,836	$1,458,469[2]	$6,361	200.4	-$1,140,666	$10,602	137.6	-$1,235,191
54	$524,236	$506,389	$9,161	NA	$210,786	$15,269	33.2	-$184,824
710A	$122,557	$361,347	$2,344	101.9	-$189,434	$3,906	92.5	-$279,087
810	$629,084	$570,748	$9,821	NA	$265,162	$16,368	34.9	-$226,038

[1]Certain installations had lower actual installed costs than the estimated cost of a near-condensing replacement. This makes the incremental replacement payback immediate. These are denoted "NA".
[2] Note that the high initial cost associated with this retrofit included a full steam-to-hot water conversion and asbestos abatement costs.

With the actual initial costs used in calculations, as can be seen in Table 9, the retrofits at buildings 45 and 710A no longer have positive net present values. The variation between the average installed cost and actual installed cost calculations demonstrates the fact that actual installed costs can vary significantly due to a variety of factors including: boiler room size/access, access for flue stack venting, complexity of boiler room piping, and various other factors. The retrofit at Building 45 included a full steam to hot water conversion which included the installation of hot water piping throughout the building, asbestos removal and installation of necessary hot water pumps and controls. Although GSA does not have itemized costs for this building the installed costs for the condensing boiler made up a small percentage of the overall retrofit costs for this building.

A sensitivity analysis on the cost of natural gas can be seen in Figure 13 and Figure 14. This analysis utilizes the average (not actual) installed boiler costs. Figure 13 shows simple payback for varying natural gas rates when a boiler replacement is necessary (end-of-life replacement). Figure 14 shows the same data for the case where a boiler replacement is not required (efficiency upgrade only). As expected the payback period is shorter for higher natural gas costs and it is also significantly shorter payback when a boiler replacement is necessary. It can be noted that for higher gas rates, the "efficiency only" replacement for can be cost effective.
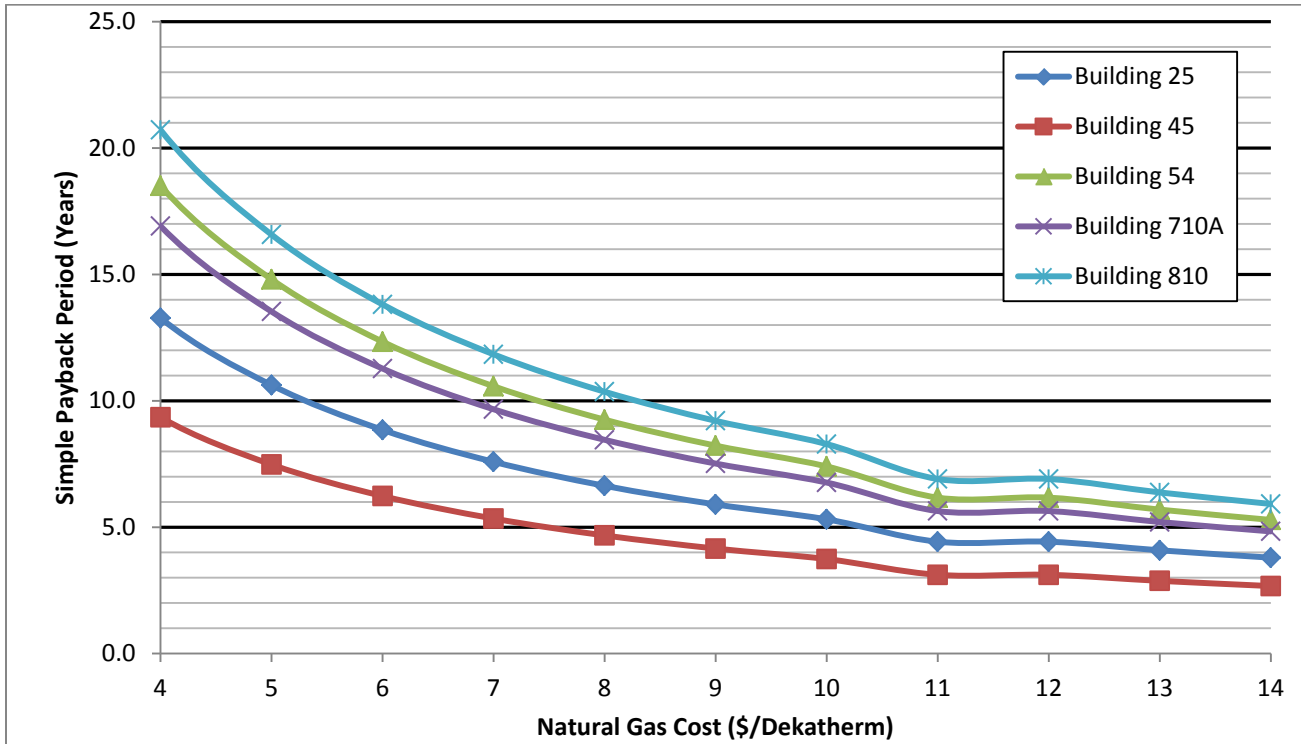

Figure 13 – Simple Payback Period vs. Natural Gas Cost for Normalized Boiler Costs When a Boiler Replacement is Necessary
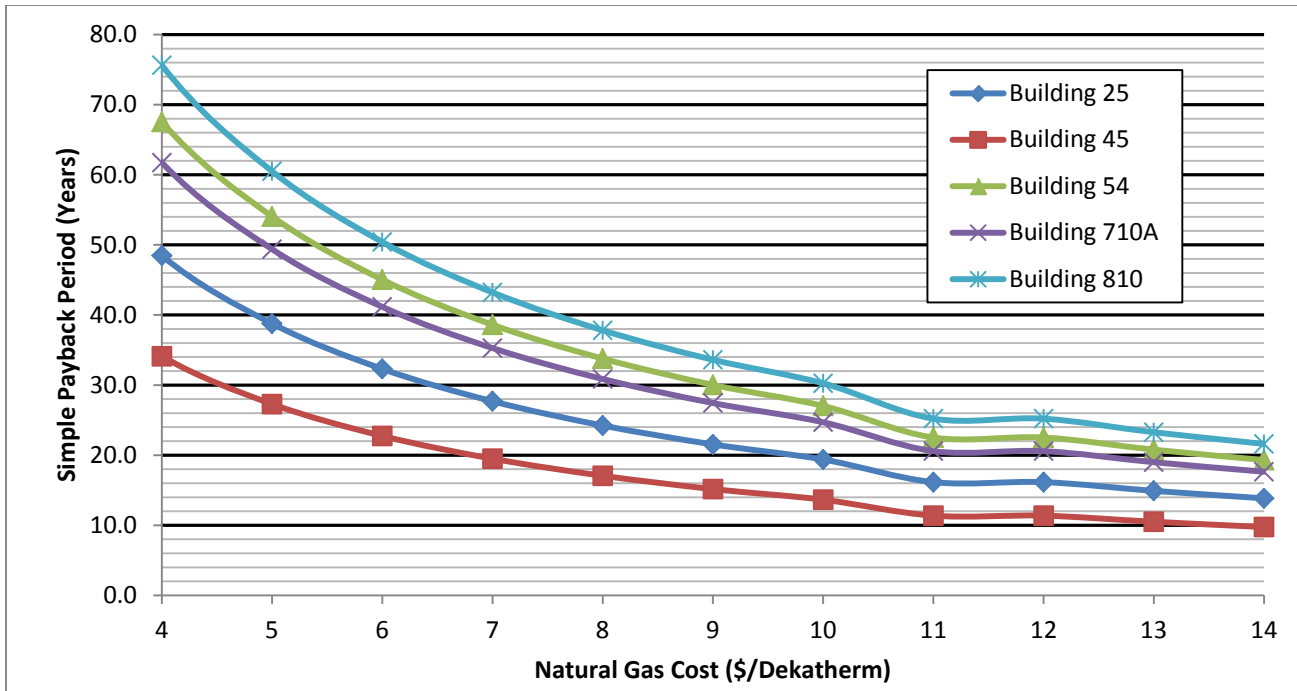
Figure 14 - Simple Payback Period vs. Natural Gas Cost for Normalized Boiler Costs When a Boiler Replacement is not Required (efficiency upgrade only)

Net present value was calculated in this report according to the National Institute of Standards and Technology (NIST) Handbook 135[xiv] with an assumed boiler life of 25 years, a discount rate of 3% and natural gas as a fuel for a commercial building located in Colorado. The life expectancy of 25 years is the estimate provided by the Federal Energy Management Program's Energy Efficient Product Procurement guide.[xv] The replacement necessary category considers the difference in costs of a standard versus condensing boiler, while the replacement optional category considers only the cost of a new condensing boiler.

B.   Metered Data Analysis

The BAS data was gathered from February 7, 2012 through April 15, 2012. These data were provided to NREL by the head of advanced metering at the DFC. The BAS data was used to analyze the actual performance of the boiler systems in each of the five buildings. This section looks directly at the interaction of the boiler plant, the staging controls for the plant, and the hot water distribution system.

The effect of the return water temperature and firing rate on the boiler efficiency for the boilers that were installed at the DFC is shown in Table 10. In general, the lower the return water temperature and firing rate, the higher the efficiency.

Table 10 – Efficiency values at various firing rates and return water temperatures for boilers at DFC

Firing Rate	Return Water Temperature °F (°C)						
[%]	68 (20)	80 (27)	105 (38)	120 (49)	130 (55)	140 (60)	160 (72)
20	99	99	98	97	95.5	93.7	88
50	98.25	99	97	93	91.5	89.5	87.5
75	98	97	93	89	88	87.5	86.5
100	97.2	96.5	91	88.25	87.5	87	86.25

The efficiency is affected by the staging of the boilers, the boiler firing rate and the return water temperature. The annual operational efficiency of the each boiler plant was estimated and compared to the efficiencies of the old boilers and the results of the utility analysis section.

Outside Air Reset

The design supply water temperature for the boiler plants that were monitored is between 180 °F and 200 °F and the hot water supply temperature is reset based on outside air temperature. A lower supply water temperature can allow for lower firing rates and also will lead to lower return water temperatures to the boilers. Both of these effects will increase the operating efficiency of the boiler plant.

The outside air reset control directs the control system to reduce the supply water temperature when the outdoor temperature rises, essentially allowing the supply water temperature to be lower when there are lower loads on the system. The 15-minute supply water temperature data for each building was compared to the 15-minute outdoor air temperature (OAT) data. The relationship between the supply water temperature and OAT is shown for building 25 in Figure 15. Building 25 showed very high supply water temperature for some of the coldest OATs (close to 200°F) and also did not appear to be turning off appropriately at the stated 72°F outdoor air cutoff temperature. Inspection of the remaining buildings demonstrated that the outdoor air reset control had been implemented in each building. There did not appear to be a cutoff temperature for any of buildings (except for building 810). Supply water temperatures for the other four buildings remained around 120°F with OATs reaching as high as 90°F. It is important to note that ensuring desired operation with the outdoor air cutoff could provide significant savings to GSA with minimal upfront costs and should be investigated on a building-by-building basis. It is difficult to quantify the exact savings that a correctly implemented cutoff temperature would provide, yet eliminating boiler operation when outside air temperatures are above 72°F will reducing total operating hours and contribute to overall savings.
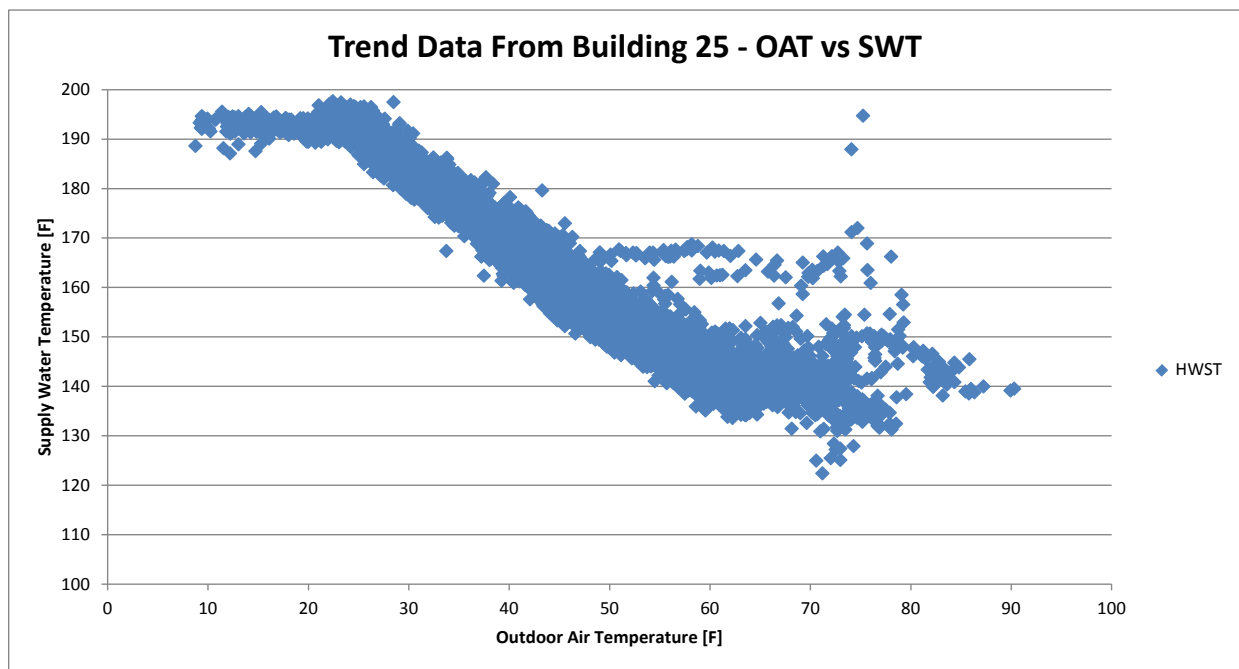

Figure 15 – Demonstration of outdoor air reset control (building 25)

Boiler Staging/Sequencing Controls

The firing rate of the boilers also has a large impact on the efficiency of the boilers. Condensing boilers have a different relationship with part load operation than traditional boilers, as they operate at a higher efficiency at lower partial loads. The staging of the boiler plants was investigated through discussion with the distributor who was responsible for the boiler installations at the DFC.[xvi] The staging control that was implemented for the DFC boiler plants was a lead/lag staging, where a certain boiler is designated as the lead boiler and it controls when the other boilers are turned on. The specific boiler that is the lead boiler can be alternated to achieve equal runtime. The control sequence ramps the lead boiler up to a 70% firing rate and then turns on a second boiler. Once the second boiler is turned on the two boilers are controlled to ramp up at the same firing rate, for example, instead of one boiler operating at 80%, both would fire at 40%. These two boilers would ramp up to 70% and then a third boiler would be turned on, and so on down the line. It was stated that the 70% threshold was selected for two reasons:

- To allow for adequate warm-up time for the lag boiler and still be able to meet an increasing load; and
- To eliminate any cycling (even with a 5:1 turn down ratio there is the possibility for cycling at low loads, which reduces overall efficiency).

This parallel staging of the boilers is an effective way to reduce firing rates and increase efficiency. The exact threshold for lead/lag staging is difficult to determine and the initial programming of 70% could potentially be evaluated and optimized for maximum operation time at low firing rates while avoiding cycling, yet this is generally the appropriate control for boiler plants with multiple condensing boilers.

Return Water Temperature Analysis

The return water temperature is the variable that has the largest impact on condensing boiler efficiency. The return water temperature for each building was binned into ten bins of 10°F each. The bins ranged from 90°F to 180°F, with each bin value representing the frequency with which the return water temperature was monitored in that range of temperatures. The value of each bin represents the upper limit of the bin (for example, the 130°F bin contains all instances where the return water temperature was between 120°F and 130°F).
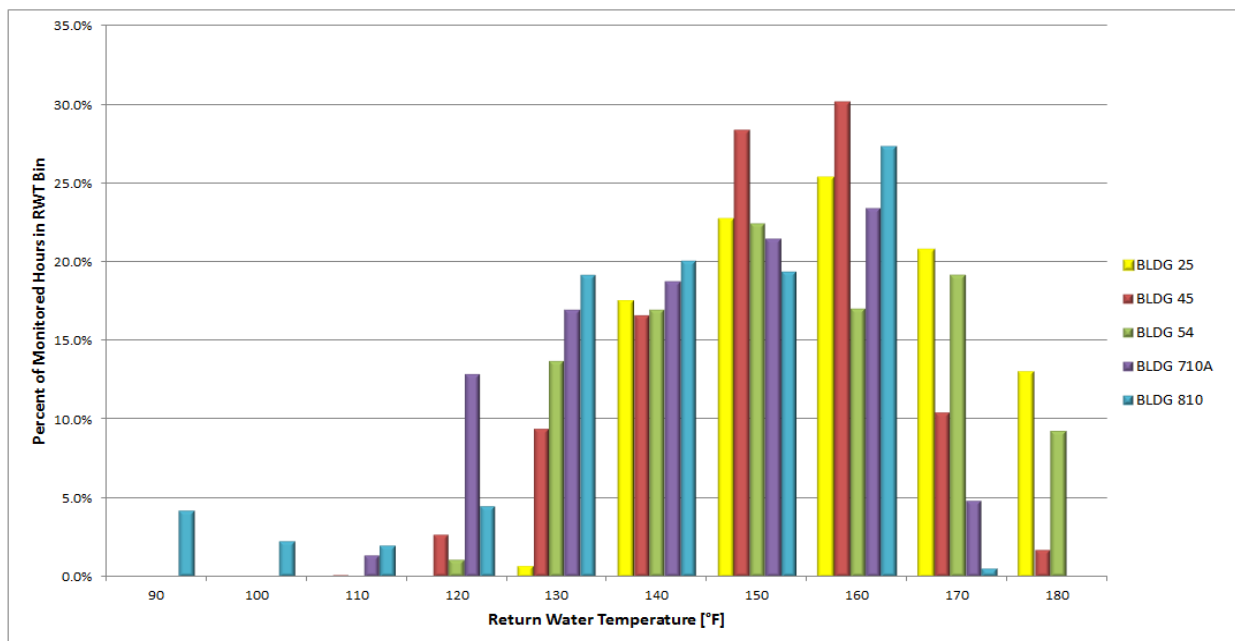

Figure 16 – Histogram showing percent of monitored hours that return water temperature was in various temperature bins

For the boiler to be in condensing mode, the return water temperature needs to be less than approximately 130°F. It can be noted that the return water temperature was often higher than this 130°F for all of the buildings. The exact percentage of time that the return water temperature was monitored at or below 130°F is shown in Table 11. One performance metric that was established at the beginning of the study was a requirement that the system would operate in condensing mode for at least 20% of the time. It can be seen that only buildings 710A and 810 achieved that goal. It should also be noted that the monitoring period consisted of relatively warm temperatures for the Denver area (due to both a warmer than average winter and the fact that the period stretched into the middle of April), and that the percent of time on an annual basis for future years might be lower than those noted below.

Table 11 – Percent of time in condensing mode (assuming 130°F)

Building				
25	**45**	**54**	**710A**	**810**
0.7%	12.4%	14.9%	31.4%	32.5%

To accurately compare the installed performance of the boilers to the incumbent technology, it was necessary to estimate an annual efficiency for the condensing boilers. This was done by correlating the return water temperature to the OAT during the monitoring period by means of a linear regression. Typical meteorological year (TMY) data for outdoor dry bulb was then gathered for the Denver/Golden location. Using the regression correlation, return water temperature was estimated for a typical year. The operating efficiency was then calculated for each hour that was below 72°F (the stated cut off temperature for the boilers at select facilities). Due to the difficulty in estimating firing rate, the efficiencies were calculated for three different firing rates. The annual efficiencies for each of the different buildings are presented in Table 12.

Table 12 – Estimated annual efficiency for each building (for firing rates of 20-75%)

	Building				
Firing Rate	**25**	**45**	**54**	**710A**	**810**
20%	90.1%	90.7%	90.8%	93.4%	92.3%
50%	88.2%	88.6%	88.7%	90.6%	90.1%
75%	86.7%	86.9%	87.0%	87.9%	87.9%

From the control logic for boiler staging, it can be determined that the boilers would be firing between 35% and 70% for the vast majority of the year. The only times when a firing rate would be below 35% is at very low loads when only the lead boiler is on and is below 35%. The only time when a firing rate would be above 70% is at very high loads when all of the boilers have been called on and then need to fire at over 70% to meet the load. Therefore, an average of the boilers would be in the 50% firing rate range for the majority of the year.

To accurately compare the calculated efficiencies of the condensing boilers (presented above in Table 12) with the pre-existing boilers, it was necessary to calculate an installed efficiency for the old boilers. This was done by utilizing the weather normalized utility data to calculate the load on each building. This load was divided by the pre-retrofit energy usage (again weather normalized) to estimate an annual efficiency. These results are

presented in Table 13. It can be noted that the calculated annual efficiencies are significantly lower than the reported steady state efficiencies listed in Table 5. These were listed as 80% for all buildings except 710A, which was listed at 66%.

Table 13 – Calculated efficiencies of the pre-existing boilers

Building	Pre Retrofit Energy Use (therms)	Actual Load (therms)	Original Annual Efficiency
25	192,576	138,120	72%
45	53,224	33,927	64%
54	136,567	102,059	75%
710A	13,576	7,315	54%
810	147,831	112,425	76%

Ideally, firing rates would have been calculated from the load in the building (calculated using the formula $\dot{Q} = \dot{m}C_p\Delta T = 500.4 \times GPM \times (SWT - RWT)$). The supply water temperature and return water temperature was gathered from the metered data. The GPM could be calculated by multiplying the VFD speed (in percent) by the rated GPM for the pump (valid due to the variable flow aspect of the pump). A correlation between load and OAT could then be calculated and firing rates could be estimated for the TMY data, allowing a more accurate estimate of annual efficiency. This was generally not possible due to the fact that:

- Building 54 did not report VFD speed.
- Building 810 reported 80% VFD speed for all of its pumps for the entire monitoring period.
- Building 45 ran the pumps at approximately constant speed of 49-52% making any correlation between load and outdoor air temperature very weak.
- Building 710A ran at such low loads (calculated at less than 19% of a single boiler capacity for the entire monitoring period) that it was not necessary to calculate.
- Building 25 presented the best data and this calculation is documented in the Appendix. The calculated average firing rate of 49.4% compared very well with the 50% estimated rate based on sequencing control logic.

Though the data limitations listed above limited the ability to calculate an exact annual efficiency for each boiler combination, they did provide some interesting insight on how the different buildings were operating. These will be evaluated in the last section of the results.

C. Hot Water Distribution Effects on Boiler Operation

Heating Coil Design
As previously mentioned, condensing boilers are best matched with coils specifically designed for a large temperature differential or for low supply water temperatures, or both. This allows for low return water temperatures, both at design conditions (where a 50°F ΔT coil can take supply water temperature at 180°F and provide 130°F return water temperature) and at lower load conditions where low supply water temperature coils maintain significant temperature differentials at low supply water temperatures. In a retrofit scenario, it is often difficult and costly to retrofit the heating coils. The condensing boiler retrofits at the DFC did not include coil retrofits. This limited the ability of the boilers to achieve the upper end of their efficiency potential due to

the consistently higher return water temperatures. The impact that the pre-existing hot water distribution system has on return water temperatures can be seen in Figure 17 for building 45. It is clear that the hydronic system was designed for a 20°F temperature differential at near-design conditions. This temperature differential drops to only a few degrees at lower supply water temperatures. With higher ΔT coils, and low supply water temperature coils, the return water temperature points would most likely have seen much larger separation from supply water temperature points, allowing for more return water temperatures in the condensing range for the boilers.
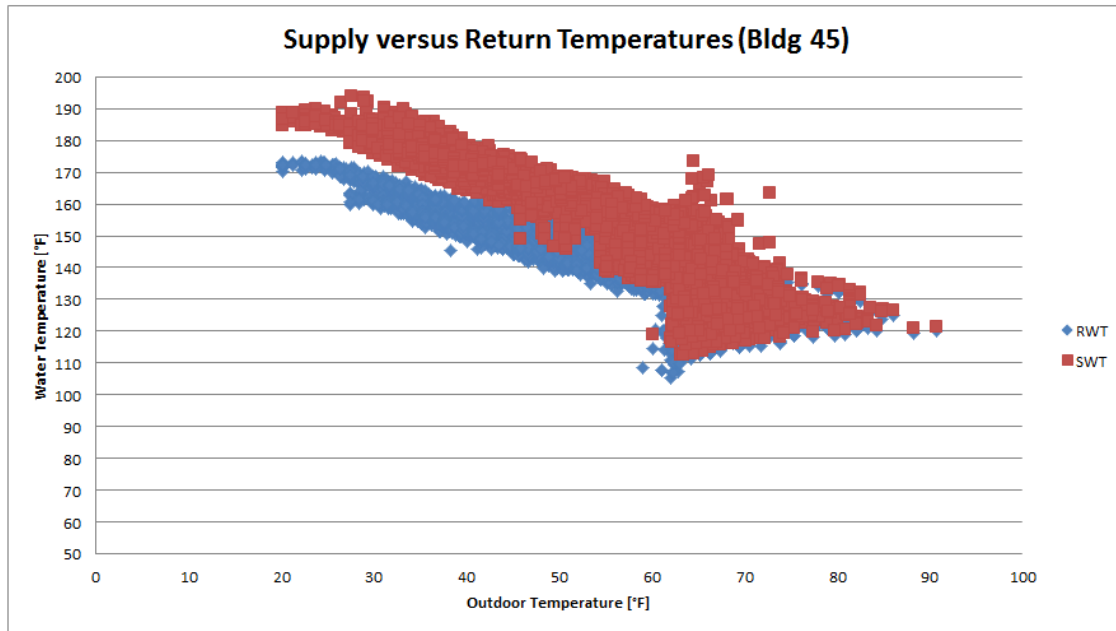

Figure 17 – Supply and return temperatures for Building 45

Control Valve/Piping Design
The type of control valve and piping design also can drive higher return water temperatures. The use of three way control valves mixes return water with supply water and increases the return water temperature.

In buildings 25, 54, and 810, there are a number of large AHUs that had three way valves and booster pumps that led to mixing of return and supply water. In addition to the control valve issues at the coil level, there were certain loops in parallel with unbalanced loads that were remixed before returning to the boilers. The effect of the bypass piping at each AHU (from three-way valves) and remixing is shown for a single week in February in building 25 (Figure 18). The solid lines are the supply water temperature and return water temperature from the boiler plant. The dashed lines are the supply water temperature and return water temperature from the EPA loop. The return water temperature from the EPA loop reached temperatures that would have allowed condensing operation, yet it was remixed with return water from some of the other loops (which have significant bypass at the AHUs, though not at the VAV boxes) and the final return water temperature seen by the boilers returned into the 150°-170°F range, disallowing any condensing operation during this time period.
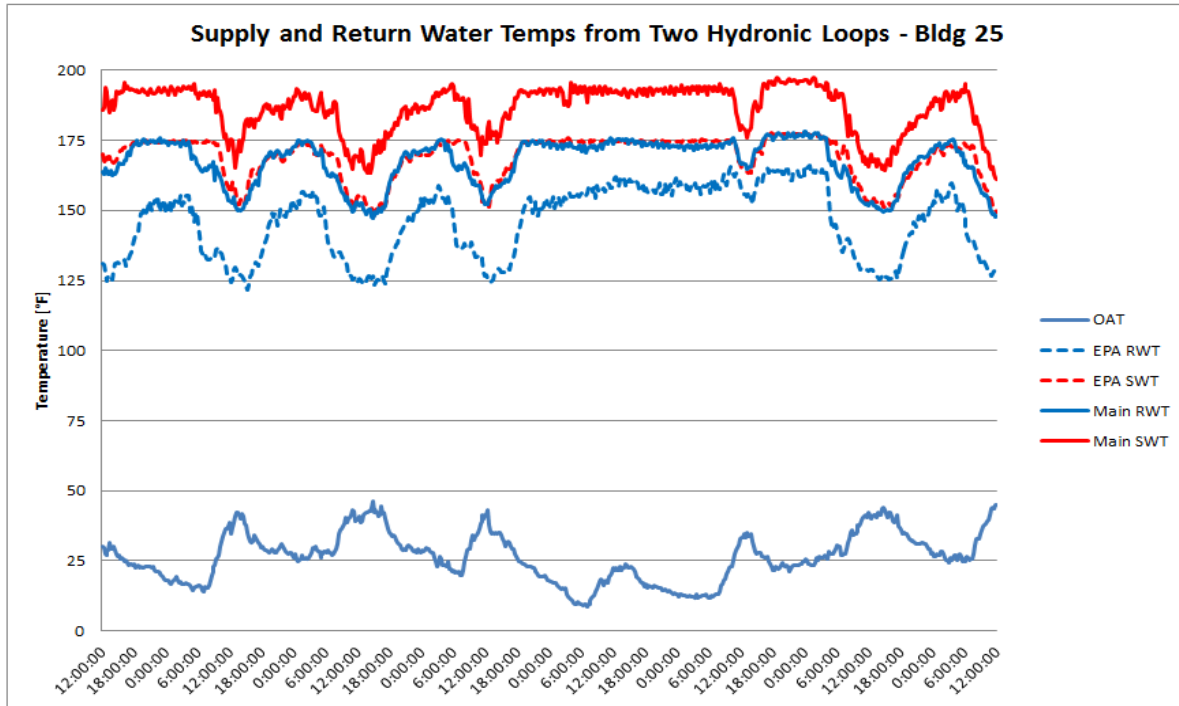
Figure 18 – Trend data for building 25 (2/7/12-2/14/12)

VI. Summary Findings and Conclusions

A. Overall Technology Assessment at Demonstration Facility

Condensing boilers offer the potential for reduction in natural gas usage through improved operating efficiencies. The steady-state efficiency increase can be anywhere from 6% to 18% over a standard natural gas fired boiler. This could offer Region 8 significant savings in many of its buildings. The combination of utility data and BAS trend data offered quality information on both the operation and the realized savings of the condensing boiler installations at the DFC.

The utility data analysis showed that all of the installations were realizing significant savings. These savings ranged from 16% to 41%. This analysis included weather normalization to compare pre- and post-retrofit gas usage on equal grounds.

The economic analysis demonstrated that all five of the projects had positive net present value (using a 25-year lifetime) for the case where a boiler replacement was necessary. Boiler replacements were necessary for four of the five installations. These four buildings all had existing boilers that were more than 20 years old. ASHRAE maintains a database on equipment lifetimes and the replacement age for boilers in that database was 18-25 years (depending on exact boiler type).[xvii] Only Building 810 made the replacement only for improved efficiency.

One of the criteria set out in the objectives section was achieving condensing mode operation for more than 20% of the year. Analysis of the BAS trend data showed that only two of the five boiler plants achieved this goal during the monitored period. The higher return water temperatures seen by the boilers led to calculated annual efficiencies ranging from 87% to 93% depending on firing rate. When the boiler staging control sequence was taken into account (to determine approximate firing rate), it was estimated that those efficiencies were in the 88% to 90% range depending on the building. These efficiencies could be improved if the return water

temperature to the boilers was brought down further in to the condensing zone (less than 130°F) for a larger portion of the year. Increased hours in condensing mode could be achieved in a number of different ways. Some methods require little upfront investment. A more comprehensive approach is the piping retrofit discussed in subsection VI-B, Best Practices, below.

Low cost/No cost:
- A more aggressive OAT reset to reduce the supply water temperature and therefore the return water temperature (good approach, unless occupant complaints are registered due to reduced heating delivery).

- Another control option that can save more energy than an OAT reset is a load based reset that resets supply water temperature based on heating coil valve position. For example if all of the valves are not 100% open the supply water temperature would be reduced until one valve opens to 100% open. This is more complicated control logic, yet is also more precise control.

- Adjust the balancing valves in the bypasses on the three-way valves to limit the amount of water that bypasses the coil while still maintaining adequate valve authority (if VFDs are installed, closing bypass valves should be investigated, assuming sufficient head delivered by the pumps).

Retrofit:
- Piping retrofits to address mixing of supply and return water streams.

- Coil retrofit to higher ΔT coils that will return water below condensing temperature.

A summary of the results and findings from the current study is presented here:
- Two out of five of the condensing boilers operated in condensing mode for more than 20% of their operating hours.

- All of the boilers that were replaced at the end of their life (4 of 5 of the boiler plants) achieved lower life-cycle costs than a conventional boiler plant.

- A systematic review of valving, hot water piping, and heating coils in each building can increase the efficiency of the condensing boiler plant by reducing return water temperatures.

- Low cost improvements include a lower outdoor air cutoff above which the boilers are shut off and checking to ensure that the cutoffs in place are working appropriately. A more aggressive outdoor air reset schedule should reduce the temperature of the return water and improve the boiler plant performance.

B.   Best Practices

Condensing boilers are an effective technology for reducing the energy consumed for space heating if best practices are followed during installation. As noted above, installing a modular condensing boiler plant alone does not guarantee savings beyond what near-condensing boilers can achieve, and there are a number of best practices related to the design and operation of a condensing boiler plant, the majority of which can be applied to retrofit installations.

New Construction - High Performance Condensing Boiler Plant Example

The following design example (Figure 19) is intended to illustrate the design considerations and best practices for a high-performance condensing boiler heating system. The following schematic depicts a typical heating water system.
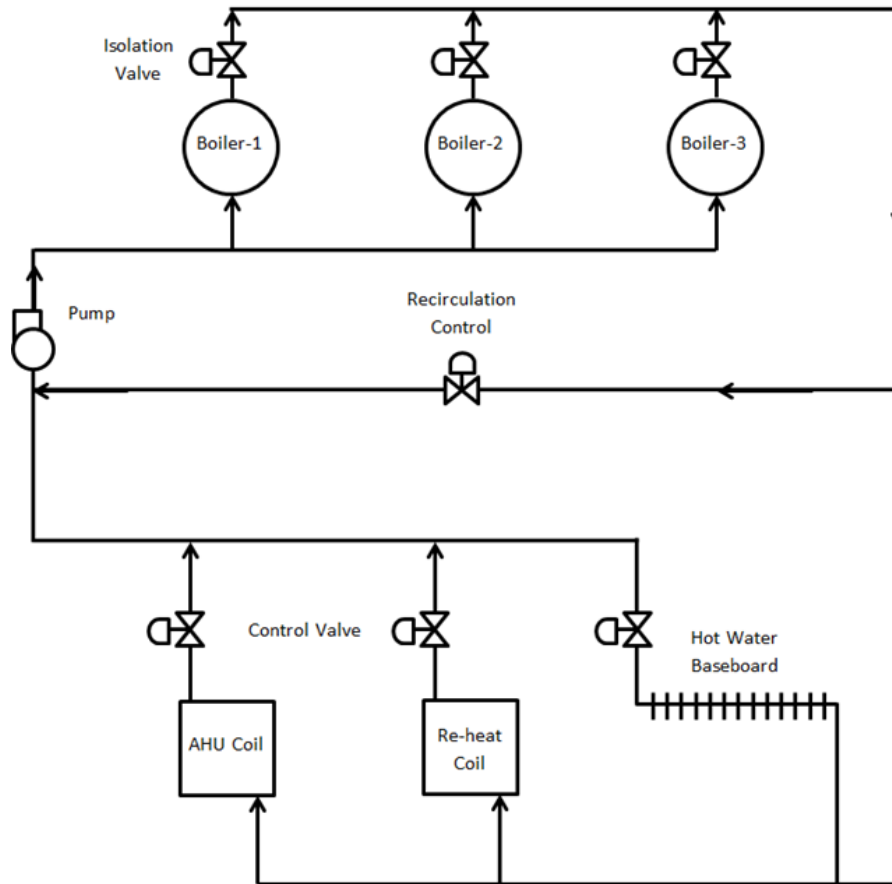

Figure 19 – New Construction Condensing Boiler Plant Schematic

The system has the following components:

- A variable speed pump controlled to maintain a pressure differential set point between supply and return piping.
- Three condensing boilers, each with an isolation valve. A boiler controller sequences the boilers according to a control strategy designed to optimize system performance.
- A recirculation control valve operates at low load to maintain a minimum flow rate through the operating boiler.
- Two heating coils and a hot water baseboard unit are depicted. Each is equipped with a two-way control valve to control coil heat output to a leaving air or room temperature set point.

The representative design goal for a high performance condensing boiler plant should be similar to:
- Meet the design 100% heating load with a 180˚F supply water temperature and a 120˚F return water temperature.
- Maintain a 120˚F return water temperature through full load range down to 5% load. The supply water temperature may be reset downward as loads decrease.

High Performance Condensing Boiler Plant Design Elements

A listing of the high performance elements that should be included in the design are provided and discussed in relation to the hypothetical schematic.

Primary-only vs. primary-secondary distribution system

Figure 19 depicts a primary-only piping system; meaning the system has one variable-speed pump that provides variable flow rates through both boilers and coils. Traditional systems with multiple boilers often use primary-secondary piping where each boiler has a dedicated constant-speed primary pump and the coils share a variable-speed secondary pump. Primary-secondary piping is not recommended for condensing boilers. The problem with primary-secondary is, if boiler and load flow rates are not exactly the same, there will be mixing of supply and return water. Mixing will result in either elevated return water temperatures to the boilers or reduced supply water temperatures to the coils. Designing a high ΔT system requires minimizing mixing of supply and return water. A primary-only system almost always matches boiler and load flows and should be implemented when designing and installing condensing boiler plants.

Boiler Turn-Down Ratio

Condensing boilers are typically designed with a low burner turn-down ratio to 20% or lower. Some condensing boilers have a turn-down ratio as low as 5%. If loads drop below the turn-down ratio, the boilers must cycle on and off to meet the load, which significantly reduces the efficiency of the boiler. A boiler with a low turn down ratio should be selected. The boilers at the DFC have a 5:1 turndown ratio.

Boiler Flow Requirements

Minimum and maximum operating water flow rates (gpm) are usually more important than the burner turn-down ratio. For instance, the boilers in the example can turn down to 5% at the gas burner, but the water flow through the boiler can only be turned down to 15%. Thus, operation at low load will result in a low ΔT across the boiler and throughout the entire system. Some condensing boilers have a minimum flow ratio as high as 40%, which isn't likely to work for most high-performance systems. A boiler with a low minimum flow ratio should be selected. The boilers installed at the DFC do not have a minimum flow requirement.

Boiler Sizing

Accurate equipment sizing is important to the operational performance for any system; operation below minimum turndown must be minimized for good energy performance. Low-mass boilers can be installed as modules in banks of 2 to 5 boilers. The controls then enable the number of boilers required to meet the load. Larger and smaller boilers can be combined into modular systems and controlled to cover the full operating range of heating and flow demands. For condensing boiler plants multiple smaller boilers should be designed to meet a peak heating load rather than one large boiler.

Boiler Sequencing

Boiler sequencing can be complex given multiple boiler sizes, varying burner and minimum flow turn-down, boiler performance characteristics, temperature reset strategies, and the desire to optimize efficiency. Boiler sequencing strategies include the following:

- Traditional series control in which one boiler is fully loaded before the next boiler is brought on line.
- Parallel control in which boilers are operated in parallel at low loads; condensing boilers are most efficient at low loads provided they operate above their minimum turn-down ratios.

For boilers with a minimum flow ratio of 40%, the above sequences may be nearly identical. In general, parallel control is the recommended control sequence for condensing boilers.

Heating Coil Selection

Proper heating coil selection is the most important element of designing a high-performance heating water system. Traditionally, a ΔT on the water side is used to size heating coils. High-performance systems require coil selection at a much higher ΔT, 60˚F, for this example. Performance of a hot water heating coil is given by the following equation:

$$Q = (\dot{m}C_p)_{min} \times \epsilon \times (\text{EWT} - \text{EAT})$$

Where

$Q =$	Rate of heat transfer (Btu/hr)
$(mCp)_{min} =$	Minimum fluid capacitance rate (Btu/hr-°F)
$\epsilon =$	Heat exchanger effectiveness
EWT =	Entering water temperature (°F)
EAT =	Entering air temperature (°F)

Fluid capacitance rate is the product of the mass flow rate and the fluid specific heat for both the air and water sides of the coil. For water-side control (control valve), the water-side capacitance rate must be less than the air-side capacitance rate at design conditions. The heat exchange rate is a function of the minimum capacitance rate and the control valve will vary the minimum capacitance rate to control the leaving air temperature. Coils may be selected using any manufacturer's coil selection software and coils with a 60 °F ΔT are recommended for condensing boiler plants.

Hot Water Baseboard Design

Hot water baseboard selection is more difficult than forced air coil selection. Hot water baseboard relies on the air temperature exiting the unit to drive the airflow. As a result, the heat output is strongly affected by the entering water temperature as the adjacent chart indicates. However, it is possible to achieve a low leaving water temperature by adding additional baseboard length. The next chart (Figure 20) indicates the heat output along 60 feet of baseboard operating with a flow rate of 0.35 gpm and a supply water temperature of 180˚F.
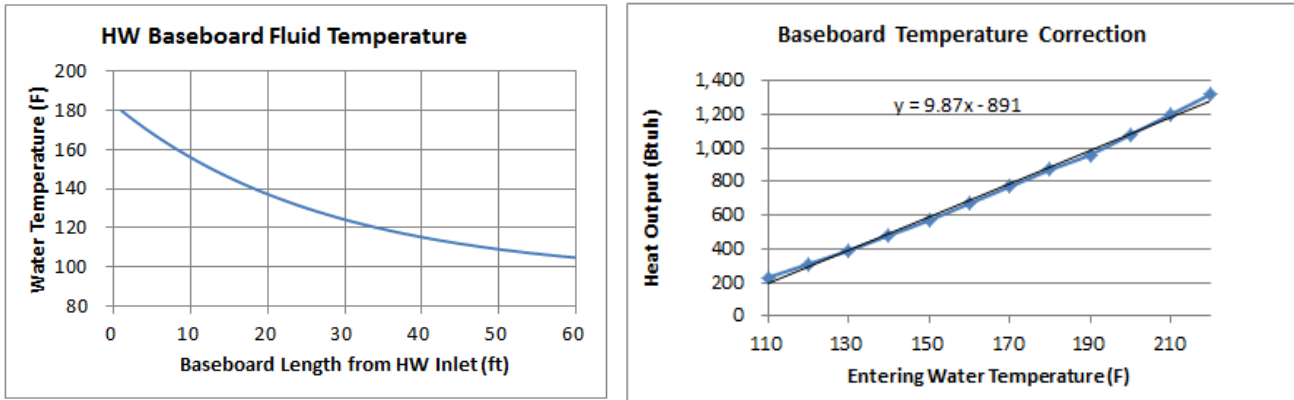
Figure 20 - Hot Water Baseboard Temperature

A return water temperature of 120˚F is achieved with 30 feet of baseboard length. The average heat output is also a function of entering water temperature and design of Hot water baseboard for high-performance condensing boiler plants requires a model to calculate heat output based on supply water temperature, gpm, pipe diameter, and baseboard length. Hot water baseboard designs should target leaving water temperatures of 120°F at design conditions.

Control Valve Selection

Control valves can negatively affect the ability of the system to maintain a high ΔT at low loads. Theoretically, fluid ΔT will increase at low load; restricting the water-side capacitance (flow) with the control valve increases the ΔT. Poor performance is caused by imprecise control at low flow rates, which causes the valve to cycle between fully closed and a valve position where stable control is possible. The cycling results in higher return water temperatures from the coil. For example, the figure indicates a typical hot water control valve operating with a constant supply water temperature; the valve loses its ability for proper control at 40% load where the curve gets close to vertical. As can be seen in Figure 21, the performance can be greatly improved with a supply water temperature reset strategy based on outdoor air temperature or on response to control valve position. It is recommended that all high-performance systems be equipped with modern pressure independent control (PIC) valves. PIC valves can provide accurate control down to the range of 0.5% load.
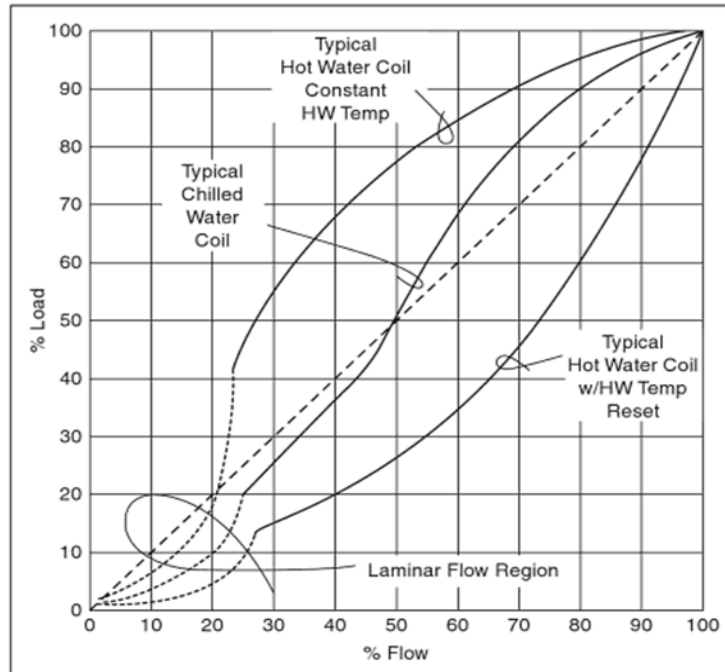
Figure 21 – Control Valve Capacity versus Flow Rate[xviii]

Hot Water Recirculation Control

Most systems are designed for some hot supply water flow into the return piping without going through a heating coil. Design piping features may include:

- A recirculation pipe connecting the supply and return piping at the end of the supply piping to ensure hot supply water is available to all heating coils and that pumps are not forced to operate with zero flow, which could over heat the motor. The pipe may include a balancing valve.
- Similarly, the last control valve at the end of the supply piping may be equipped with a three-way valve serving the same purpose as the recirculation pipe described above.
- A recirculation control valve may be included to maintain the required minimum flow through the boilers. This valve is controlled to maintain a water flow set point at a flow measuring device in the supply piping leaving the boilers, or to maintain a minimum pressure drop across the boilers corresponding to the boiler minimum flow. This feature is nearly unavoidable in a primary-only system.

It is recommended that the recirculation valve be installed towards the end of the supply piping to insure hot supply water temperatures at the end of the piping. Recirculation can be minimized through selection of boilers with low minimum flow rates in combination with multiple boilers sequenced for maintaining minimum boiler flow.

System Control

When it comes to optimizing hydronic system controls, the main focus is centered on reducing boiler supply water temperature to maximize boiler condensing time and efficiency. Control strategies, including optimal boiler sequencing, outdoor air reset, and load reset are commonly employed.

- **Optimal Boiler Sequencing** for a variable-flow primary-only distribution system is dominated by the minimum boiler water flow (gpm). If the flow turn-down is 20% and the boiler is operating at 15% load,

roughly 25% of the hot water supply must be recirculated to the return water header. This characteristic favors a control strategy of loading one boiler fully before bringing the next one on. However, operating more boilers at lower load fractions will improve efficiency, if recirculation is avoided. Boiler efficiency is more sensitive to supply water temperature than percent load, as illustrated in Figure 22.
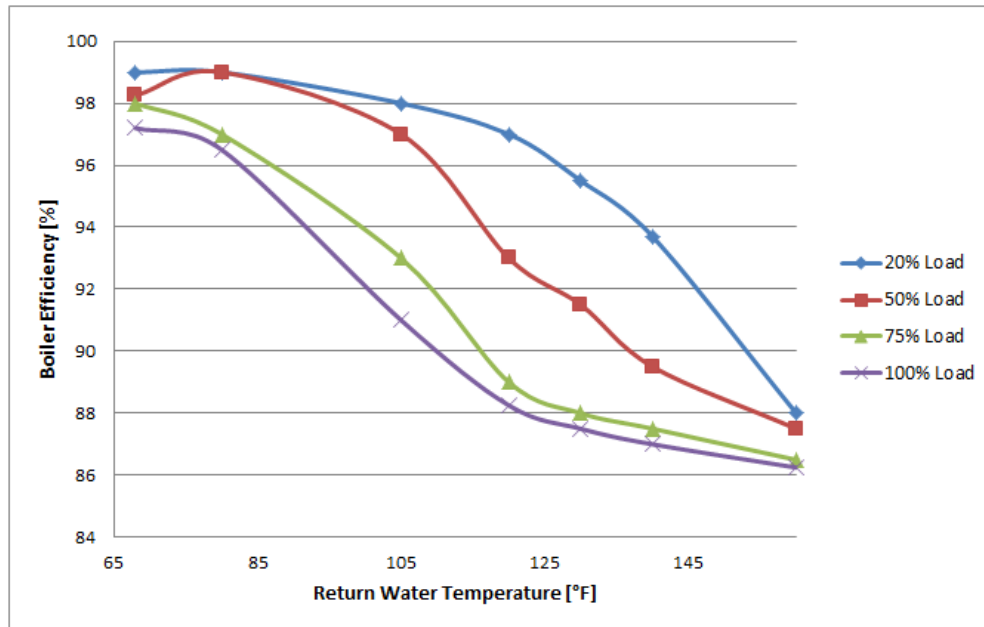

Figure 22 – Boiler Efficiency Curve

- **Outside Air Temperature (OAT) Reset** is common boiler control strategy that reduces boiler return water temperature in response to OAT. Traditionally OAT reset is focused on reducing control valve cycling at low flow, but OAT reset also will reduce boiler supply water temperature and, thus, increase condensing boiler efficiency. For each installation the site is encouraged to implement the most aggressive outside air reset that they can for the given installation. A previous GSA Green Proving Grounds report on condensing boilers entitled 'Condensing Boiler Assessment: Peachtree Summit Federal Building Atlanta, Georgia' has a good example of an aggressive outside air reset schedule that could be applied to future installations and would have resulted in more hours in condensing mode for this installation.**Error! Bookmark not defined.**

- **Load Reset** is like OAT reset, except boiler supply water temperature is reset in response to zone temperatures or control valve position. With the feedback from the loads, load reset is more effective than OAT reset and is the recommended control sequence for condensing boiler plants.

Retrofit - Condensing Boiler Plants

The design and system integration options are limited when installing condensing boiler plants as a retrofit. The major obstacle is addressing the design ΔT of the existing hot water coils, which are not cost effective to replace unless the entire HVAC system is being upgraded through a facility modernization. Of the best practices listed above, the following apply to retrofit projects:

- Primary-only vs. primary-secondary distribution system
- Boiler Turn-Down Ratio

- Boiler Flow Requirements
- Boiler Sizing
- Boiler Sequencing
- Control Valve Selection
- Hot Water Recirculation Control
- System Control

Each of these best practices should be implemented for condensing boiler plants. The boiler plants installed at the DFC were installed correctly as modular systems with the proper controls to ensure that the boilers maintained a low firing rate throughout most of the year. The installation of an outdoor air reset reduced the supply hot water temperature on warmer days, which, in turn, reduced the return water temperature to allow the boilers to operate in condensing mode more often. The installation of a condensate treatment system in the boilers at DFC reduces the environmental impact of the acidic condensate water.

Improvement could be made to the existing system to further improve the efficiency of the system, such as the implementation of a load based reset, more aggressive outdoor air reset, installation of pressure independent control valves, removal of three-way control valves and the installation of variable speed drives on booster pumps. This will reduce mixing and lower the return water temperature. The economics of addressing these issues was analyzed for building 25. A total of 28 AHU's serve the office space in building 25. The AHU's are currently set up with a small hot water booster pump and a two way control valve with a bypass. The booster pumps are rated at ½, ¾ and 1 hp depending on the size of the AHU. Figure 23 shows the piping arrangement for the control valve and bypass leg. The supply water into the heating coil is modulated with the two-way control valve and the excess water that is diverted through the by-pass pipe. The supply water that by-passes the coil is mixed with return water.

Figure 23 – Two Way Control Valve with Bypass
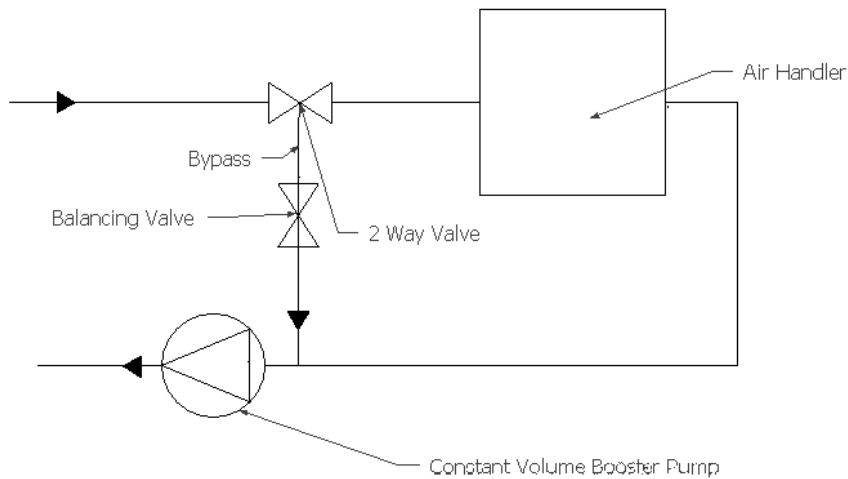**Image Credit: Jesse Dean (NREL)**

Figure 24 – Schematic of Two Way Control Valve with Bypass

One potential solution to eliminating the mixing problem would be to close the balancing valve on the by-pass leg and turn off the booster pumps. If the booster pumps need to operate to overcome the static pressure within the unit, then the site can explore the option of installing a variable frequency drive on each pump and modulating the booster pump flow rate based on hot water valve position. The installed costs were estimated assuming the average booster pump size was ¾ hp. The associated costs would consist of installing a small VFD and a new control point. The cost per control point was estimated as $1,000 per point and the installed costs were estimated with RSMeans and were 50% higher than the values provided in RSMeans Electrical Cost Data 2011.

Table 14 – Building 25 Variable Speed Booster Pump Cost Estimate

Building 25 Variable Speed Booster Pump							
Item	Description	No. of Units	Unit	Equipment / Materials Unit Cost	Install Man hours	Man hour Rate	Labor & Equip Cost
1	3/4 HP VFD	28	VFD @	$800	10	$80	$44,800
2	Control Point	28	Point @	$0	12.5	$80	$28,000
						Subtotal	$72,800
						Contingency 30%	$21,840
						Total	$94,640

The energy savings were estimated using a sensitivity analysis that reduced the return water temperature in increments of 5%, 10%, and 20%. The current efficiency at the annual average operational firing rate of 50% is 88.2%. The new boiler efficiency, if the return water temperature is reduced by 5%, 10%, and 20% is 89.5%, 90.8%, and 93.2% respectively. The annual cost savings were estimated to range from $2,826 to $8,386 per year, which includes the cost savings from the increased boiler efficiency and electricity savings from the variable speed booster pumps. The simple payback ranged from 11 to 33 years. This modification has the potential to be cost effective. For this particular building the installed costs would not have been reduced if this was implemented when the boiler plant was installed since the modifications need to be made at the AHU's

themselves. Additional analysis would be required to determine the specific percent reduction in return water temperature and the project would need to bid out to determine the exact installed costs. The specific reduction in return water temperature could be estimated with an energy modeling program. If some of the booster pumps can be eliminated, the savings have the potential to be even greater at reduced initial costs.

For the facilities that do not have CV booster pumps and have more traditional three-way control valves and CV primary pumps, the energy savings from the variable flow primary pump will typically pay for itself with electrical energy savings alone, and the reduced boiler energy use would only further reduce the total energy savings and reduce the payback period. The hot water piping system for building 54 is currently set up as a CV system. The three-way control valves on the 27 AHU's should be replaced with two way control valves, as this would significantly reduce pumping energy use and boiler energy use. Building 810 has limited potential to reduce the return water temperatures due to the high entering water temperatures required by the unit heaters in the warehouse and the baseboard radiators. Although the energy savings will not be as significant in buildings 810 and 45, this measure should be evaluated to determine the cost effectiveness for each facility. Building 710A is an ideal candidate for control adjustments to reduce the return water temperature. All of the heating is controlled by VAV boxes equipped with two-way valves. Experimenting with the outdoor air reset to lower the supply water temperature could result in significantly colder return water temperatures. Although no hot water bypass of the VAV systems was pointed out by the staff, it is likely that one is installed to maintain minimum flow through the boilers. Adjusting the control of the valve in the bypass to maintain only the minimum flow though the boilers will minimize mixing of supply water and return water and could further reduce return water temperatures. These low cost items should pay for themselves quickly in building 710A.

Condensing Boiler Design Tool

There are many variables to consider in designing a high performance system, too many for the human mind to consider simultaneously. Therefore, Group14 Engineering Inc. developed a Condensing Boiler Design Tool (CBDT), to predict system performance over the full range of part-load operating conditions. Design information is entered on AHU heating coils, terminal unit reheat coils and baseboard radiators within the facility. Boiler and control valve characteristics, control options and set points are all entered into the tool to determine the impacts of the total system design on the operational efficiency of the boiler plant. The CBDT determines the boiler supply water temperature from the system and uses conditional formatting to identify problem areas, such as high return water temperature, control valve cycling, and coil bypass operation. The user can address each performance issue individually at each component to optimize performance. In the future, the CBDT will calculate the seasonal efficiency of the system and determine annual operating costs.   The excel based design tool is available upon request from Sue Reilly at Group14 Engineers (sreilly@group14eng.com) and can help inform both design decisions and energy model input parameters.

C.   Barriers and Enablers to Adoption

A condensate treatment system, shown in Figure 25, may be required to treat the acidic condensate before it enters the drain. All of the boiler installations at the DFC included condensate treatment. The increased cost for installation of this piece of equipment, as well as the stainless steel exhaust flue, increases the installation costs significantly, compared to a standard boiler.
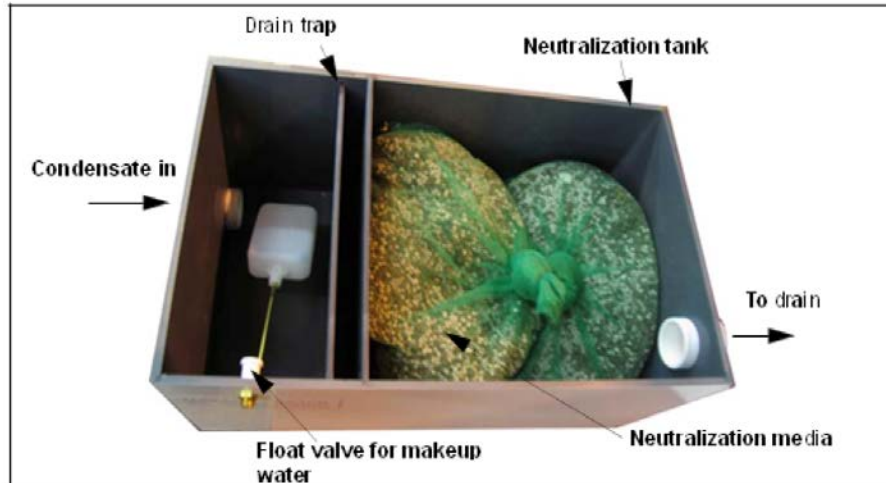
Figure 25 – Example condensate neutralization system
Image Credit: Cleaver Brooks

In addition to the boiler system costs, there are potential hydronic system upgrades that need to be monetized and accounted for. As shown above, the correct integration of the condensing boiler technology with the rest of the HVAC system is critical to achieving maximum return on investment. The complexity involved in the retrofit of the hot water system can be a barrier to entry. Development of a process for each system assessment is recommended to ensure consistency in the decision making.

D.   Market Potential within the GSA Portfolio

Condensing boilers should first be considered for retrofit in buildings that already return water temperatures below 130°F throughout much of the year. The building automation system in many building can provide this information. Typical candidates include buildings with low temperature heating systems, such as in-floor radiant heating, and buildings with hot water loops that can easily be retrofitted to avoid coil bypasses and three way valves. In buildings where it is impossible or difficult to avoid return water temperatures above 130°F, high efficiency near-condensing boilers, with thermal efficiencies above 84%, may be more cost effective. It is important to note that basic steps, like a more aggressive outdoor air temperature reset and balancing the three-way valves, should be taken before a conclusion can be made regarding the return water temperature. Comprehensive retrofits, including replacement of three-way valves with two-way valves and installation of VFDs on the pumps should be considered as well.

To conduct an assessment of the cost effectiveness of the condensing boilers at the DFC, and evaluate the larger market potential for the GSA portfolio, market research was conducted on the installed costs of condensing boilers. This market research covered numerous sources including: RSMeans, the Consortium for Energy Efficiency, NREL's National Residential Efficiency Measures Database, and the actual installed costs from the DFC. Information available for the initial costs of commercial, condensing boilers is limited in general. The results from the market research are listed here and an "average" installed cost is used to evaluate the condensing boiler technology.

RSMeans costs were calculated by taking the average cost of three small boilers listed in RSMeans. These boilers had an average output of 167 MBH and an average Annual Fuel Utilization Efficiency of 83%.[xix] This average cost was $50.56/MBH. The Consortium for Energy Efficiency's market analysis estimated the initial cost of condensing boilers to be approximately 3 times that of a conventional boiler.[iii] At that time, the market for

condensing boilers was only around 2% of total boiler sales, according to the Consortium. NREL's National Residential Efficiency Measures Database estimates the average cost of a condensing boiler retrofit to be $55/MBH. The three larger condensing boiler plants at the DFC, with a total output of greater than 1,000 MBH, averaged only $41.36/MBH. Discussions with two local boiler distributors (including the installer for the DFC projects) placed the installed cost of condensing boilers at approximately 175% to 200% the cost of a standard boiler. The cost of a near-condensing boiler was estimated to be roughly 10% less than a condensing boiler. Near-condensing boilers require the same stainless steel flue that condensing boilers require, which increases the installation cost to almost that of a condensing boiler.

The estimate from NREL's database and the three large DFC installation costs were averaged to calculate the expected initial costs for condensing boiler installations used in this analysis. For simple payback and net present value calculations with the actual DFC installed costs, see the Utility Bill Analysis subsection located in the Results section (pg. 24). The standard boiler installed costs shown in Table 15 were gathered from RSMeans (including removal costs of the existing systems), and near condensing costs were calculated as 10% less than the condensing boiler cost (as per the distributor's estimate).

Table 15 – Installed cost estimates for the three boiler types

Boiler Type	Rated Efficiency	Installed Cost ($/MBH)
Standard	80%	26.21
Near-Condensing	86%	43.46
Condensing	86-98%[1]	48.18

[1]Depending on return water temperature and part load operation.

The costs established here were compared with the cost estimates documented by Pacific Northwest National Laboratory (PNNL) in a report assessing condensing boiler performance at a GSA site in Atlanta, Georgia[xx]. The costs established by PNNL are shown in Table 16.

Table 16 – Initial cost estimates established by PNNL report

Boiler Type	Rated Efficiency	Installed Cost ($/MBH)
Standard	80%	35.40
Near-Condensing	84%	38.50
Condensing	95%	42.60

It can be noted that that the costs for the condensing boilers are very similar between the PNNL report and the current report (12% difference between estimates). The near condensing costs are also similar, especially considering that the higher cost shown in Table 15 is for a slightly higher efficiency model (which incurs more of the high cost stainless steel).

Table 17 shows the economic evaluation of replacing the existing boilers with condensing boilers for each of the five sites at the DFC. The initial costs used for the condensing boiler systems were based on the normalized cost of $48.18/MBH, established in this report. The cost of the standard replacement boilers were estimated using the 86% efficient boiler costs from Table 15. The standard replacement costs were used in calculating the

incremental cost when a replacement is necessary, therefore it was necessary to use a system cost that would reflect the typical replacement option. It was assumed that GSA would replace older boilers with at least a near-condensing system in order to pursue energy reduction on-site and stay compliant with current federal requirements. When calculating the incremental energy cost savings of the condensing boiler over the near-condensing replacement option, the calculated energy cost savings were multiplied by the ratio of the rated efficiency improvement ($\frac{95-86}{95-80}$ or 60% of the savings achieved by the condensing boilers).

Table 17 – Calculated simple payback and net present value for the five sites for condensing boilers (using normalized initial costs)

Building	Initial Cost Replacement Boiler	Initial Cost Condensing Boiler	Replacement Necessary			Replacement Optional		
			Incremental Energy Cost Savings	Simple Payback Period (Years)	Net Present Value	Energy Cost Savings	Simple Payback Period (Years)	Net Present Value
25	$629,084	$697,406	$15,326	4.46	$254,452	$25,544	27.30	-$159,449
45	$183,836	$203,801	$6,361	3.14	$114,001	$10,602	19.22	$19,477
54	$524,236	$581,171	$9,161	6.21	$136,004	$15,269	38.06	-$259,606
710A	$122,557	$135,868	$2,344	5.68	$36,046	$3,906	34.78	-$53,607
810	$629,084	$697,406	$9,821	6.96	$138,504	$16,368	42.61	-$352,695

Net present value was calculated according to NIST Handbook 135[xxi] with an assumed boiler life of 25 years, a discount rate of 3% and natural gas as a fuel for a commercial building located in Colorado. The life expectancy of 25 years is the estimate provided by the Federal Energy Management Program's Energy Efficient Product Procurement guide.[xxii] The replacement necessary category considers the difference in costs of a standard versus a condensing boiler, while the replacement optional category considers only the cost of a new, condensing boiler.

E.   Recommendations for Installation and Commissioning

One important factor in achieving an economic condensing boiler retrofit is to size the boiler plant so that it operates efficiently without purchasing more heating capacity than is necessary. In the data analyzed for building 710A for the period beginning February 22 and ending April 1, the actual heat output of the plant is only around 10% of the maximum output that the boiler plant is capable of producing. For every boiler plant replacement, a heating load calculation should be conducted by an engineer to ensure that a plant is installed that meets the load, while limiting the size of the plant to a minimum to keep installed costs at a minimum. Relying on the size of the previous plant is not a sizing method, given changes that have occurred to the buildings, as well as having to rely on previous sizing methods that may or may not be accurate.

A potential boiler plant design that warrants further investigation by GSA is the use of several condensing boilers that serve as the primary boilers, coupled with an existing conventional boiler that serves as a backup. The condensing boilers could be sized to serve the heating load approximately 75% of the year, and the conventional boiler will only be used as backup during the coldest weather. This set up would keep initial costs at a minimum, while providing the potential to operate in condensing mode for most of the year. This strategy, coupled with an aggressive outdoor air reset during moderate weather, could allow the condensing boilers to operate in condensing mode throughout much of the year without significant investments in new valves, piping, and coils. Of course, the return water temperatures are building-specific and must be treated as such. Conducting an

independent analysis of the heating system of each building that receives a boiler retrofit is the surest way to achieve condensing operation as often as possible while meeting GSA's stated objective of seeking the lowest life cycle cost system.

As stated throughout the report a systems approach to condensing boiler installations will help to achieve the high operating efficiencies that condensing boilers can provide. Taking from the lessons learned in this study and following the best practices outlined in this report will assist in achieving the highest level of savings for the capital investment.

Appendices

A.   Utility Regression Analysis

Utility regressions, often described as inverse modeling, were performed on the natural gas use within the buildings before and after the condensing boiler plants were installed. The regressions analyze natural gas usage per day vs. heating degree days per day to estimate the relationship between outdoor temperature and gas usage. The analysis attempts to normalize natural gas consumption over different weather conditions so that natural gas usage can be compared before and after the new boiler plants were installed over a year with average weather conditions.
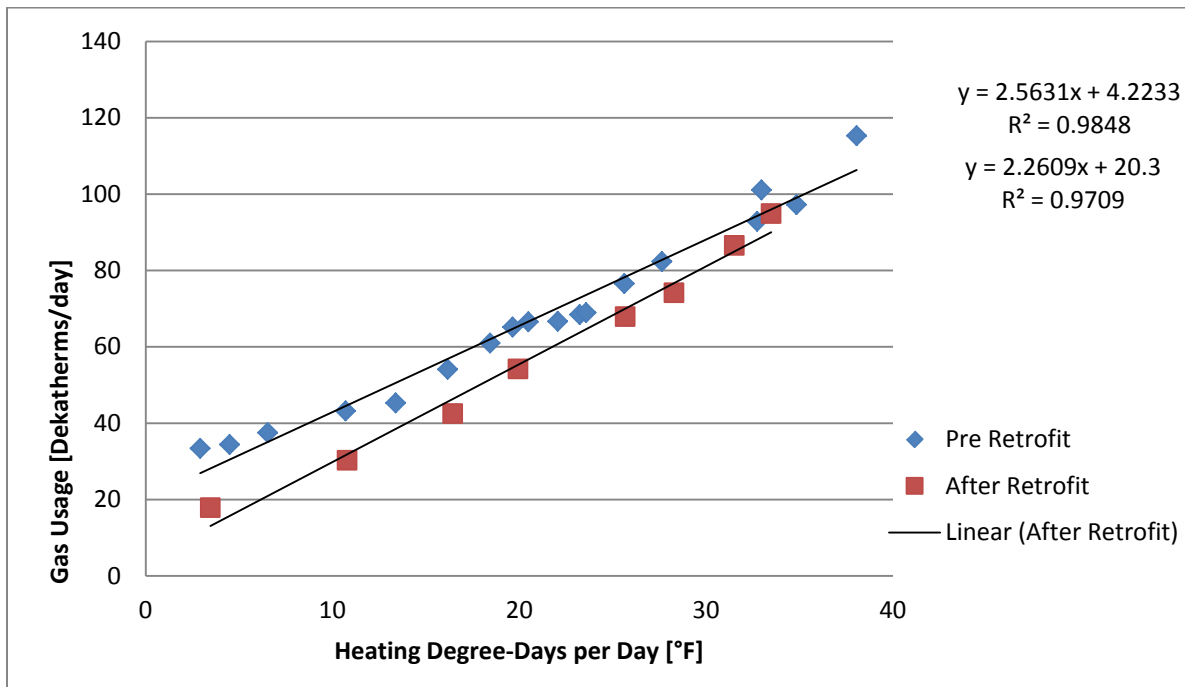
Figure 26 – Building 25 Utility Regression Analysis
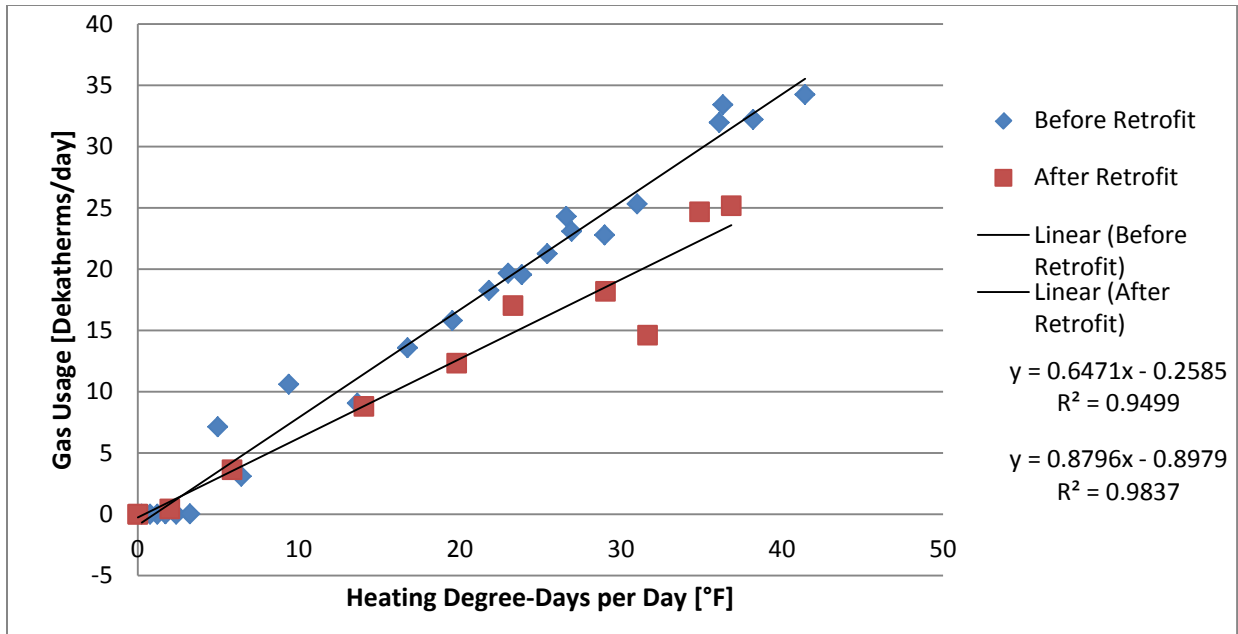
Figure 27 – Building 45 Utility Regression Analysis
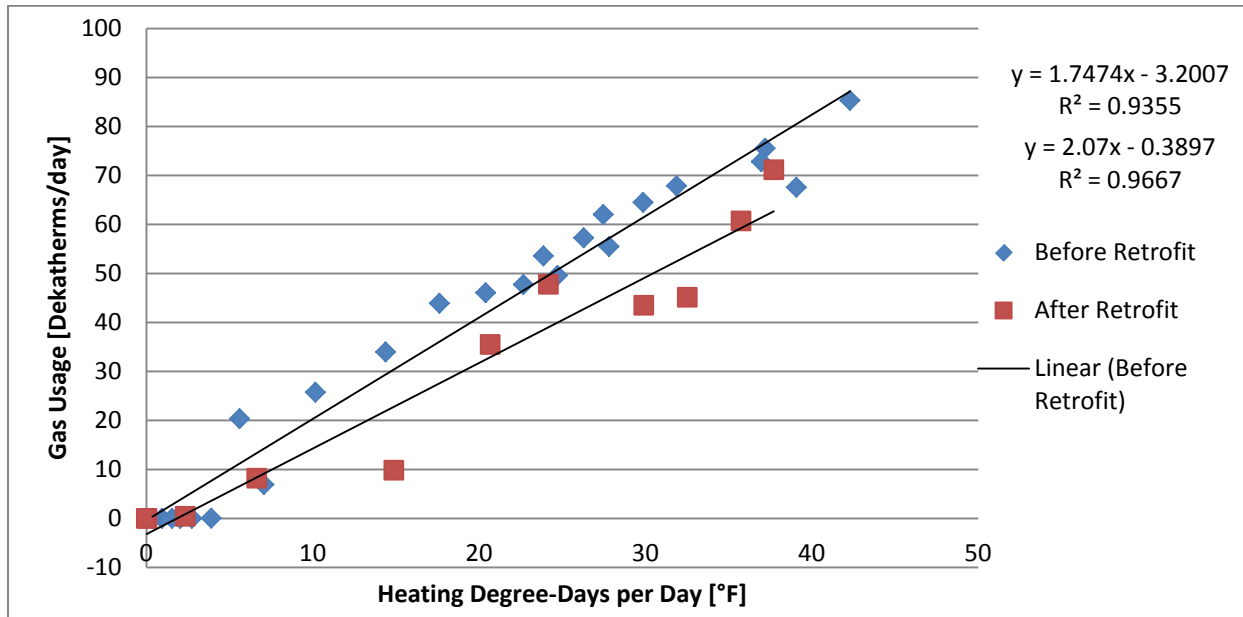
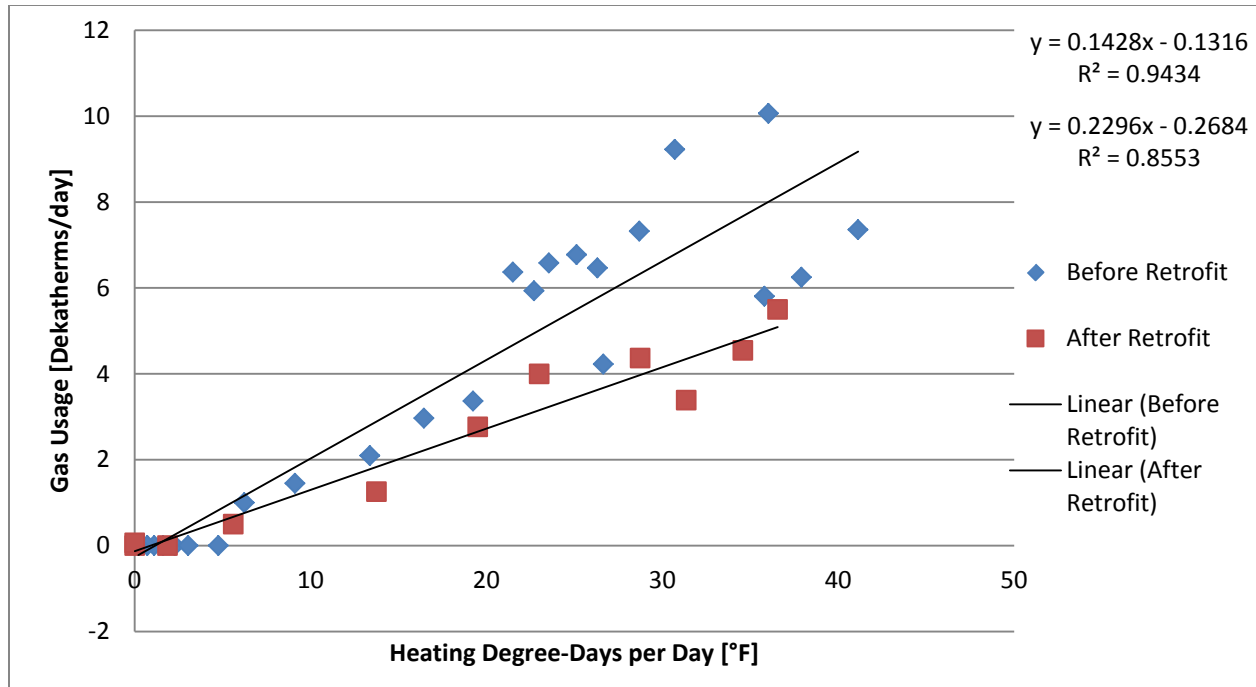

Figure 28 – Building 54 Utility Regression Analysis

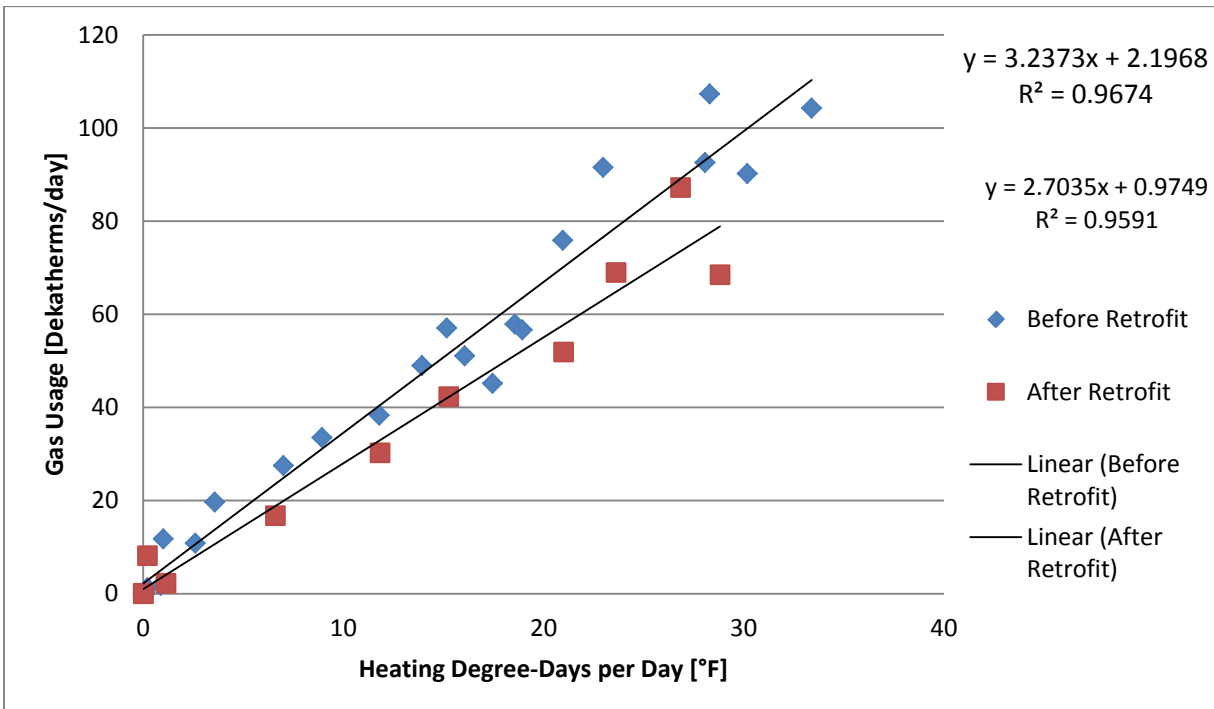**Figure 29 – Building 710A Utility Regression Analysis**

$y = 0.1428x - 0.1316$
$R^2 = 0.9434$

$y = 0.2296x - 0.2684$
$R^2 = 0.8553$

Figure 30 – Building 810 Utility Regression Analysis

$y = 3.2373x + 2.1968$
$R^2 = 0.9674$

$y = 2.7035x + 0.9749$
$R^2 = 0.9591$

B.   Efficiency Analysis with Metered Data

To calculate the annual efficiency of the boilers, an hourly estimate of the return water temperature is needed for each building's boiler plant throughout the year. To estimate the return water temperature throughout the year, a linear regression was performed with the metered data. These regressions are shown below. Hourly TMY weather data was used to estimate the return water temperature throughout the year. The boilers are modeled as being off if the outside temperature is above 72°F, due to the outdoor air reset controls. The return water temperature was used to calculate boiler efficiency at each firing rate by performing a linear interpolation of the efficiency of each boiler at the different return water temperatures. Interpolating was necessary, because the boiler manufacturer only provides efficiencies at several return water temperatures.
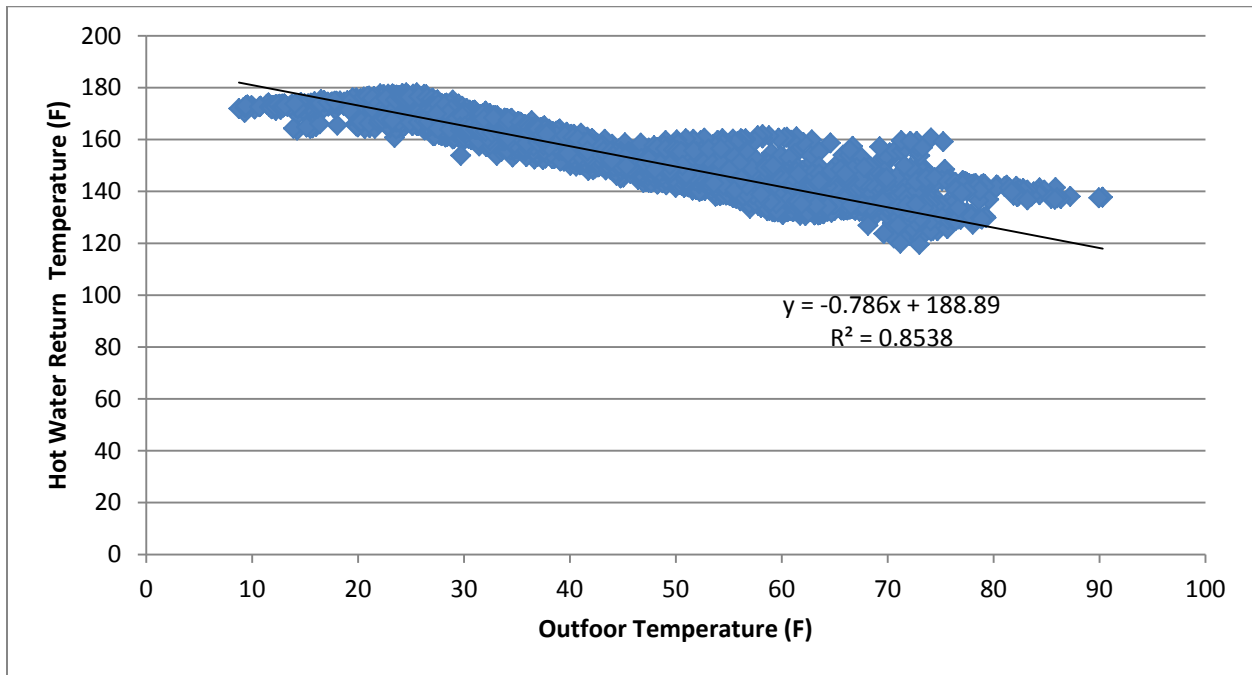

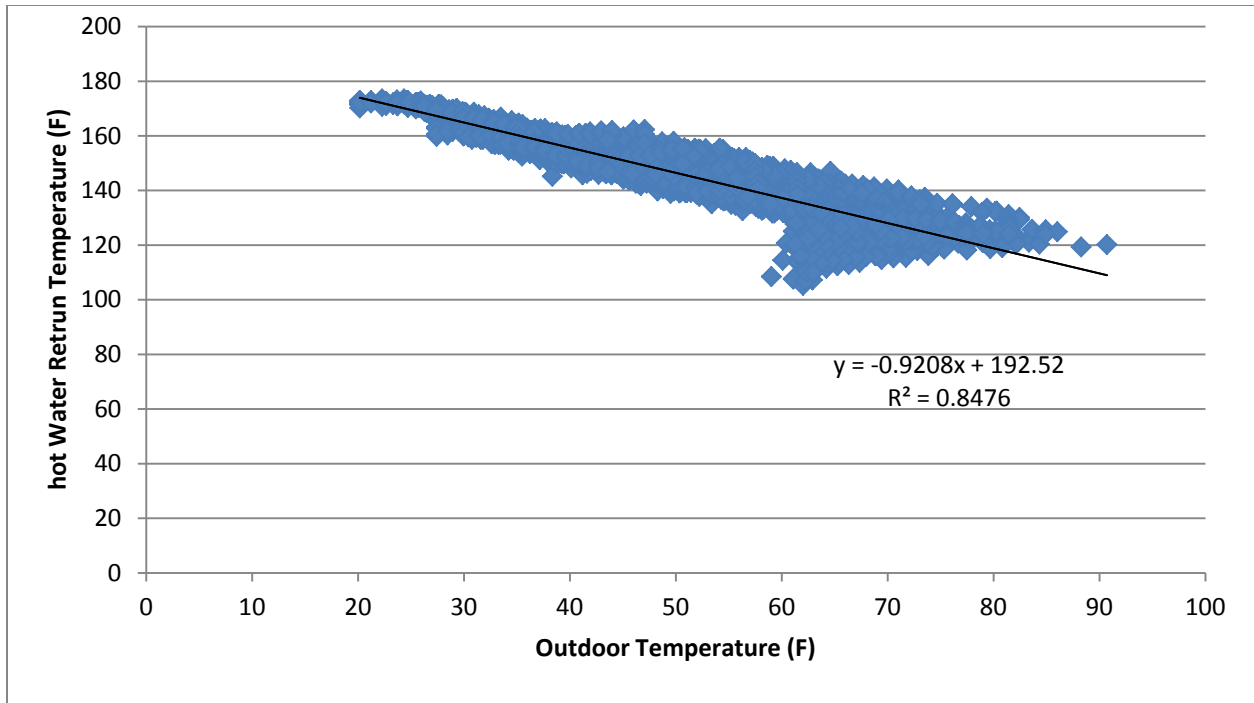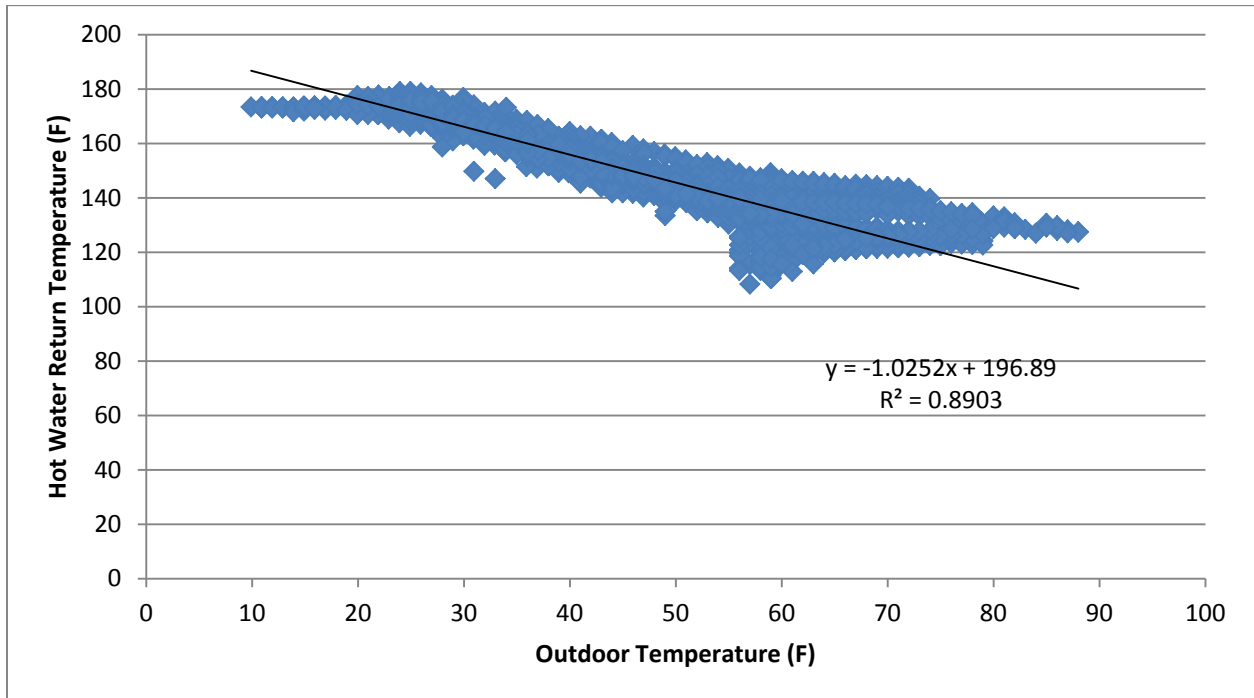$y = -0.786x + 188.89$

$R^2 = 0.8538$

Figure 31 – Building 25 Hot Water Return Temperature

Figure 32 – Building 45 Hot Water Return Temperature
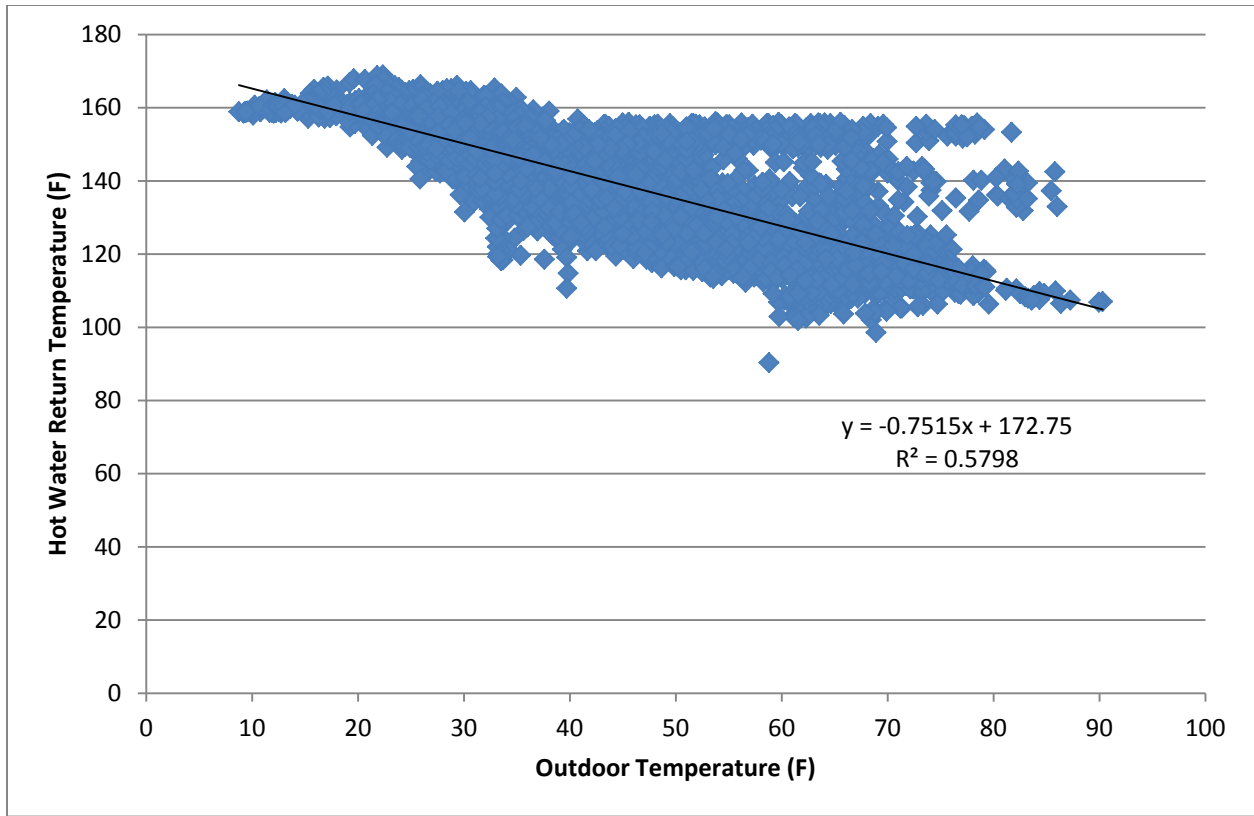

Figure 33 – Building 54 Hot Water Return Temperature

$$y = -0.7515x + 172.75$$
$$R^2 = 0.5798$$

Figure 34 – Building 710A Hot Water Return Temperature

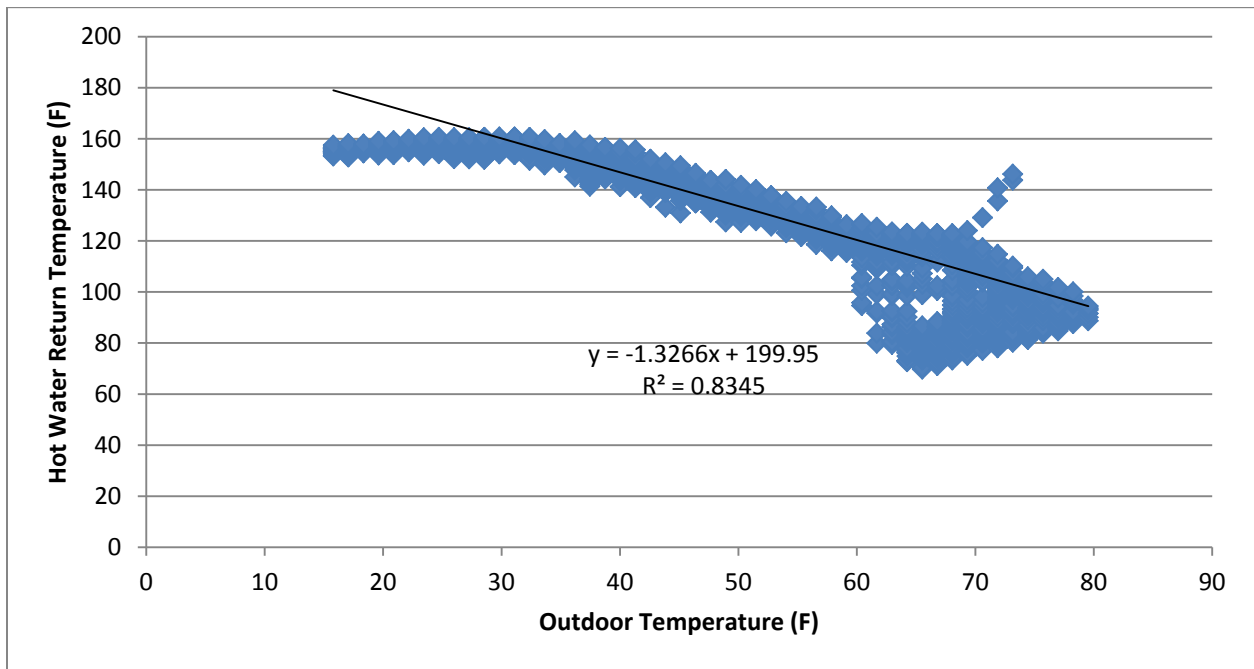$$y = -1.3266x + 199.95$$
$$R^2 = 0.8345$$

Figure 35 – Building 810 Hot Water Return Temperature

C.　　　Calculation of Average Firing Rate in Building 25

The average firing rate in building 25 was estimated by comparing the outdoor air temperature with the heat produced by the boiler plant over a TMY in Denver. Boiler heat output can be calculated from the metered data, using the formula: $\dot{Q} = \dot{m}C_p\Delta T = 500.4 \times GPM \times (SWT - RWT)$. The heat output calculated from the metered data was correlated to the outdoor air temperature (this was done for both occupied and unoccupied hours). The resulting linear regression was applied to hourly data throughout a TMY data set. Once a load was estimated for every hour, the staging control logic was implemented to predict the firing rate for each boiler at every hour. This allowed for a prediction of annual firing rates for the boilers in building 25.

D.　　　Glossary

Δ T – Temperature Differential

AHU – Air Handling Unit

BAS – Building Automation System

BTU – British Thermal Unit

CV – Constant Volume

GPM – Gallons per Minute

HVAC – Heating, Ventilation, and Air Conditioning

LCC – Life Cycle Cost

MBH – 1,000 BTU per hour

OAT – Outdoor Air Temperature

O&M – Operations and Maintenance

RWT – Return Water Temperature

SWT – Supply Water Temperature

TMY – Typical Meteorological Year

VAV – Variable Air Volume

VFD – Variable Frequency Drive

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[i] GSA Portal. http://www.gsa.gov/portal/content/104501, Accessed 5/15/12.

[ii] Cleaver Brooks Website. http://www.cleaver-brooks.com/Products-and-Solutions/Boilers/Commerical/ClearFire-C/Index.aspx Accessed 5/20/12

[iii] A Market Assessment for Condensing Boilers in Commercial Heating Applications. http://www.cee1.org/gas/gs-blrs/Boiler_assess.pdf. 2001

[iv] ASHRAE Equipment Database, http://xp20.ashrae.org/publicdatabase/system_service_life.asp?selected_system_type=5. Accessed 6/5/12.

[v] Federal Energy Management Program Regulations. http://energy.gov/eere/femp/covered-product-category-commercial-boilers Accessed 5/22/14

[vi] Buildings Data Book. http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=5.3.12 Accessed 4/30/12

[vii] Buildings Data Book http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=5.3.5 Accessed 4/30/12

[viii] High Performance Boilers for Existing and New Buildings. http://www.nesea.org/wp-content/uploads/2012/03/Roger_Harris_High_Performance_Boilers_for_Existing_and_New_Buildings.pdf Accessed 6/15/12

[ix] Technology Readiness Levels Presentation http://www1.eere.energy.gov/femp/pdfs/ns/ntwg_032012_livingood.pdf. Accessed 6/12/12.

[x] A Market Assessment for Condensing Boilers in Commercial Heating Applications. http://www.cee1.org/gas/gs-blrs/Boiler_assess.pdf. 2001

[xi] GSA Denver Federal Center, Building 25 Energy Information, http://www.epa.gov/oaintrnt/facilities/denver_neic.htm

[xii] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2009 ASHRAE Handbook - Fundamentals (I-P Edition). 2009

[xiii] Weather Underground. www.wunderground.com, accessed 3/18/2012

[xiv] Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2010. Annual Supplement to Handbook 135 and NBS Publication 709. U.S Department of Commerce. http://www1.eere.energy.gov/femp/pdfs/ashb10.pdf

[xv] Federal Energy Management Program. Covered Product Category: Commercial Boilers. December 2011. http://www1.eere.energy.gov/femp/technologies/eep_boilers.html

[xvi] Personal Correspondence, 5/3/12

[xvii] ASHRAE Equipment Database, http://xp20.ashrae.org/publicdatabase/system_service_life.asp?selected_system_type=5. Accessed 6/5/12.

[xviii] McDowall, Robert and Montgomery, Ross. Fundamentals of HVAC Control systems: IP Edition. ASHRAE, 2008.

[xix] 2011 RS Means Green Building Cost Data. 1st Annual Edition. Construction Publishers and Consultants. Reed Construction Data. 2010.Norwell, MA

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[xxi] Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2010. Annual Supplement to Handbook 135 and NBS Publication 709. U.S Department of Commerce. http://www1.eere.energy.gov/femp/pdfs/ashb10.pdf

[xxii] Federal Energy Management Program. Covered Product Category: Commercial Boilers. December 2011. http://www1.eere.energy.gov/femp/technologies/eep_boilers.html