U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES OFFICE

Steam System Balancing and Tuning for Multifamily Residential Buildings in Chicagoland—Second Year of Data Collection

Jayne Choi, Peter Ludwig, and Larry Brand
Partnership for Advanced Residential Retrofit

August 2013

Building America
U.S. Department of Energy

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Steam Balancing and Tuning for Multifamily Residential Buildings in Chicagoland—Second Year of Data Collection

Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

Golden, CO 80401

NREL Contract No. DE-AC36-08GO28308

Prepared by:

Jayne Choi, Peter Ludwig, and Larry Brand

Partnership for Advanced Residential Retrofit

2125 W North Avenue

Chicago, IL 60647

NREL Technical Monitor: Stacey Rothgeb

Prepared Under Subcontract No. KNDJ-0-40346-00

August 2013

[This page left blank]

Contents

List of Figures

Unless otherwise indicated, all figures were created by PARR.

List of Tables

Unless otherwise indicated, all tables were created by PARR.

Definitions

Btu	British thermal unit
CDD	Cooling degree day
CNT	Center for Neighborhood Technology
DOE	U.S. Department of Energy
EUI	Energy use intensity
HDD	Heating degree day
NBP	Near boiler piping

Executive Summary

Of the 470,000 multifamily housing units in the Chicago region, an estimated 70,000 are steam heated. With these centrally metered systems, the cost of heat for tenants is reflected in the owners' operating costs. Highly variable and rising energy costs have placed a heavy burden on building owners. In the absence of well-designed and relevant efficiency efforts, increased operating costs would be passed on to tenants who often cannot afford those increases.

Steam-heated buildings often suffer from uneven heating as a result of poor control of the amount of steam entering each radiator. In order to satisfy the heating load to the coldest units, other units are overheated. As a result, some tenants complain of being too hot and open their windows in the middle of winter, while others complain of being too cold and are compelled to use supplemental heat sources.

Building on previous research, the Center for Neighborhood Technology identified 10 test buildings in Chicago and conducted a study to identify best practices for the methodology, typical costs, and energy savings associated with steam system balancing. A package of common steam balancing measures was assembled and data were collected on the buildings before and after these retrofits were installed to investigate the process, challenges, and the cost effectiveness of improving steam systems through improved venting and control systems. The test buildings that received venting upgrades and new control systems showed 10.2% savings on their natural gas heating loads, with a simple payback of 5.1 years. The methodologies for and findings from this study are presented in detail in this report. This report has been updated from a version published in August 2012 to include natural gas usage information from the 2012 heating season and updated natural gas savings calculations.

1 Problem Statement

1.1 Introduction

The majority of Chicago's multifamily housing stock (five or more units) was built between 1910 and 1939 and uses gas-fired heating with central boilers and single-pipe steam distribution systems (Biederman and Katrakis 1986). Single-pipe steam heating was the best option for buildings constructed in the first few decades of the 20th century; only after 1928, when the first circulating pump was invented, did hydronic systems become the standard in modern apartment buildings (Peterson 1985; Holohan 2011). Though these original steam systems have been converted from coal to gas and many have undergone boiler replacement or other small upgrades, the distribution systems remain largely the same as when they were first installed. Single-pipe steam systems were designed for longevity but not for energy efficiency (Peterson 1985). Steam system efficiency is limited by the fact that a steam boiler cannot have a rated efficiency of greater than 83%.

Old one-pipe steam systems are often controlled by a timer or by a single thermostat. When the thermostat or timer calls for heat, the boiler comes on, heats the water, and generates steam. The steam moves through the piping that is initially full of air, heating the metal and pushing the air out through vents on the main distribution lines and radiators. As steam reaches each vent, the vents close so no steam escapes. Within each radiator, the steam condenses and releases latent heat, allowing more steam to enter. The water that has condensed inside the radiators runs back (through the same pipes that carry the steam) to the return lines and down to the boiler. When the building has been heated according to the thermostat or timer's specifications, the boiler shuts off.

The boiler can also be regulated by a pressuretrol that will shut the boiler off if the pressure in the boiler builds to greater than the allotted amount. One-pipe steam systems should typically operate at ½–1½ psig of pressure. It is important to adjust pressuretrols to these settings. Incorrect pressure settings can result in short boiler cycles and distribution problems.

As the radiators cool, the air vents open and allow air to re-enter the system. A schematic of this entire system is shown in Figure 1. The system shown in Figure 1 is a gravity return system, meaning that the return condensate relies on gravity to return from the radiator through the piping back down to the boiler.

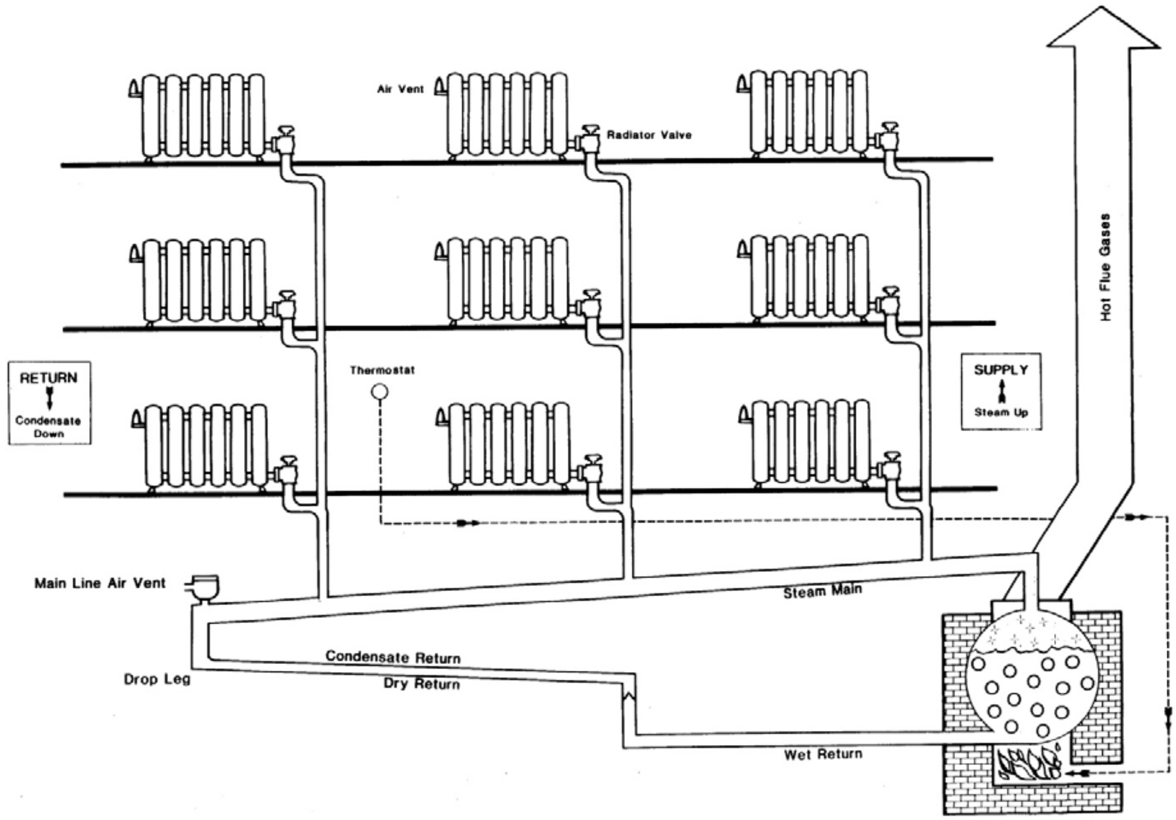


Figure 1. Schematic of single-pipe steam system

(adapted and used with permission from Peterson 1985)

These buildings often suffer from significant temperature gradients, with differences between units often reaching up to 15°F. As a result, some tenants complain of being too hot and others too cold.

With insufficient air venting of the radiators and main lines, air can become trapped in the system and block steam from entering radiators. Radiators may partly heat as air is compressed within the system, but the system must be properly vented in order for the radiators to fully fill with steam. If the thermostat for the boiler is located in an area of the building that heats more slowly than others, the thermostat will keep calling for heat until that area reaches the desired temperature. This setup has the problem of overheating units that receive steam more quickly and wasting heating fuel. Alternatively, if the thermostat is located in a section of the building that heats quickly, the boiler cycle will end before steam is able to reach and release its latent heat to units that are further from the boiler or vented more slowly. Systems with multiple indoor sensors that are able to calculate an average temperature to determine when to call for heat can help to avoid these issues.

Insufficient venting, large differences in steam arrival times, excessively short boiler cycles, lack of zone control or temperature averaging, and variable steam main lengths can all contribute to uneven heating in a building (Peterson 1985).

Providing a balanced building, where adequate heat is provided to all of the apartments at the times that the heat is needed, minimizes wasted heating fuel and is therefore an opportunity for cost savings. Additionally, a balanced building improves tenant comfort. This study explored whether steam balancing can be an efficiency measure that building owners and utility companies can implement as a cost-effective and beneficial retrofit.

More specifically, this study examined the effects of installing large-capacity air vents on steam main lines, replacing radiator vents, and upgrading boiler controls from thermostats or timers to indoor averaging systems. All of the test buildings in this study were low-rise multifamily buildings in Chicago with centrally metered boilers with single-pipe steam distribution systems.

1.2 Previous Studies

Previous research performed by the Minneapolis Energy Office, the Center for Neighborhood Technology (CNT) in Chicago, and New York State Energy Research and Development Authority in New York City documented techniques and savings associated with steam balancing. Improved venting and controlling the steam cycle were identified as important measures for ensuring even temperatures throughout a building and increasing tenant comfort. These findings were taken into consideration when assessments were done and measures selected for this study (Peterson 1985; Biederman and Katrakis 1986; Karins 1994).

Biederman and Katrakis (1986) also determined that ensuring tenant awareness in advance of and during the project increases its success and facilitates a smoother experiment. This project took this into consideration as a part of its technical approach.

Although the costs and savings associated with upgraded venting and control systems will vary depending on the pre-retrofit conditions of a building as well as the specific scope of work administered, previous studies have shown these to be cost-effective measures. Katrakis et al. (2010) reported energy savings of 5%–10% with a payback of 0–2 years for installing larger main line air vents and savings of 3%–5% with a payback of 0–3 years for utilizing control systems to reduce boiler short-cycling. Peterson (1985) reported that rebalancing a steam heated building can reduce space heating costs by as much as 15%–25%.

1.3 Relevance to Building America's Goals

The U.S. Department of Energy's (DOE) Building America program is designed to "reduce the home energy use by 30-50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes)." To this end, the program looks to conduct research to "develop market-ready energy solutions that improve efficiency of new and existing homes in each U.S. climate zone, while increasing comfort, safety, and durability" (DOE 2011).

This project looked at multifamily residential buildings in Chicago. As a colder humid continental climate, Chicago has an average of 6,500 heating degree days (HDDs) and 800 cooling degree days (CDDs) per year; heating is therefore the focus of residential energy use. Since the majority of Chicago's multifamily housing stock (five or more units) was built between

1910 and 1939 and uses gas-fired heating with central boilers and single-pipe steam distribution systems, it is important to address any common issues with these heating systems (Biederman and Katrakis 1986). When the distribution of steam is not properly balanced in steam systems, certain units become overheated. In a study conducted in Minneapolis, which has a climate similar to that of Chicago, it was estimated that the cost of overheating is 3% of space heating costs per 1°F of overheating (Peterson 1985). By this estimate, imbalances in steam distribution and the resulting overheating can be very costly for a building owner. Therefore, finding methods to streamline and improve the process of balancing steam systems has the potential to contribute an effective energy solution to the marketplace.

2 Experiment

2.1 Research Questions

- How do steam balancing measures affect the temperature variations within buildings?
- Will steam balancing affect the average length and frequency of boiler cycles?
- How will steam balancing affect the amount of natural gas used for heating?
- How cost effective are steam balancing measures?
- What further research is needed to conclusively determine the efficacy of steam balancing measures?

2.2 Technical Approach

A package of common steam balancing measures (replacing radiator vents, installing high-capacity air vents on main lines, and installing indoor averaging boiler controls) was assembled and data were collected on 10 buildings before and after these retrofits were installed. This project built on the relationships between building owners and contractors and the CNT Energy Savers Program.[1]

All the building owners involved in this project had previously worked with the CNT Energy Savers Program, so all the potential test buildings had already received energy assessments. An initial pool of candidate buildings was identified according to the following criteria:

- Single-pipe steam heating system
- Around 15–30 units
- Non-uniform temperatures throughout the building (based on qualitative observations from the auditor, building manager, and/or tenants)
- Well-maintained boiler.

Boiler replacement was not tested in this study, so the boiler had to be well maintained and appear to produce dry steam for a building to participate. This was assessed both from information collected during the previous energy audit and from the steam heating contractor about the boiler condition and its regular maintenance.

The previous assessment data and reports were reviewed and candidate buildings were revisited by a CNT energy analyst. The buildings were then examined by a Chicago steam heating contractor who diagnosed the building's problems and submitted a scope of work for each building. Final test buildings were chosen based on, among other criteria, potential for energy savings and building type (see Figure 2).

[1] Energy Savers is a program run by CNT Energy that works with multifamily building owners in Chicago to identify cost-effective energy efficiency measures and connect them with resources to implement these upgrades (Evens et al. 2008). Since 2007, the Energy Savers program has retrofitted more than 10,000 units for efficiency.


Figure 2. Two of 10 test buildings. The buildings chosen were brick three-story walk-ups, a common structure for multifamily housing in Chicago. See Appendix A for specifications on all of the test buildings.

(used with permission from CNT Energy 2011)

Access to units and the boiler room is an important factor for assessing and fine-tuning a building's steam heating system, so the relationships and communication between the building owners and tenants were also considered in choosing buildings. Regular communication with tenants (both to ensure minimal tampering with the data collection and for ready access to the apartments) was necessary for project success. Tenants were given notice by their building managers before each visit and letters explaining the project (a sample of which can be seen in Appendix B) were distributed during the data collection periods.

2.3 Assessment of One-Pipe Steam Heating Systems: What To Look For

After the test buildings were selected, their boilers and distribution systems were assessed to determine their current effectiveness. Monitoring of the buildings was conducted before and after the packages of steam balancing measures were installed. The following sections detail what was examined in this study. They are divided into subsections to indicate which system components particular data relate to and outline the guidelines for studying the following components:

- Main line air vents
- Near boiler piping
- Boiler controls
- Radiator vents
- Unit temperatures
- Tenant comfort.

2.3.1 Main Line Air Vents

2.3.1.1 Guidelines

The purpose of main line air vents is to rapidly vent the large amounts of air in the steam lines. These vents lower the back pressure during the fill part of a boiler cycle and aid the flow of steam down the main distribution pipes. Without main line air vents, all the air in the lines must be purged at the radiators, in which case steam would fill the radiators closest to the boilers much faster than those furthest away. This can cause uneven heating, particularly if the boiler shuts off before the whole system is full (see Figure 3). As such, there should be at least one main line air vent per steam main line. Proper air venting can be used to control the relative speed of steam delivery to radiators in various parts of a building. Main line air vents should be installed on the main distribution lines after the last riser and before the dry return drops into the wet return. The valve is open until the steam reaches it, at which point it shuts and prevents steam from escaping through it (Peterson 1985).

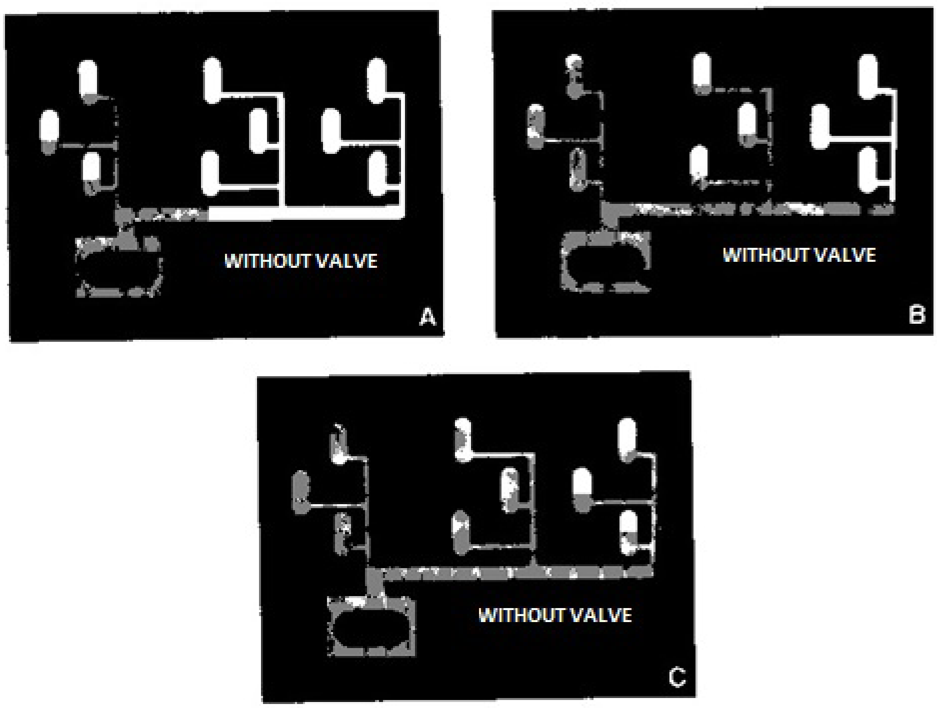


Figure 3. At the beginning of a boiler firing cycle, the piping system and radiators are filled with air and quite cool, meaning that the steam must heat a large mass of piping and push air out of the air vents. The furthest radiators will receive heat more slowly than the closest. As shown in (C), in the absence of main line vents, steam may never even reach the furthest radiators if the boiler shuts off before it can reach them.

(adapted and used with permission from Peterson 1985)

2.3.1.2 Measurements

Measurements for the main line piping consisted of:

- A census of all the main lines in the building
- The approximate length of each main line
- Varying thickness of pipe for each main line
- Pipe insulation for each main line
- Positions of vents on each main line
- Sizing and condition of main line vents.

Vents are often hidden in unused basements or storage facilities, and a thorough inspection was conducted to assess the current efficacy of the venting. This information was then either confirmed by or relayed to the heating contractor for determination of which vents needed to be replaced or whether vents needed to be added to the distribution lines. The e-booklet "Balancing Steam Systems Using a Venting Capacity Chart" by Gerry Gill and Steve Pajek (2005) includes resources for determining the required amount of venting.

2.3.2 Near Boiler Piping

2.3.2.1 Guidelines

The size and configuration of the near boiler piping (NBP) are important for producing dry steam (Holohan 1992). As steam boilers are replaced, their accompanying piping is often incorrectly configured to be either too large or too small. Figure 4 shows an example of an insufficiently sized replacement header.

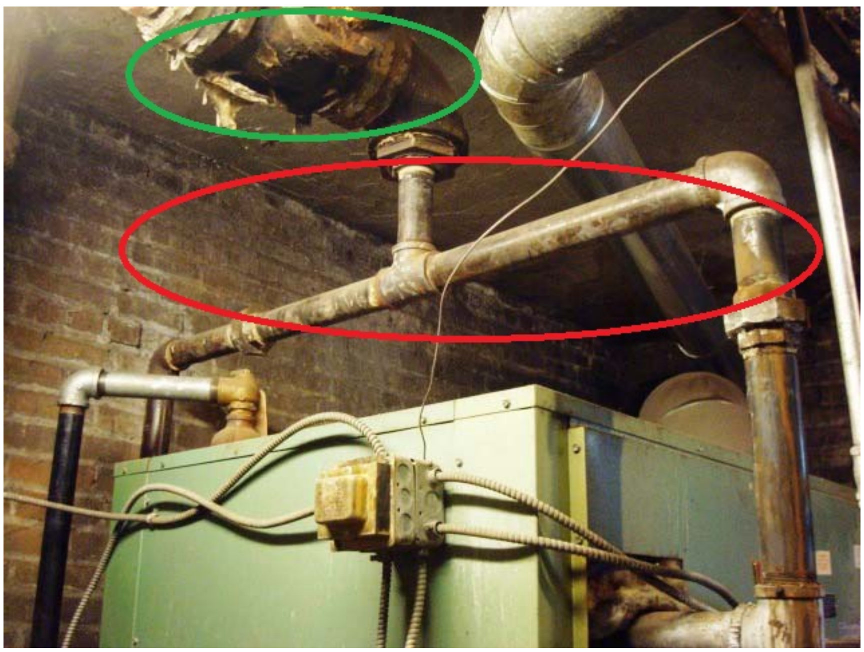


Figure 4. The header piping is smaller than the boiler manufacturer's specifications.

(used with permission from CNT Energy 2011)

As shown in Figure 5, the risers leading from the boiler takeoff to the header piping should be at least 24 in. The supply line leading from the header should not be directly aligned vertically with any of the risers or with the equalizer. This configuration ensures that wet steam, which decreases the amount of latent heat available from the steam and therefore decreases the efficiency of the system, will not collect in the header piping or supply lines. The steam must be dry to reach the furthest radiators. The boiler manufacturer's specifications provide instructions about how to correctly pipe a boiler (see Figure 5 for an example).

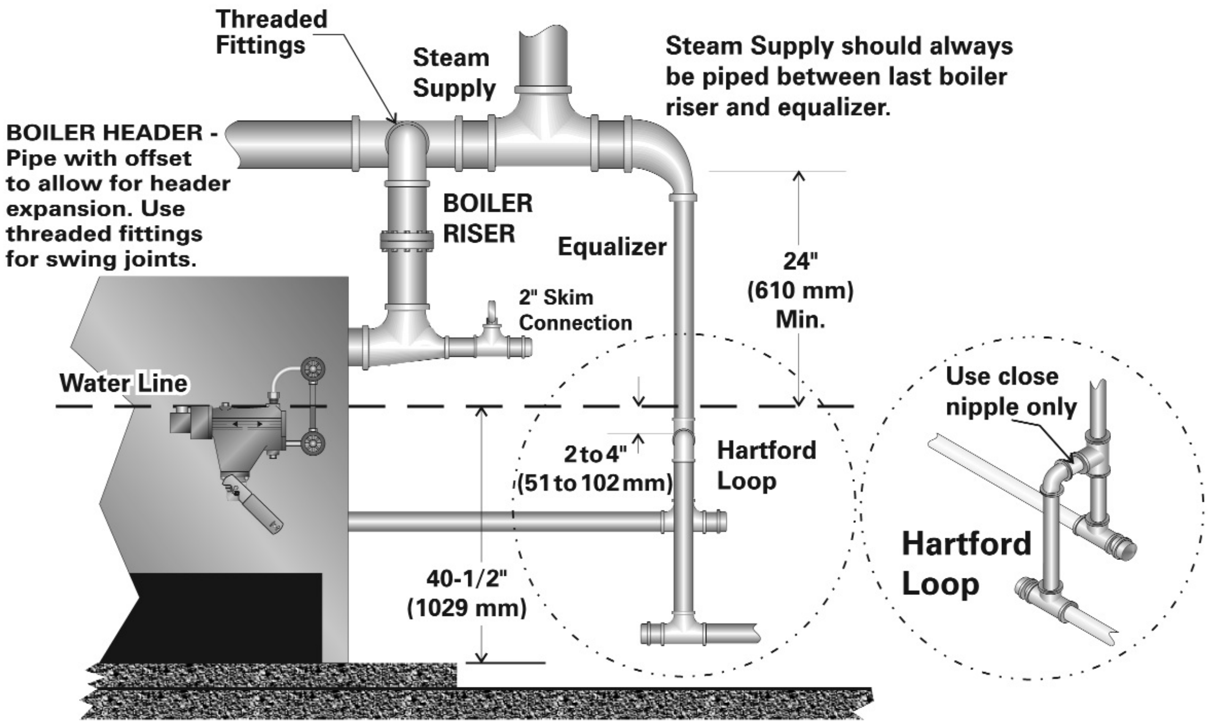


Figure 5. Specifications for how to pipe a Series 211A™ natural gas steam boiler by Peerless®

As shown in the diagram, the boiler risers should always be at least 24 in. long and the steam supply should always be piped between the last boiler riser and the equalizer.

(used with permission from Peerless® Boilers)

The NBP should also include a Hartford Loop, which consists of an equalizing pipe connecting the steam header to the condensate inlet at the bottom of the boiler. It acts as a backup safety measure to the low-water cutoff by allowing steam pressure to build in the boiler without forcing water into the return line and protecting the boiler against low water in the event of a return line leak (Ahlgren 1994). If there is a leak in a return line, water can only back out of the boiler to the point where the wet return line connects into the equalizer. The loop acts as a siphon that runs out of water, stopping the boiler from emptying completely, which allows for additional time to notice a leak and have it fixed (Holohan 2010a). This reduces the chance of a boiler dry-firing, which can be extremely dangerous as well as cause damage to the equipment. Local codes should always be consulted when considering boiler repiping.

2.3.2.2 Measurements

Measurements for the NBP consisted of:

- Height of the header piping
- Width of risers and header
- Descriptive geometry of the NBP.

The NBP was examined at each test building and, if necessary, corrected before the data logging period or before any other steam balancing measures were installed. One of the 10 buildings had incorrectly installed NBP that had to be corrected.

2.3.3 Boiler Controls

2.3.3.1 Guidelines

Steam heating systems are often controlled by a single thermostat, or an aquastat and time clock. Boilers are also often switched on and off manually by building maintenance staff, depending on tenant feedback. All 10 test buildings were controlled by either a thermostat or time clock and aquastat setup with building staff frequently manually adjusting controls. These controls do not consider temperature variations within a building and frequently contribute to the problems of unbalanced temperatures in a building. If a thermostat is located in a warmer area of the building, the boiler cycle might end before the colder units are satisfied. If a thermostat is in a cooler area of the building, certain areas of the building will be overheated as the boiler will not shut off until this cooler area reaches the temperature set point. Control systems that have indoor temperature sensors and cycle the boiler on and off according to an average building temperature can help prevent these issues.

2.3.3.2 Measurements and Data

Information collected for the boiler and boiler controls consisted of:

- Rated boiler capacity (Btu/h)
- Boiler annual fuel utilization efficiency
- Boiler size (number of sections)
- Burner condition
- Boiler firing pattern
- Combustion analysis (steady state efficiency, carbon monoxide, carbon dioxide, oxygen)
- Description of control type
- Daytime and nighttime set points
- Observation of how controls are being operated by maintenance staff.

A boiler runtime sensor and a data logger were wired to the boiler in each test building to assess and monitor the patterns of the current boiler controls. The monitors logged the activity of the boiler to determine the boiler cycling patterns. Using the cycling patterns and the boiler efficiency, the fuel consumption of each boiler was determined.

2.3.4 Radiator Vents

2.3.4.1 Guidelines

Just as the distribution of steam heating is affected by the condition of the main line air vents, it is also affected by the condition of the radiator air vents. If an apartment unit is too cold, the heat input must be increased or the heat loss decreased; often this can be achieved by replacing radiator vents that are blocked or not functioning properly (Peterson 1985).

If no steam ever reaches a radiator, the radiator valve should be checked to see if it is open and operating properly. Radiator valves should always be completely open or completely closed and were not designed to be frequently throttled. Tenants should be informed that these valves should typically not be tampered with. If the valve does not completely open or shut, it may need to be replaced. Having a partially open valve will not allow the condensate to properly drain out of the radiator, which will obstruct steam from entering the radiator.

If the vent is loudly whistling when the radiator fills with steam, its orifice may be too small and in this case, the vent should be replaced. A whistling vent could also be indicative of debris clogging the opening or the boiler operating pressure being higher than necessary. Alternatively, if an apartment is too hot, the steam reaching the radiators can be slowed by a smaller vent or controlled by a thermostatic radiator valve. Though studies have shown that there is a point at which an increased orifice size has little influence on fill time (Peterson and Otterson 1985), proper air venting can be an effective way to largely control the relative speed of steam delivery to various radiators. Figure 6 shows an example of a radiator vent that comes in different models of varying orifice size.

Figure 6. Gorton No. 4 angle radiator vent. Gorton models are made in No. 4, 5, 6, C, and D, ranging from 4 with the smallest orifice to D with the largest.

(used with permission from CNT Energy 2011)

The size of the radiator is also important when considering the appropriate vent size. Large radiators contain more air than small ones, so larger radiators need larger air vents to fill with steam more quickly. Two vents can be used on larger radiators; a second vent can be positioned a few inches lower than the first and the two vents will work together to vent the air. Once the steam reaches the first vent and closes, the second air vent will continue to vent air. The larger radiator will thus heat more completely (Holohan 2010b). The e-booklet "Balancing Steam Systems Using a Venting Capacity Chart" by Gerry Gill and Steve Pajek (2005) includes resources for determining the amount of air in a radiator and the venting capacities of different air vents.

2.3.4.2 Measurements

Information collected about the radiator vents consisted of:

- Sizes of radiators in the building
- The size and condition of radiator vents.

The radiator air vent should be removed and tested; if it is not passing air, it should be cleaned or replaced. Figure 7 shows the common problem of a radiator vent that has been painted over and no longer works.

Figure 7. Painting over radiator vents is a common oversight that can have a serious effect on the heating in an apartment. Blocked radiator vents must be cleaned or replaced.

(used with permission from CNT Energy 2011)

For this study, the condition of the radiator vents in a sample number of units was examined and an assessment was made about whether to replace some or all of the vents. Adjustable air vents can be considerably more expensive and subject to tampering by tenants (negating their usefulness of being able to adjust to the location and size of the radiator); therefore, they were not used in this study. Removing, rearranging, or replacing radiators can be difficult and expensive and were also not considered in this study.

2.3.5 Temperature

2.3.5.1 Guidelines

Many factors influence the temperature of an apartment unit; for example, tenants often open windows to cool their overheated apartments, even during winter months. Temperature measurements over the heating season are important for studying the distribution of heat in a steam-heated, multifamily building. Identifying the patterns of temperature change over these time periods can help researchers infer exactly how the heating distribution is failing.

2.3.5.2 Method

Temperature data loggers were placed in six units in each building and recorded the temperature every 5 min for 4 weeks. Both the pre- and post-balancing logging periods were during the 2011–2012 heating season. The loggers were placed in units directly above the boiler (predicted to be the most overheated) and in units that were furthest from the boiler (predicted to be receiving the least heat) on at least two floors to capture the different unit temperatures. The loggers were installed on the walls at approximately 5 ft from the ground, and were not placed on external walls, above radiators, or in kitchens or bathrooms. The buildings used in this study were low-rise brick walk-ups. (For a detailed description of the buildings used, refer to Appendix A.)

Temperature loggers and boiler runtime loggers were also placed in the boiler rooms. Table 1 lists the logger equipment that was used for this study. Figure 8 depicts a test building and a typical setup for the data logger placement.

Table 1. Logger Equipment

Measurement	Model	Description	Accuracy*
Outdoor Air Temperature	HOBO U23 Pro v2	Outdoor temperature/relative humidity data logger	± 0.38°F from 32° to 122°F
Indoor Air Temperature	HOBO U10-003	Indoor temperature/relative humidity data logger	± 0.95°F from 32° to 122°F
Boiler Firing Pattern	HOBO U9-001	State logger	Approximately ± 1 min/month at 77°F
AC Current/Boiler State (On/Off)	CSV-A8	AC current switch/sensor	–

*Logger specifications from manufacturer: www.onsetcomp.com/products

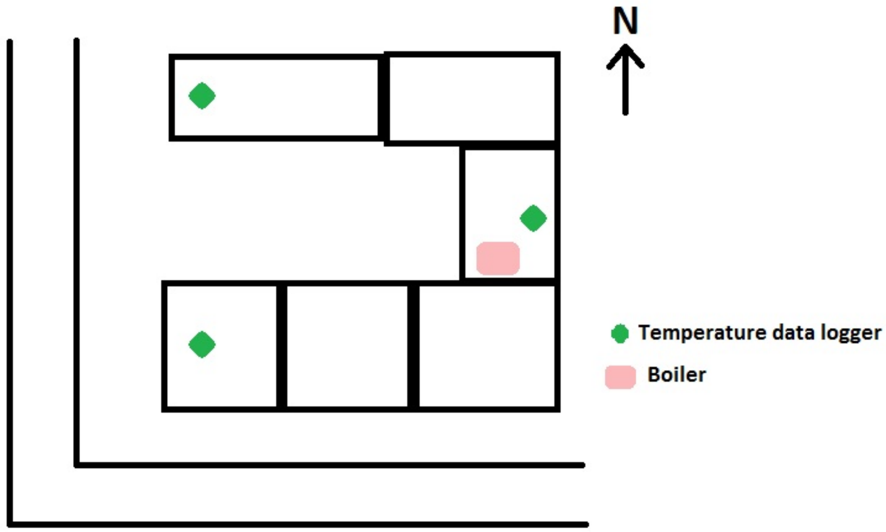


Figure 8. Schematic plan of Building 1 in the study

Temperature loggers were placed in units in each of three sections: directly above the boiler, in the north wing, and in the south wing.

2.3.6 Tenant Comfort

2.3.6.1 Guidelines

Interviewing the tenants and building manager enables a comparison of temperature data to the residents' perceptions of the unit temperature. It may also be useful in explaining abnormalities in the temperature data. If a unit far from the boiler, and therefore predicted to be cold, shows higher than average or expected temperature readings, the tenants may be using space heaters or the oven to additionally heat their unit. If a unit close to the boiler, and therefore predicted to be warm, shows lower than average or expected temperature readings, the tenants may be opening their windows. Also, surveying the tenants is useful in determining which parts of the building are too cold and which are too hot, especially in the absence of sensors.

2.3.6.2 Method

A tenant survey is an inexpensive method of understanding tenants' perceptions of the heating in their apartments and information about how the system operates (Peterson 1986). A tenant comfort survey was conducted in this study when the pre-measure temperature data were collected (before any steam balancing measures were done) and when the post-measure temperature data were collected (after the steam balancing measures were completed by the contractor). (A copy of this survey is shown in Appendix C.) The survey was administered and the responses were recorded in the field.

2.4 Measurements and Equipment

Although most of the building information (other than the temperature data and boiler runtime data) were collected by observation during the site visits, some additional equipment was necessary for the study. Table 2 outlines the additional equipment needed.

Table 2. Measurements and Equipment

Measurement	Equipment Needed
Census of Radiators	Observation
Radiator Vent Size	Observation
Radiator Vent Condition	Observation
Census of Main Lines	Observation
Main Line Lengths	Laser distance meter
Thickness of Main Lines	Calipers
Vertical Tier Position	Laser distance meter
Position of Vents	Laser distance meter
Main Vent Size	Observation
Main Vent Condition	Observation
Main Line Steam Time	Infrared camera
Rated Boiler Capacity (Btu/h)	Observation
Boiler Size (sections)	Observation
Burner Condition	Observation
Boiler Efficiency	Combustion analyzer
Header Piping Height	Laser distance meter
Riser and Header Width	Calipers
NBP Geometry	Camera
Return Line Condition	Observation
Description of Boiler Controls	Observation
Number of Functioning Sensors	Observation
Daytime/Nighttime Set Points	Observation
Current Boiler Operation	Observation

3 Measure Implementation

3.1 Determining a Scope of Work

CNT Energy worked with a steam heating contractor to develop a final scope of work for each test building. These scopes were highly detailed. It was decided that one contractor would do all the work, as this would minimize variability in installation methods, techniques, materials, and cost, and thus enable a consistent analysis of the effects of the main measures for a steam balancing package. The contractor proposals included itemized costs and descriptions of each steam balancing measure, informing the analysis on cost effectiveness.

3.2 Measure Costs

When examining the scopes of work for balancing the steam systems of the test buildings, the measures most frequently recommended by the steam heating contractor were:

- Adding or replacing the main line air vents
- Replacing the radiator vents
- Upgrading or adjusting the boiler control system.

Table 3 summarizes the average costs for each measure, including equipment and installation.

Table 3. Average Costs for Steam Balancing Measures

Measure	Average Cost
Adding or Upgrading to High-Capacity Main Line Air Vents (With New Risers)	$1,800 ($200–$250/vent)
Replacing Radiator Vents	$3,680 ($38–$52/vent)
Upgrading Boiler Control System	$5,060 ($3,900–$6,995)

For a detailed breakdown of all of the measures completed on each building (between December 2011 and January 2012) as well as their cost breakdowns, see Appendix D.

4 Analysis and Results

4.1 Temperature Control and Steam System Behavior

The air temperature data provided useful insights to the building steam delivery system performance. More uniform air temperatures will theoretically lower energy bills and improve tenant comfort, as there is no longer a need to overheat apartments close to the boiler to ensure that there is adequate heat for distant apartments. It was indicated in a previous study that gas consumption for heating can be reduced on the order of 16% by reducing a temperature spread through balancing a system (Biederman and Katrakis 1986). As described in the Technical Approach, six units in each building were fitted with temperature data loggers that recorded readings every 5 min for 1 month before the steam balancing, and for 1 month afterward. Unfortunately, in a couple of instances, tenants removed loggers from the walls or moved them. The data recorded by these loggers were therefore not accurate depictions of what the in-unit temperatures were. These instances are noted in Appendix E.

The temperature data were analyzed by looking at the average temperature of each logger at each hour of the day over the pre- and post-balancing logging periods. Buildings 2, 4, 8, and 9 showed decreases in temperature differentials between units. Buildings 1, 3, 5, 6, and 10 did not show decreases in temperature differentials. Data for Building 7 were inconclusive because data from two of the loggers were unavailable and a third logger had been dropped to the floor and therefore recorded much lower temperatures.

Figure 9 through Figure 12 show samples of the temperature data. These represent the fluctuations during a day and the temperature differentials between units. The rest of the temperature data graphs are included in Appendix E.

Building 10, whose temperatures are shown in Figure 9 and Figure 10, showed an increase in overall temperature across all units. The post-retrofit oversight visit revealed that the owner had increased the set point temperature on the new boiler controls. This explains the uniform temperature increase, because the distribution of temperatures remained the same. The operation and settings of the boiler controls were important factors in this project. Although the building owner or manager should decide how to set the controls (based on feedback from his or her tenants), this will be an important factor in whether the building can save on energy costs after balancing work is done. Proper building manager education on operating more complicated boiler controls is a very important step to steam balancing. Since Building 10 was using less natural gas over the course of its continued monitoring (shown in Table 6), this suggests that the increased main line venting and upgraded radiator vents are allowing the steam to reach the apartments more quickly and efficiently. This enables the building owner to save natural gas and money, even though the temperature set points on the controls are higher.

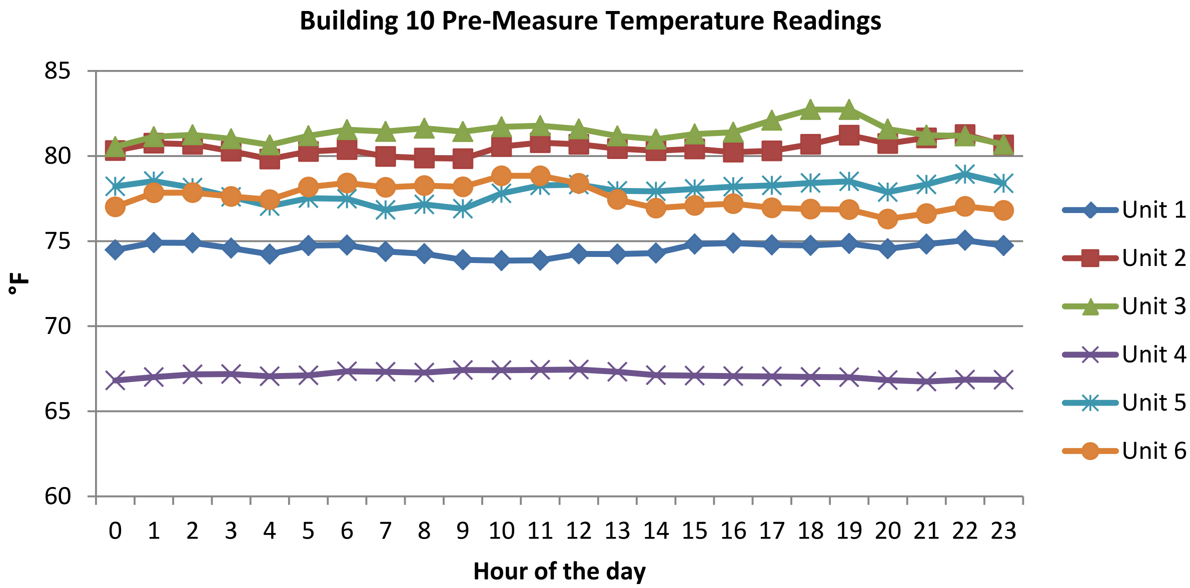


Figure 9. Building 10 average pre-measure logging period temperature readings by hour of the day

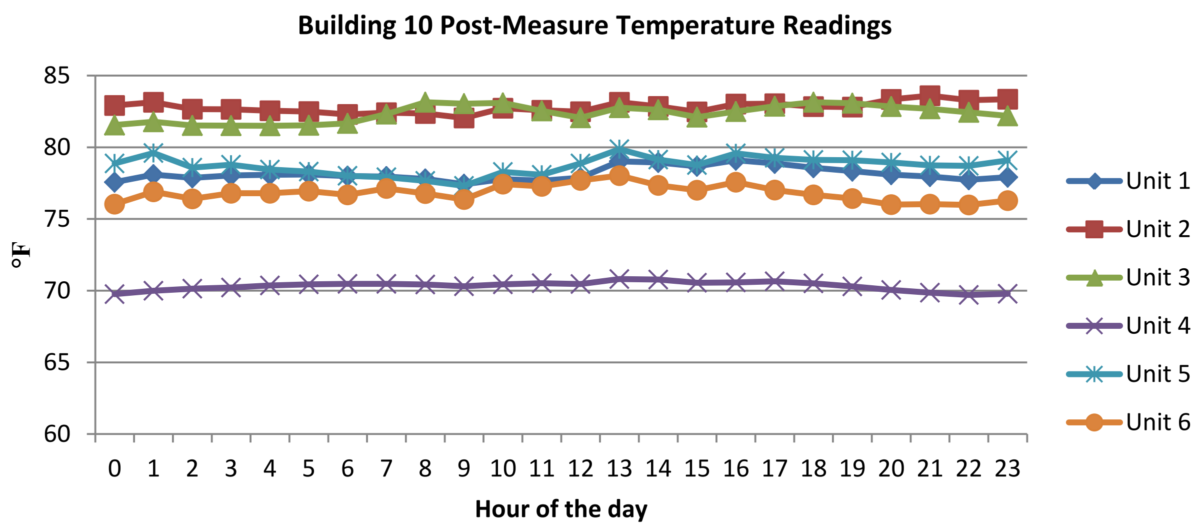


Figure 10. Building 10 average post-measure logging period temperature readings by hour of the day

In Building 4 (see Figure 11 and Figure 12 for temperature data), the two coldest units (Units 2 and 4) pre-retrofit showed an increase in temperature by about 2° overall post-retrofit. The temperature differential between the hottest and coldest units was therefore decreased, suggesting a more even distribution of heat throughout the building. The manager also reported that heat seemed to be reaching the extreme ends of the building more quickly and evenly.

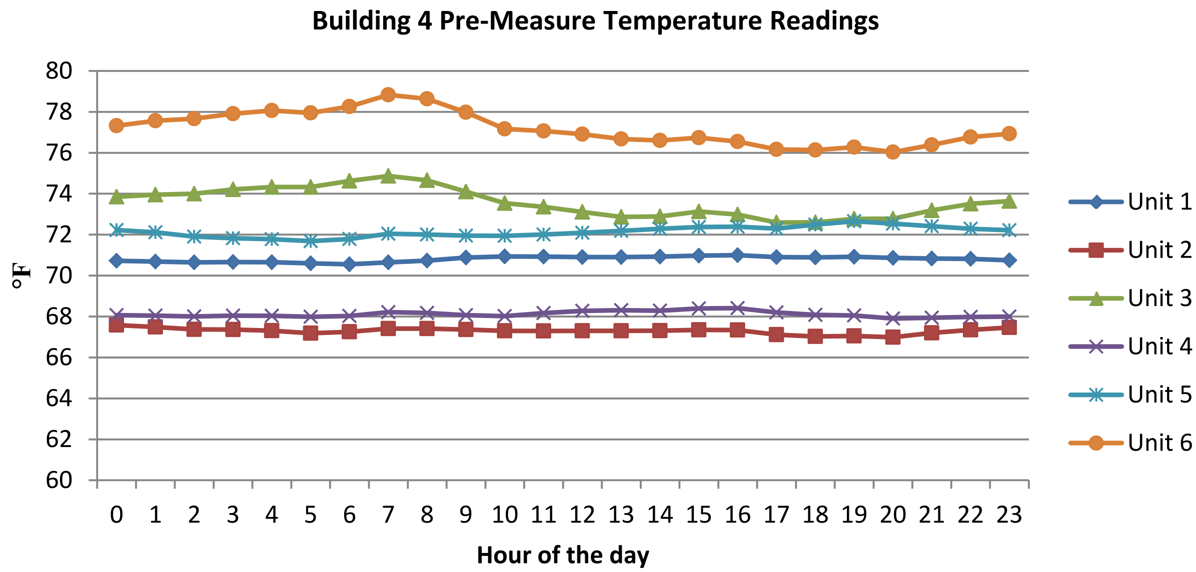


Figure 11. Building 4 average pre-measure logging period temperature readings by hour of the day

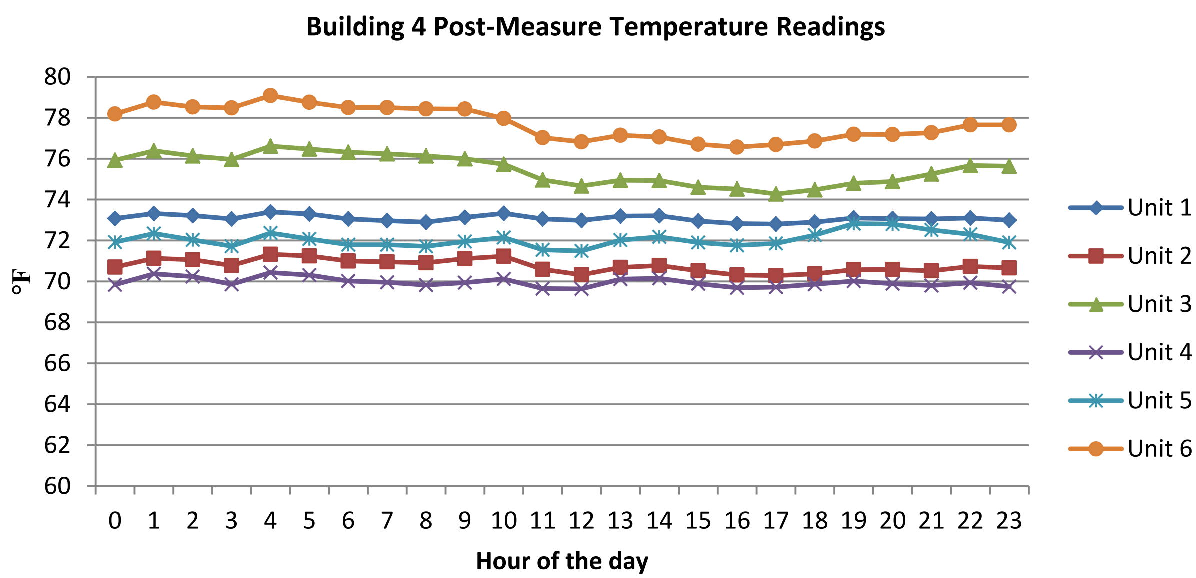


Figure 12. Building 4 average post-measure logging period temperature readings by hour of the day

The information collected from the tenant surveys and building owners revealed that some tenants in the coldest units were using space heaters or their ovens for additional heat on the coldest days of the logging periods, which could raise the average temperatures of units.

4.2 Boiler Cycles

The number of times that the boiler cycled on at each building over the pre- and post-balancing logging periods is shown in Table 4. Since this value is dependent on weather, it was weather-normalized using HDDs (see Table 5). Also shown for each building are the average lengths of the boiler cycles and the weather-normalized percent of time each boiler was on per day. Data for building 10 were unavailable because of a problem with the logger.

According to the weather-normalized data, four of nine buildings showed less frequent boiler cycles and seven showed shorter boiler cycles post-retrofit.

Table 4. Number of Boiler Cycles During Pre- and Post-Balancing Periods

Building	Pre-Balancing		Post-Balancing	
	Number of Days Counted	Boiler on Cycle Count	Number of Days Counted	Boiler on Cycle Count
1	36	193	29	257
2	36	210	55	272
3	37	214	59	548
4	37	174	42	249
5	32	42	41	306
6	34	71	45	201
7	44	72	34	146
8	38	226	69	507
9	39	197	49	487
10	Data unavailable	Data unavailable	Data unavailable	Data unavailable

Table 5. Cycle Counts per Year, Average Lengths of Boiler Cycles and Percent of Day Boiler On

Building	Average Boiler on Cycle Count per Year*		Average Length of Boiler Cycle (min)		Average % of Time Boiler on per Day (per HDD)	
	Pre-Balancing	Post-Balancing	Pre-Balancing	Post-Balancing	Pre-Balancing	Post-Balancing
1	1265.4	1699.3	68.9	59.6	0.0098	0.0112
2	1972.7	1030.1	68.9	75.3	0.0134	0.0085
3	2015.1	1902.0	72.0	46.5	0.0137	0.0099
4	1638.3	1142.9	52.6	61.5	0.0095	0.0078
5	381.9	1509.7	163.3	44.1	0.0062	0.0074
6	700.4	854.6	68.0	55.1	0.0052	0.0051
7	540.5	885.0	143.5	64.5	0.008	0.0063
8	1623.3	1458.5	78.6	78.1	0.0142	0.0124
9	1615.6	1994.8	75.6	54.0	0.011	0.0118
10	Data unavailable	Data unavailable	Data unavailable	Data unavailable	Data unavailable	Data unavailable

* The number of boiler cycles per year was weather normalized and calculated by dividing the average number of cycles per day during the four-week logging periods by the actual number of HDDs each day, then taking an average and extrapolating to a year's worth of cycles by multiplying by the (30-year average for the) total number of HDDs in a year.

The weather-normalized natural gas use of each boiler for the pre-balancing and post-balancing periods (in kBtu) is depicted in Figure 13. The numbers of months used for analysis are shown in Table 6.

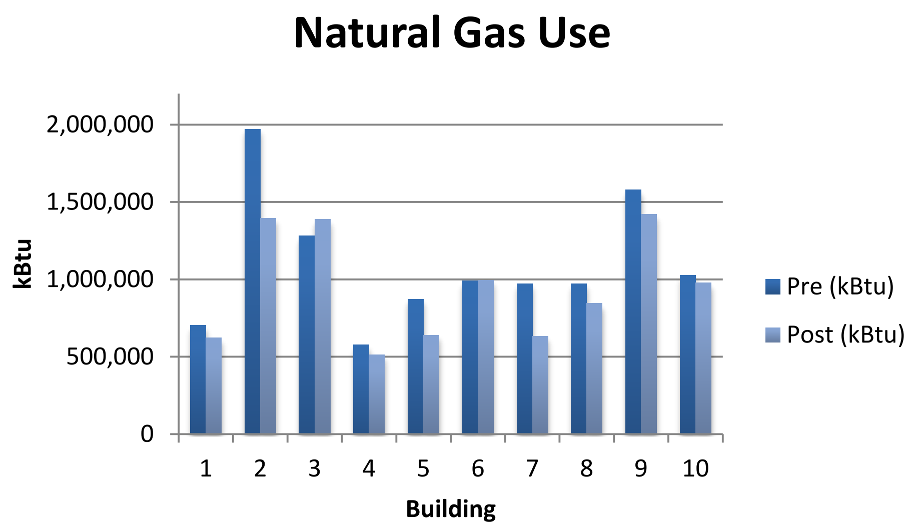


Figure 13. Weather-normalized natural gas use from utility bills during pre-balancing and post-balancing periods

Table 6. Measured Weather-Normalized Natural Gas Use (Heating Only)

Building	Natural Gas Use From EUI* (kBtu)			
	Pre-Balancing	Post-Balancing	# of Months in Analysis Periods	% Savings
1	703,119	621,371	8	11.63%
2	1,971,622	1,394,456	9	29.27%
3	1,280,991	1,388,438	11	-8.39%
4	578,751	514,142	11	11.16%
5	873,111	640,519	9	26.64%
6	990,039	995,768	11	–0.58%
7	972,393	633,350	10	34.87%
8	972,476	844,398	8	13.17%
9	1,578,954	1,420,073	10	10.06%
10	1,027,457	977,787	10	4.83%

* Energy use intensity

All buildings except Buildings 3 and 6 used less natural gas for heating after the measures were completed.

4.3 Cost Effectiveness

In order to determine the cost effectiveness of the installed measures, analysis was conducted using measure costs and measured natural gas savings. The pre- and post-balancing energy use was compared via utility bill analysis. These are shown in Table 7.

Table 7. Average Percent Natural Gas Savings,* Balancing Costs, and Simple Paybacks

	Savings (kBtu)	% Savings	Balancing Cost ($)	Simple Payback (yrs)***
Measured (All Buildings)	27,428	13.3%	9,434	3.4
Measured (Buildings Without Additional Measures Installed)**	13,606	10.2%	9,875	5.1

*The percent natural gas savings shown in this table are for heating load only.
**Some of the buildings (2, 3, 5 and 7) had additional measures installed after the balancing work and data logging periods. These buildings were excluded from this average value calculation.
***The simple payback was calculated using an estimate of $1/therm natural gas.

The EUI analysis, which uses actual billed natural gas use, was calculated and weather normalized for each building using CNT Energy's Standard Operating Procedure for energy use calculations. To calculate a weather-normalized heating load EUI, the actual period heating load usage per square foot is multiplied by a ratio of the 30-year average number of HDDs to the actual number of heating degree days in that period (Equation 1).

$$EUI_{Heating\ Load} = \frac{Actual\ Period\ Heating\ Load\ Usage}{Building\ Heating\ SF} * \frac{30\ Yr\ HDD}{Actual\ HDD} \quad (1)$$

The EUI analyses showed that all except Buildings 3 and 6 reduced their natural gas usage. Buildings 2, 3, 5, and 7 had additional measures (air sealing and insulation in the roof cavity and heating pipe insulation) installed after the data logging periods were over. In Building 3, which had additional energy efficiency measures installed but saw an increase in measured natural gas usage, it is likely that the temperature set points were increased after the post-balancing logging period. A summary of the natural gas savings are shown in Table 7.

The total cost effectiveness of the steam balancing package tested (upgrading or replacing controls, installing main line vents, replacing radiator vents) was evaluated by calculating simple paybacks from projected yearly financial savings and measure costs. The average measure cost and simple payback are shown in Table 7.

Long-term monitoring of building performance would be an interesting study to examine whether a building owner would see sustained savings from steam balancing measures. This would be accomplished by doing utility bill analyses for at least two years following construction.

4.4 Tenant Comfort

Tenants of the units where loggers were placed were surveyed about their temperature comfort and whether they opened their windows or used additional heat sources during the heating season before and after the retrofits were done. (A sample survey is provided in Appendix C.) The response rate was 44% pre-retrofit and 56% post-retrofit (this translates to an average response rate of 12% of an entire building's tenants pre-retrofit and 17% post-retrofit).

Figure 14 shows the average survey responses when tenants were asked to rate their overall temperature comfort on a scale from 1 = Uncomfortable to 5 = Comfortable. All the buildings except Buildings 1 and 6 saw improvements in rated comfort post-retrofit.

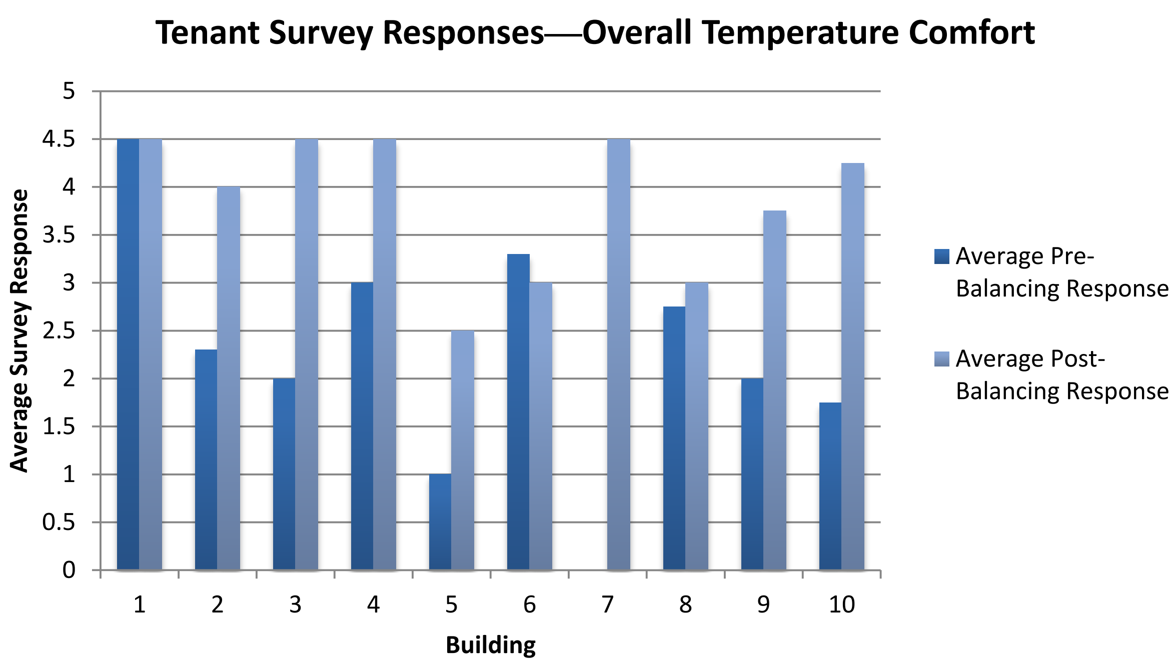


Figure 14. Tenant survey responses rating overall temperature comfort. The tenants were asked to rate the overall temperature comfort within their unit on a scale from 1 = Uncomfortable to 5 = Comfortable. Note: Building 7 received no survey responses pre-retrofit.

5 Discussion

5.1 Temperature Control and Steam System Behavior

Each test building responded differently to the steam balancing measures. Their pre-measure conditions were drastically different, so this was expected. However, some of the differences in the pre- and post-balancing temperature data were:

- Changes in the diurnal temperature patterns within units (different schedules of when the units were warmest and when they were coolest)
- Smaller temperature differentials between the hottest and coldest units in some buildings.

The changes in heating schedules (observed in Building 5) should provide heat at appropriate times and increase resident comfort. Because this change was determined by the type of controls in place, newly installed boiler controls seem to have contributed significantly to more comfortable temperature settings. The indoor averaging system and the more advanced temperature set point control (allowing for nighttime, daytime, and differential set points) seem to have more tightly regulated the heating schedules. Since these controls have the added advantage of allowing building owners to monitor unit temperatures from a central control box in the boiler room, building owners are able to make more informed decisions about their set points.

A decrease in the temperature differential between the hottest and coldest units was also seen in some buildings. This suggests that heat was being more evenly distributed, reaching units that previously received less heat. This could have been because the indoor averaging temperature controls regulated the boiler to stay on longer, until heat reached the further units, or because the increased venting allowed steam to travel faster through the mains and to the radiators. Buildings 2 and 4 showed increases in their average boiler cycle lengths, suggesting that longer cycles were needed for heat to reach the further tiers in the buildings. This more even heat distribution is also expected to increase resident comfort.

The balancing work had varying effects on the lengths and frequency of boiler cycles (shown in Table 5). Some buildings saw shorter cycles post-retrofit and some saw much longer cycles. Some saw more boiler cycles and some saw fewer. As previously stated, this was expected because each building had unique pre-retrofit conditions. It was difficult to predict exactly how the balancing work, especially the increased or upgraded venting, would change temperatures and boiler behavior. What is evident, however, is that several trips and adjustments are often needed after the initial round of balancing work is done. Building 3 (see Figure 15 and Figure 16) showed an example of a building where the midrange temperature units were more uniformly heated to a comfortable temperature, but the outliers remained after the balancing work was done. This suggests that the venting and control systems did not affect the hottest and coldest units and that there may have been some other reasons that these units were so different in temperature from the others. This represents an example of a building where issues with controlling the heat to the hottest and coldest units need to be investigated and addressed further in subsequent heating seasons.

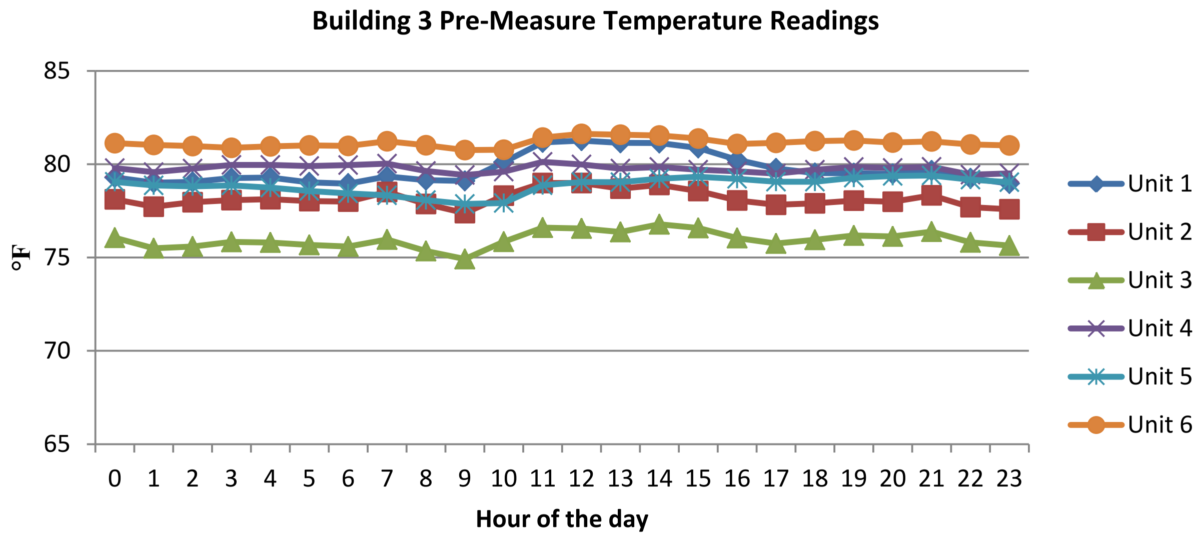


Figure 15. Building 3 average pre-measure logging period temperature readings by hour of the day

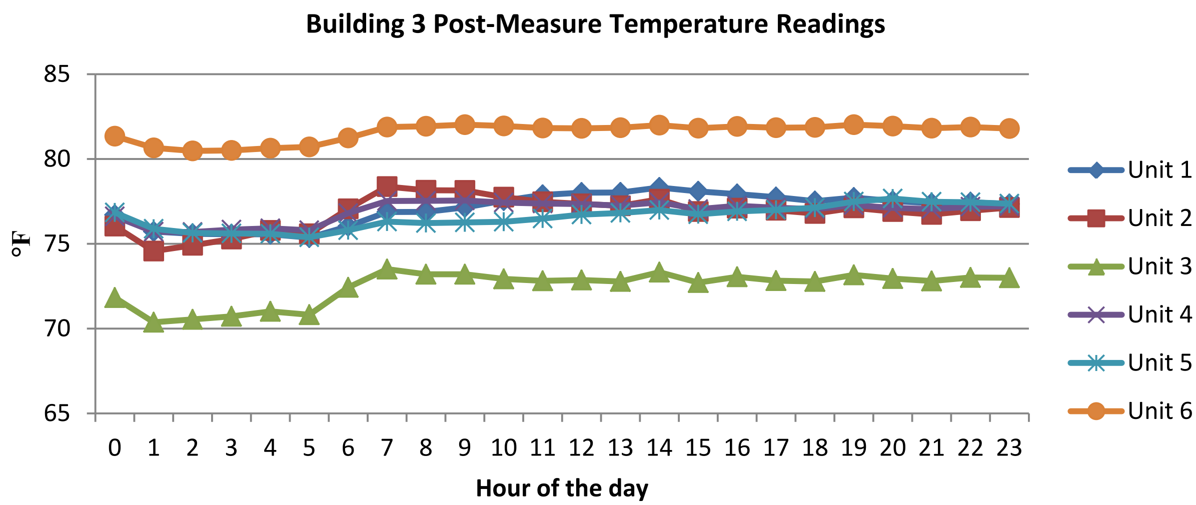


Figure 16. Building 3 average post-measure logging period temperature readings by hour of the day

5.2 Cost Effectiveness

The natural gas used for heating before and after the balancing work was calculated by looking at the actual heating bills for the buildings. The measured natural gas usage values (shown in Table 7) showed that the test buildings saved an average of 13.3% with an average simple payback of 3.4 years. However, since some of the building had additional measures installed (air sealing and insulation of the roof cavity and heating pipe insulation), the average for the buildings that had only steam balancing measures was also calculated. This value was found to be 10.2% and the average simple payback for these buildings was 5.1 years. These results are fairly consistent with previous studies. The benefit of tenant comfort (which would begin immediately after a building is properly balanced) should also be considered as an important added value.

5.3 Tenant Perceptions

Records of tenant complaints about the heat should be used in conjunction with logger data when determining how to balance a building. These often indicate where heat is not reaching.

Though five of the buildings (1, 3, 5, 6, and 10) did not see a decrease in temperature differentials, it is important to note that all of the buildings except Buildings 1 and 6 saw improvements in average rated temperature comfort according to the tenant surveys. Tenant comfort can be a very important factor when deciding to do energy efficiency measures. Along with keeping tenants happy, it can also assist building owners with tenant retention. The one building that did not see improvements in temperature differentials, natural gas usage, or tenant comfort (Building 6) will require additional assessments to see how and why the heating system is failing.

Building owners often stopped overheating their buildings because of the new controls or adjusted venting, so major heating imbalances became more obvious. Some units that received heat more slowly may have initially received even less heat after the temperature set points were turned down or adjusted, so tenants were more likely to notice heating deficiencies caused by imbalances. Also, many tenants were used to having their units overheated (often up to 80°–85°F), so they were more likely to complain once set points were adjusted properly and they were receiving less heat than before. Tenants in the two buildings that did not show improvements in average rated temperature comfort (Buildings 1 and 6) were either experiencing this phenomenon post-retrofit, or they were still being overheated. Though the venting was adjusted, these buildings may require more follow-up visits to further assess the distribution and control systems.

6 Conclusions and Recommendations

6.1 Establishing Steam Balancing Guidelines

Several additional points are important to consider when deciding to balance a building:

- **Balancing is a multistage process.** All the information in the Experiment section should first be collected on a building thought to need balancing. Once a building has initially had the steam balancing measure package installed, the effectiveness of the retrofits should be assessed based on conversations with the building manager and tenants and on temperature data. The building may need to be rebalanced, reassessed, and perhaps further adjusted.

- **Unit locations and building layout are important to consider when assessing and balancing a building.** Each building will have different hot and cold spots and will require different venting configurations and placement of control sensors.

- **Tenants and building managers need to be informed about the balancing process and that its success will require time and cooperation.** The balancing work will be most effective when tenants and building managers cooperate. Tenants should be informed that the work will require occasional access to their units and asked not to tamper with monitoring equipment. Tenants should also be informed that using space heaters drives up the temperature that indoor averaging systems use to control the boiler. This means that the boiler will not come on in a building even if some units are substantially below the set point. This must be communicated to tenants, and building managers should be properly instructed on how to use the newly installed controls.

6.2 Further Recommended Studies

Though the results of this project are generally positive, further studies should be done to more conclusively determine the effects of steam balancing. Variables were monitored as closely as possible, but the test buildings were occupied and thus subject to unpredictable tenant behavior. This caused uncertainties in the physical meaning of some temperature measurements collected. More controlled studies could be done to conclusively determine the effect of balancing on temperatures within units.

The effectiveness of the three separate measures considered as a package in this project could be examined by installing them individually and assessing the temperature distributions and natural gas uses in a new set of test buildings. Measures such as thermostatic radiator valves could also be evaluated.

Taking temperature readings at more frequent intervals in every unit would also help shed light on how the balancing work affects the time to heat a unit. The data could be matched with the boiler runtime data to see how long it takes to heat a unit after a boiler cycles on. This would require either remotely monitored data loggers or entering into units more frequently to collect more data. The windows could also be monitored to see if tenants were cooling their apartments, and stoves could be monitored to see if tenants were using them as supplemental heat sources. This type of study would require much more stringent cooperation from tenants.

References

Ahlgren, R. (1994). "Low Pressure Steam Heating Systems." *ASHRAE Journal*, Sept 2009. www.nxtbook.com/nxtbooks/ashrae/ashraejournal_200909/index.php?startid=58#/58.

Biederman, N.; Katrakis, J. (1986). *Space Heating Efficiency Improvements in Multifamily Buildings*. GRI 88/0111. Chicago: Gas Research Institute.

DOE. (2011.) Building America: Program Goals. Washington, D.C.: U.S. Department of Energy. www1.eere.energy.gov/buildings/building_america/program_goals.html.

Evens, A.; Ludwig, P.; Kotewa, L. (2008). "Cook County Energy Savers: How Energy Efficiency in Chicago's Multi-Family Buildings Has Evolved to Meet New Challenges from the 1980's to the Present Day." ACEEE Summer Study on Energy Efficiency in Buildings. 2-197.

Gill, G.; Pajek, S. (2005). "Balancing Steam Systems Using a Venting Capacity Chart." Gerry Gill and Steve Pajek.

Gorton Heating Corporation. (2006). Gorton Heating. www.gorton-valves.com.

Holohan, D. (1992). *The Lost Art of Steam Heating*. D. Holohan.

Holohan, D. (2010a). *Greening Steam How to Bring 19th-Century Heating Systems into the 21st Century (and save lots of green!)*. Daniel Holohan Associates, Inc.

Holohan, D. (2010b). Balancing One Pipe Steam Systems. www.heatinghelp.com/article/11/Hot-Tech-Tips/138/Balancing-One-Pipe-Steam-Systems.

Holohan, D. (2011). *Classic Hydronics*. D. Holohan.

Karins, N. (1994). "Energy Savings in One-Pipe Steam Heating Systems Fitted with High-Capacity Air Vents." EME Group. www.osti.gov/bridge/servlets/purl/10191625-8qJZ5M/webviewable/.

Katrakis, J.; Lobenstein, M.; Hewett, M. (2010). "Cost-Effective Boiler System Retrofits." *Consulting-Specifying Engineer*. http://m.csemag.com/index.php?id=2832&tx_ttnews[tt_news]=22127&cHash=3b07e71e00.

Peerless® Boilers. (1996). *Series 211A™ – Gas Boilers – Steam – Installation, Operation & Maintenance Manual*. Bally, PA: PB Heat, LLC.

Peterson, G. (1985). *Achieving Even Space Heating in Single Pipe Steam Buildings*. CEE TR85-8-MF. Minneapolis: Center for Energy and Environment. www.mncee.org/.

Peterson, G. (1986). *Multifamily Pilot Project: Single Pipe Steam Balancing & Hot Water Outdoor Reset.* Minneapolis Energy Office. www.mncee.org/pdf/tech_pubs/86-5.pdf.

Peterson, G.; Otterson, S. (1985). *Single Pipe Steam Air Venting.* CEE TR85-3-MF. Minneapolis: Center for Energy & Environment. www.mncee.org/.

Appendix A: Test Building Details

Building	Type	# Units	Cond. Square Feet	Original Control Strategy	Natural Gas Heating Load (kBtu)		
					Pre-Balancing	Post-Balancing	# of Months in Analysis Periods
1	3-story brick courtyard building, flat roof	33	24,570	Timeclock/ aquastat	703,119	621,371	8
2	3-story brick courtyard building, flat roof	30	30,050	RD SF 201 (Non-functional, so was controlled manually)	1,971,622	1,394,456	9
3	3-story brick courtyard building, flat roof	16	18,000	Timeclock/ aquastat	1,280,991	1,388,438	11
4	3-story brick walk-up, flat roof	6, converted to 20	8,600	Thermostat on 3rd floor	578,751	514,142	11
5	3-story brick courtyard building, flat roof	15	12,600	Timeclock/ aquastat	873,111	640,519	9
6	3-story brick walk-up, flat roof	18	15,760	Timeclock/ aquastat	990,039	995,768	11
7	3-story brick courtyard building, flat roof	16	12,360	Timeclock/ aquastat	972,393	633,350	10
8	3-story brick courtyard building, flat roof	24	17,640	Timeclock/ aquastat	972,476	844,398	8
9	3-story brick walk-up, flat roof	21	16,600	Timeclock/ aquastat	1,578,954	1,420,073	10
10	3-story brick walk-up, flat roof	32	18,300	Timeclock/ aquastat	1,027,457	977,787	10

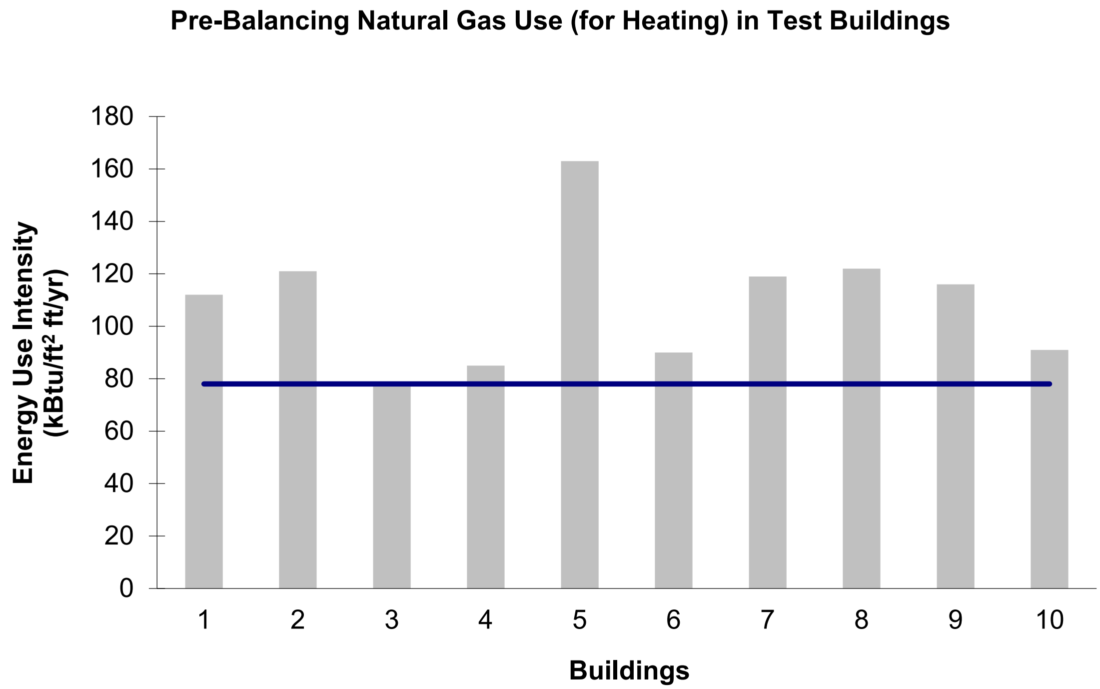


Figure 17. The pre-measure heating EUI for each test building is at or above the line representing the median EUI for 105 similar steam-heated buildings in Chicago. This suggests that the buildings chosen for this study all had potential for energy savings.

Appendix B: Sample Tenant Letter

CNTenergy

Dear Tenant,

On ___________________________, 2011, we installed a temperature data logger in your apartment unit. We are working with your landlord to find and address any heating issues within the building; this data logger provides information for that work.

We ask that you do not remove or disturb the logger. It will allow us to collect useful information that should improve your comfort during the heating season.

We will need to access your apartment again in about **4 weeks** to collect the temperature data and reset the data logger. You will be notified again by your landlord prior to our next visit.

We very much appreciate your cooperation. If you have any questions, please contact your landlord or building manager.

Sincerely,

The Energy Savers Team
CNT Energy
<Phone Number>

Appendix C: Sample Tenant Survey

CNTenergy

Pre-Measure Occupant Comfort Survey – Steam Balancing and Tuning

Address: ______________________________ Date: __________

Unit: ______________________________

How long have you lived in the unit?

Overall temperature comfort:

Uncomfortable ◯ ◯ ◯ ◯ ◯ Comfortable

How cold it gets:

Too cold ◯ ◯ ◯ ◯ ◯ Comfortable

How warm it gets:

Too warm ◯ ◯ ◯ ◯ ◯ Comfortable

Temperature shifts:

Too frequent ◯ ◯ ◯ ◯ ◯ Constant Temperature

Your ability to adjust the room temperature:

Poor or no controls ◯ ◯ ◯ ◯ ◯ Works well

Do you use the oven or space heaters to additionally heat your apartment?

Do you ever open your windows to cool down your apartment during the heating season?

Other comments about the heat:

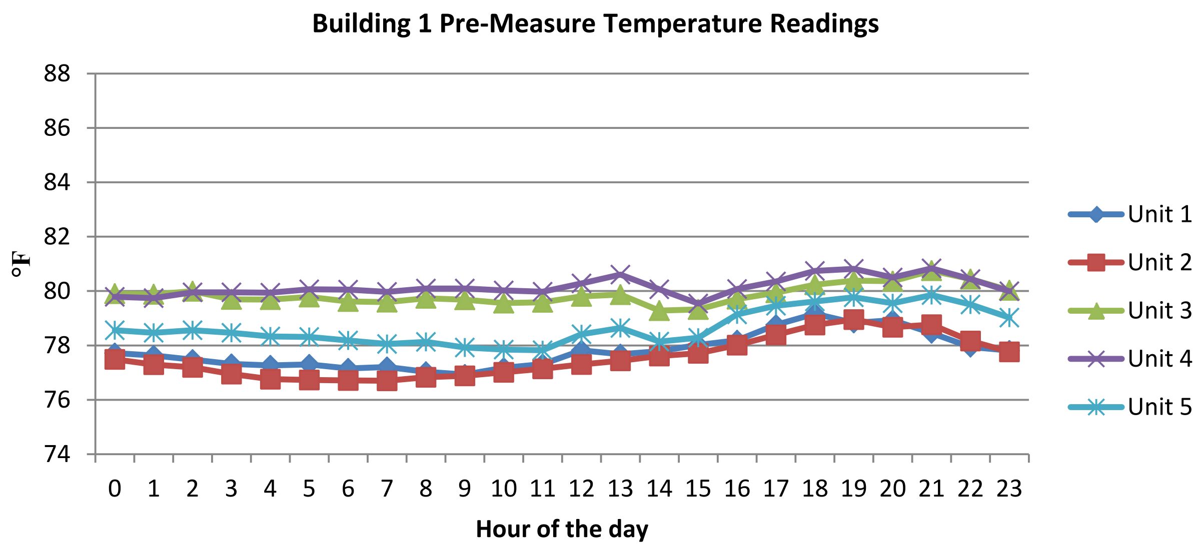
Appendix D: Detailed Measures and Costs

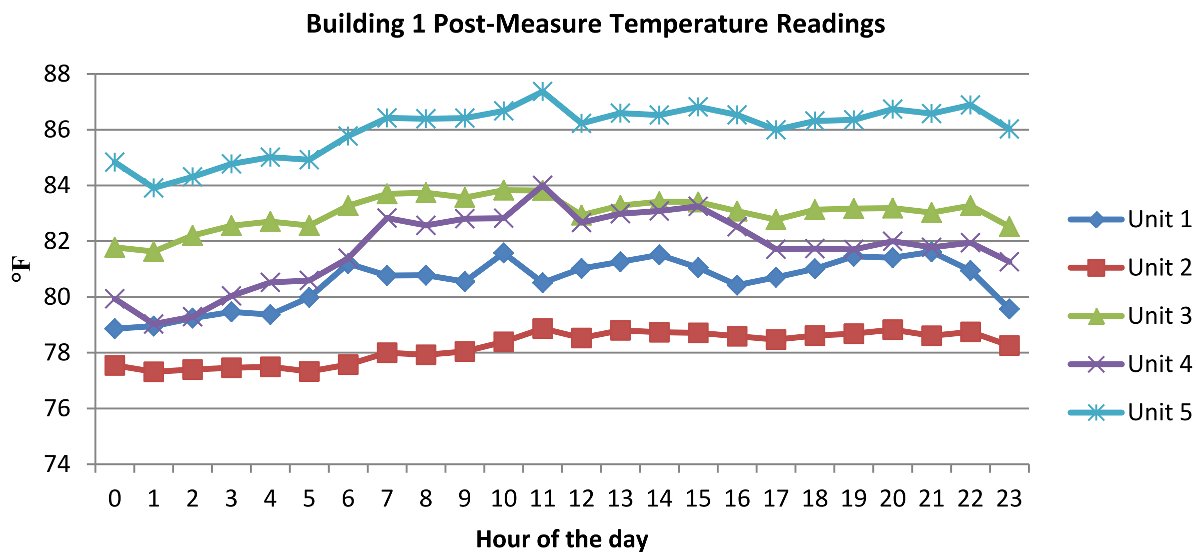
Building	Measures Completed	Individual Measure Costs ($)	Total Cost ($)
1	Main line vents (3 Gorton (2006) #1; 6 Gorton #2) Radiator vents (150) Boiler controls (RD AH207 – 6 indoor sensors, 1 outdoor sensor)	4,695 5,842 6,995	17,532
2	Main line vents (5 Gorton #1; 3 Gorton #2) Radiator vents (120) Boiler controls (RD AH207 – 6 indoor sensors, 1 outdoor sensor)	1,560 5,200 6,995	13,755
3	Main line vents (5 Gorton #2) Radiator vents (70) Boiler controls (RD 1404T – 4 indoor sensors, 1 outdoor sensor)	1,540 2,820 4,500	8,860
4	Main line vents (2 Gorton #1; 2 Gorton #2) Radiator vents (48) Boiler controls (RD 1404T – 4 indoor sensors, 1 outdoor sensor)	895 2,195 4,698	7,788
5	Main line vents (2 Gorton #1; 4 Gorton #2) Radiator vents (51) Boiler controls (RD RF207 – 6 indoor sensors, 1 outdoor sensor)	1,295 2,295 3,900	7,490
6	Main line vents (3 Gorton #1; 3 Gorton #2) Radiator vents (135) Boiler controls (RD 1206 – 6 indoor sensors, 1 outdoor sensor)	1,570 5,500 4,500 (est)*	11,570
7	Main line vents (1 Gorton #1; 2 Gorton #2) Radiator vents (54) Boiler controls (RD RF207 – 6 indoor sensors, 1 outdoor sensor)	1,495 2,395 3,900	7,790
8	Main line vents (3 Gorton #1; 4 Gorton #2) Radiator vents (72) Boiler controls (RD 1204 – 4 indoor sensors, 1 outdoor sensor)	1,798 3,589 4,000	9,387
9	Main line vents (2 Gorton #1; 4 Gorton #2) Radiator vents (90) Boiler controls (RD 1404T – 4 indoor sensors, 1 outdoor sensor)	1,500 3,295 4,500	9,295
10	Main line vents (3 Gorton #1; 4 Gorton #2) Radiator vents (71) Boiler controls (RD 1206 – 6 indoor sensors, 1 outdoor sensor)	1,678 3,695 4,000 (est)*	9,373

*The boiler control costs for Buildings 6 and 10 are estimated costs because the owner had installed these prior to the start of the project and CNT Energy did not receive the formal proposals for these installations. The buildings were run on their original timers/thermostats during the prelogging period to simulate "pre" boiler control conditions.
Note: New risers were installed for the main line vents as needed. The costs for these are included in the costs for the main line vents. All radiator vents were Gorton radiator air vents.

Appendix E: Temperature Data

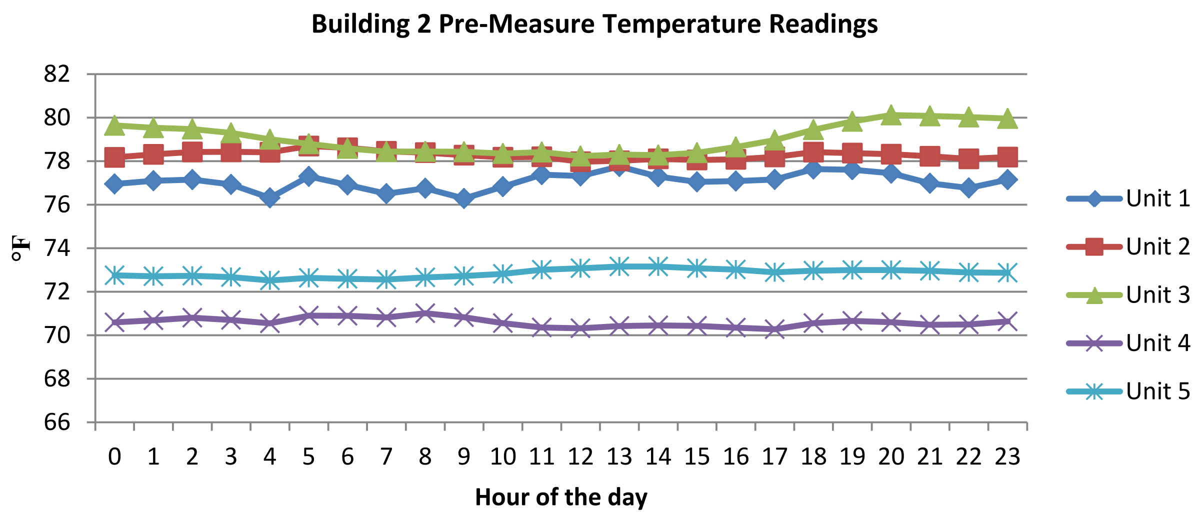
Building 1

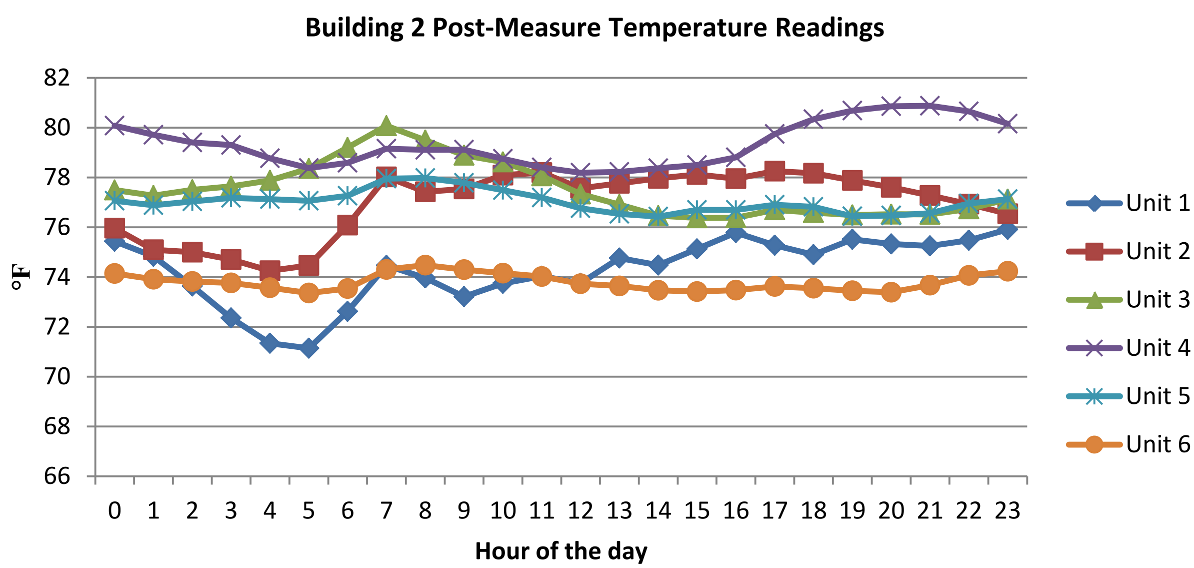




Note: Access was only granted for 5 units in this building so only 5 temperature loggers were installed.

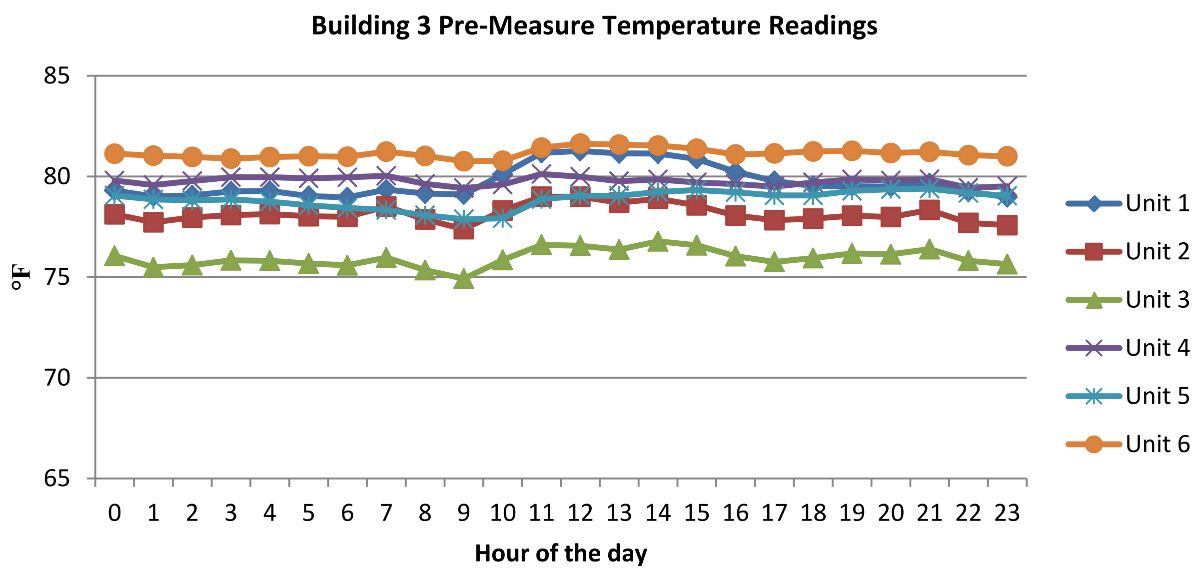
Building 2

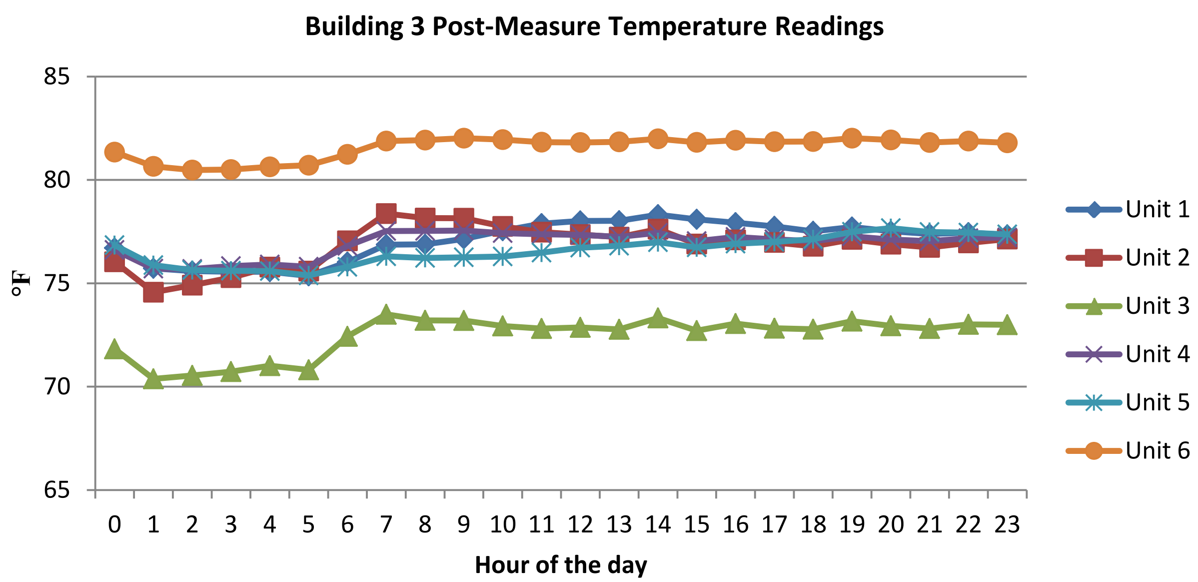




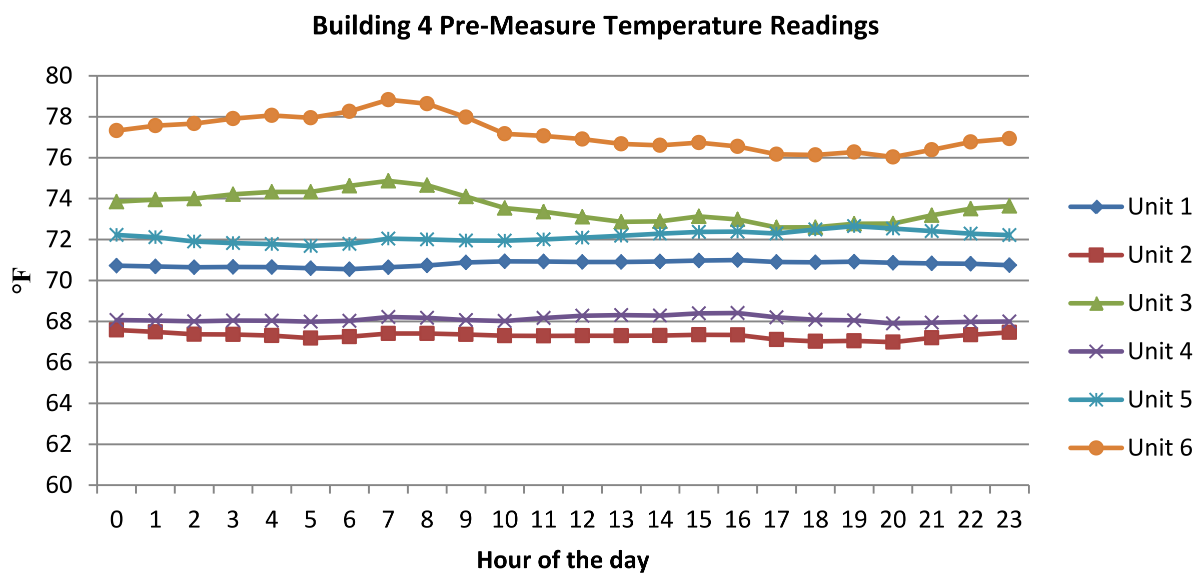
Note: Pre-measure data for Unit 6 were unavailable because of limited access to the unit.

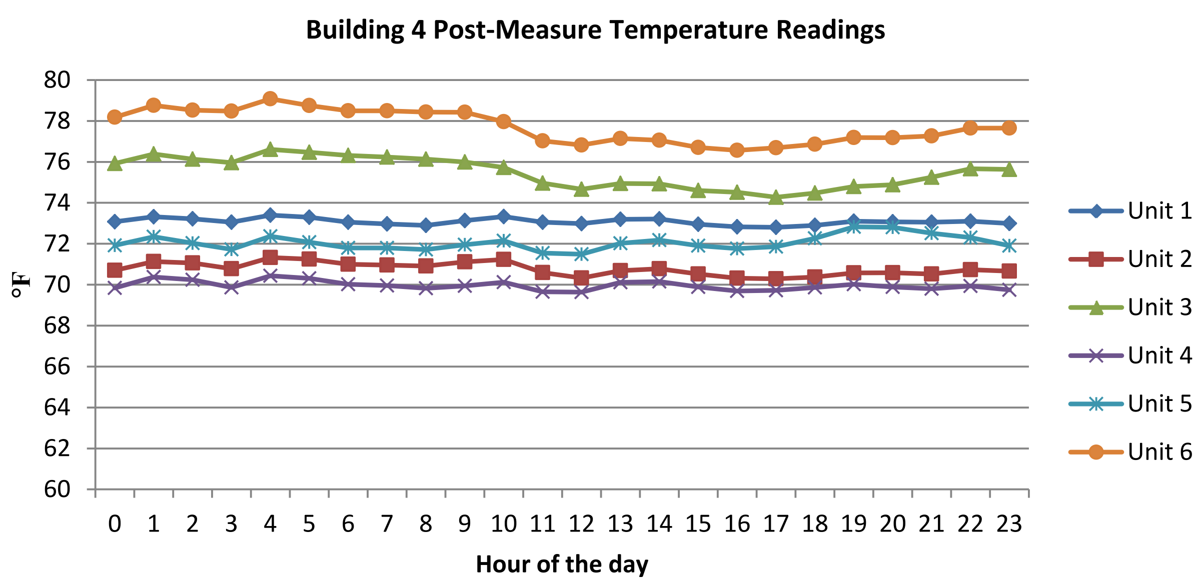
Building 3


Building 3 Pre-Measure Temperature Readings
85
80
75
70
65
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

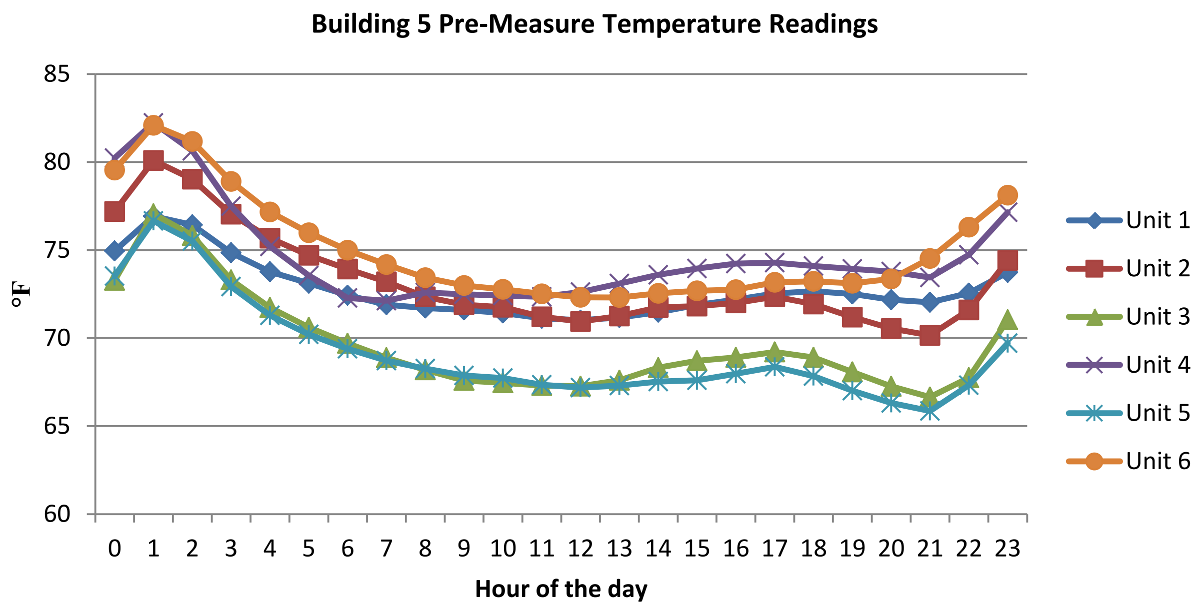

Building 3 Post-Measure Temperature Readings
85
80
75
70
65
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

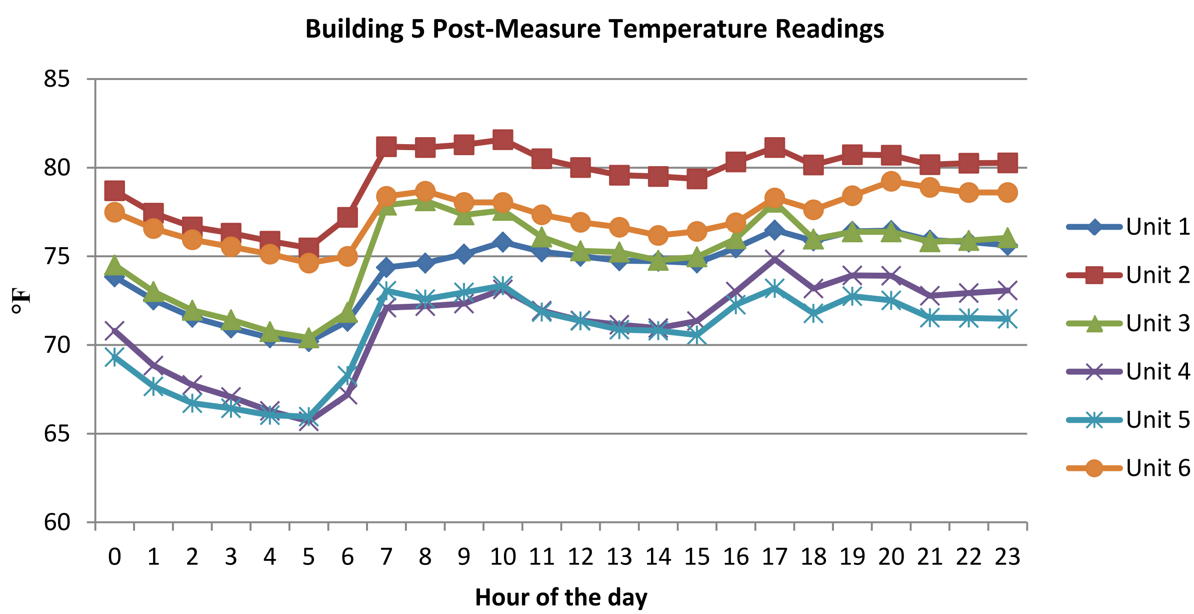
Building 4


Building 4 Pre-Measure Temperature Readings
80
78
76
74
72
70
68
66
64
62
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

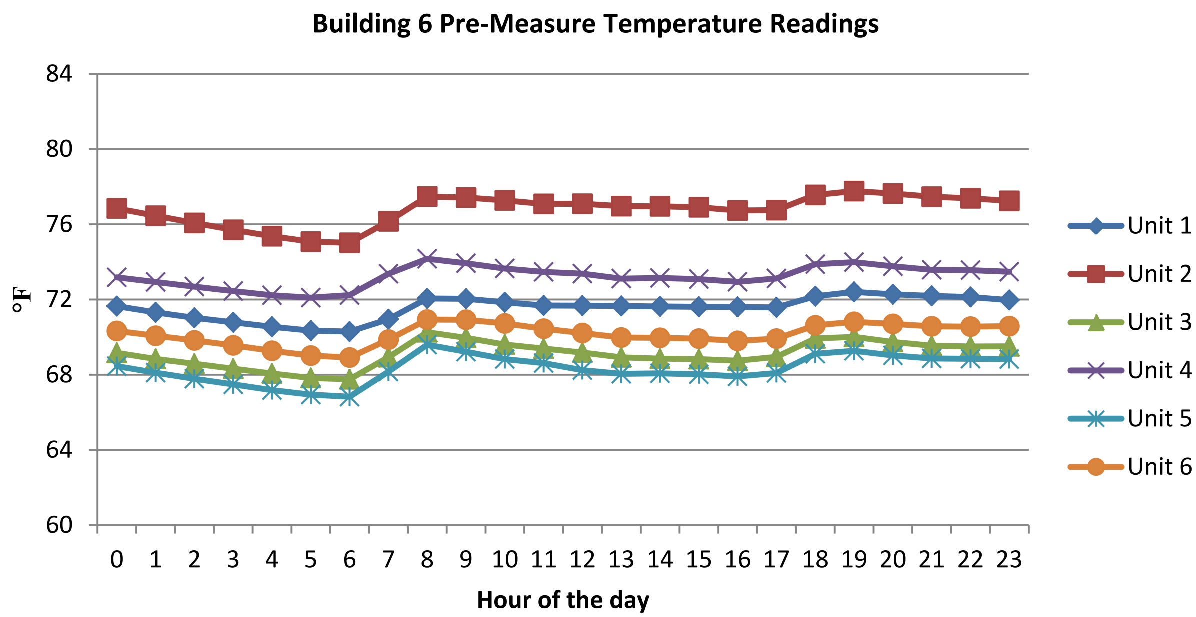

Building 4 Post-Measure Temperature Readings
80
78
76
74
72
70
68
66
64
62
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

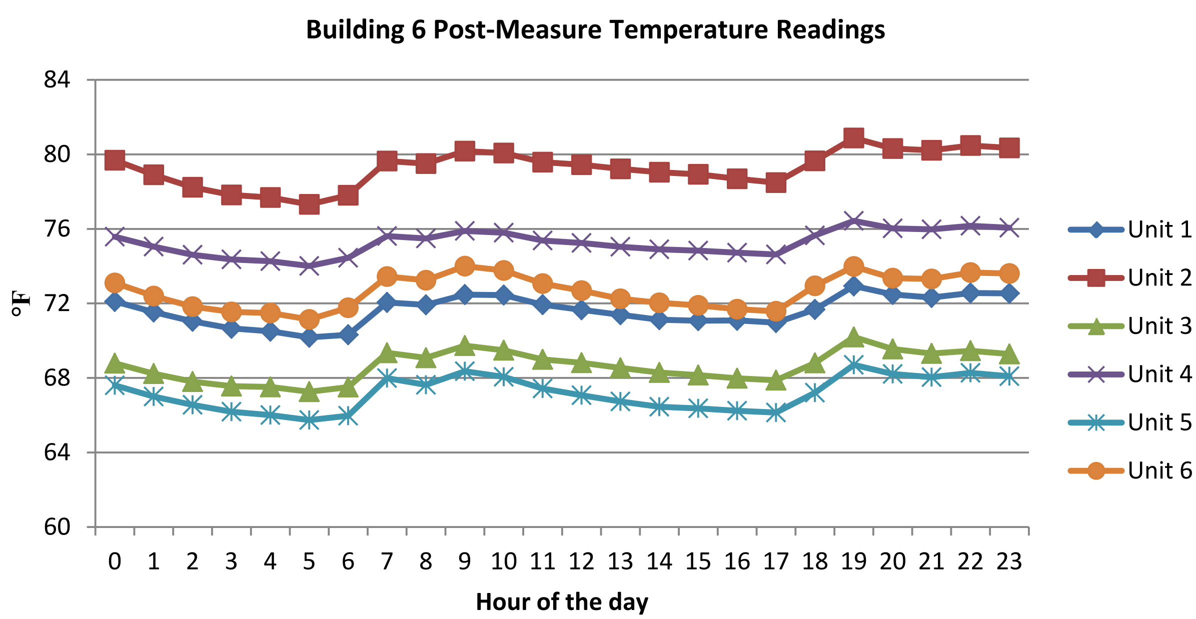
Building 5


Building 5 Pre-Measure Temperature Readings
85
80
75
70
65
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

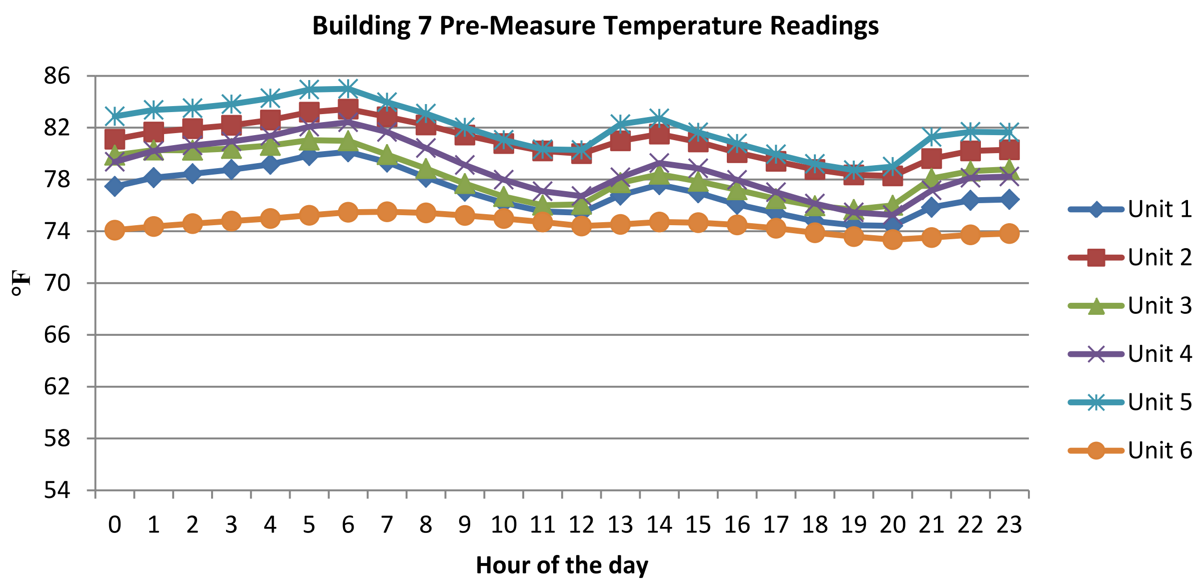

Building 5 Post-Measure Temperature Readings
85
80
75
70
65
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

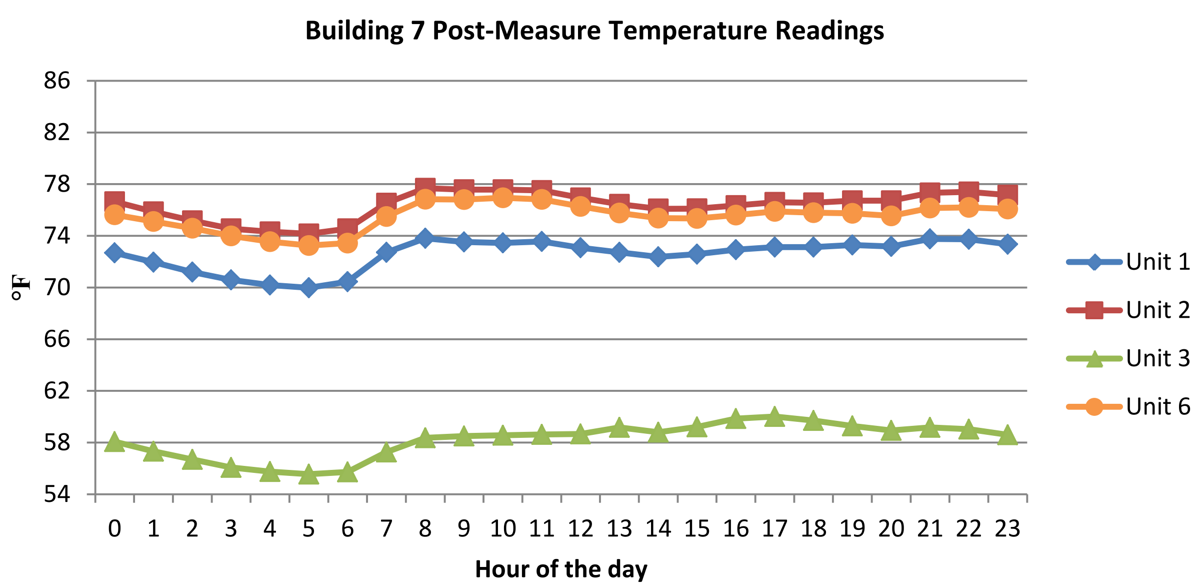
Building 6


Building 6 Pre-Measure Temperature Readings
84
80
76
72
68
64
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6


Building 6 Post-Measure Temperature Readings
84
80
76
72
68
64
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

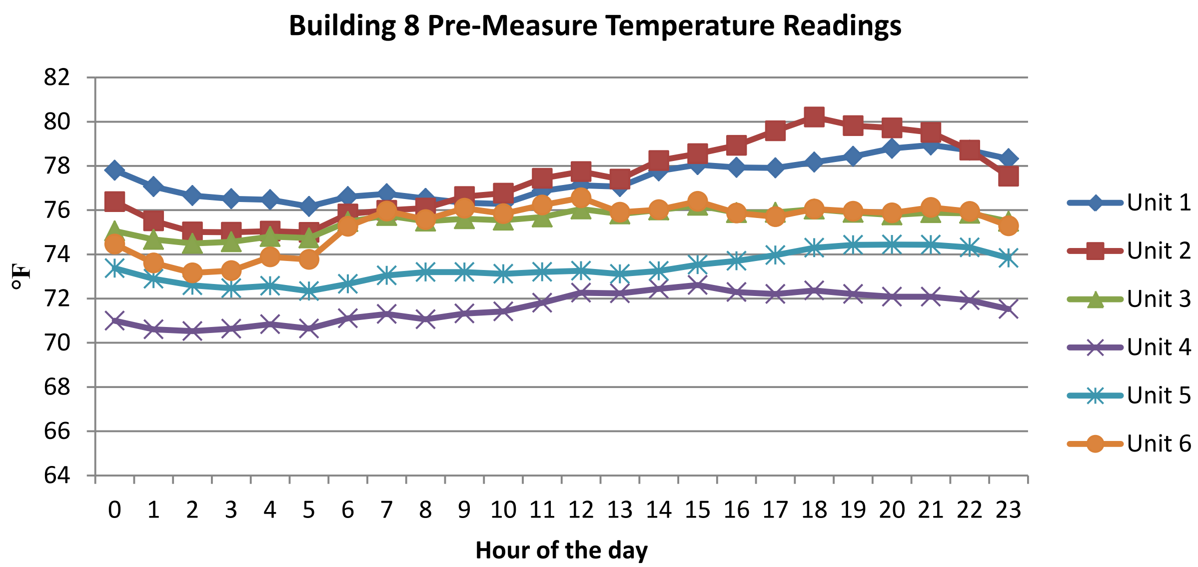
Building 7

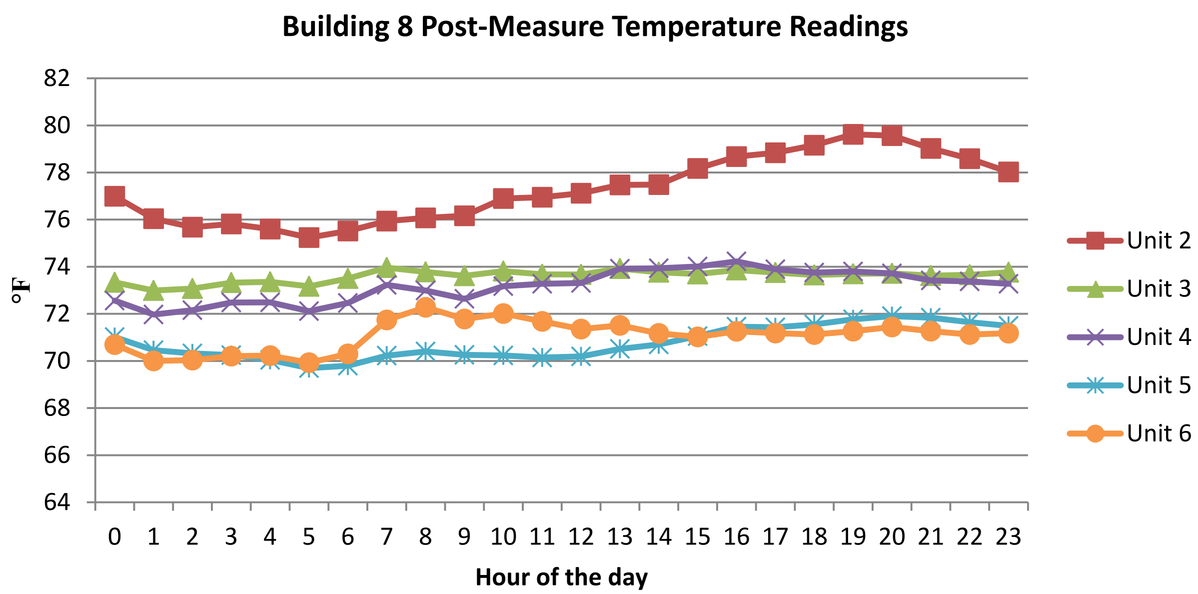




Note: Post-measure data for Units 4 and 5 were unavailable because of limited access to the units. The logger for Unit 3 had been moved from where it was installed to the floor and therefore showed very low temperatures.

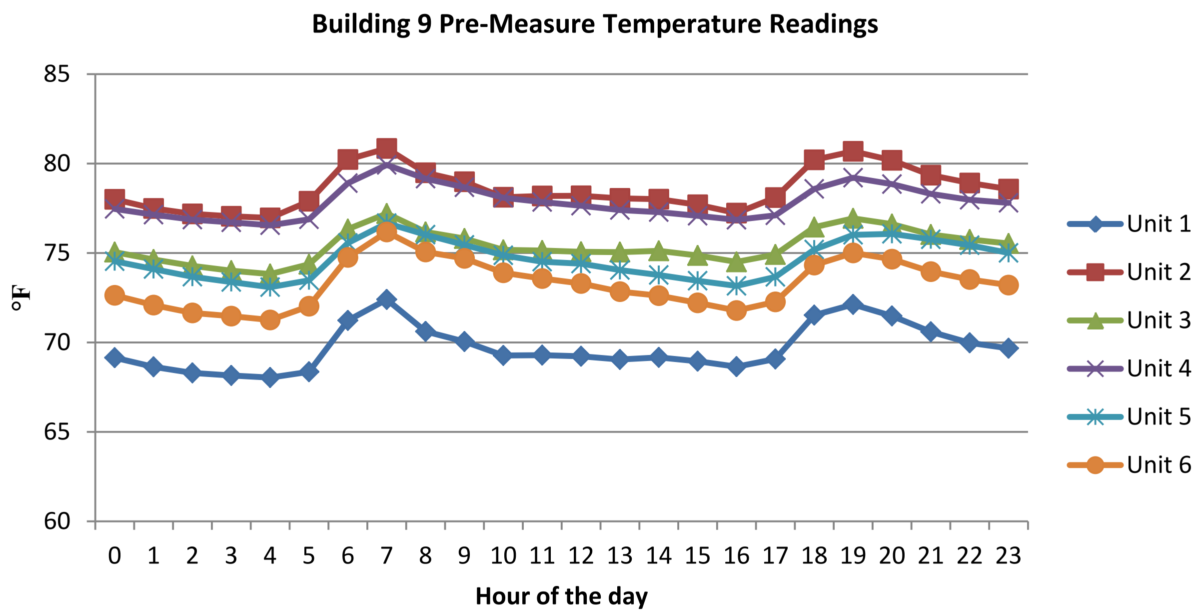
Building 8



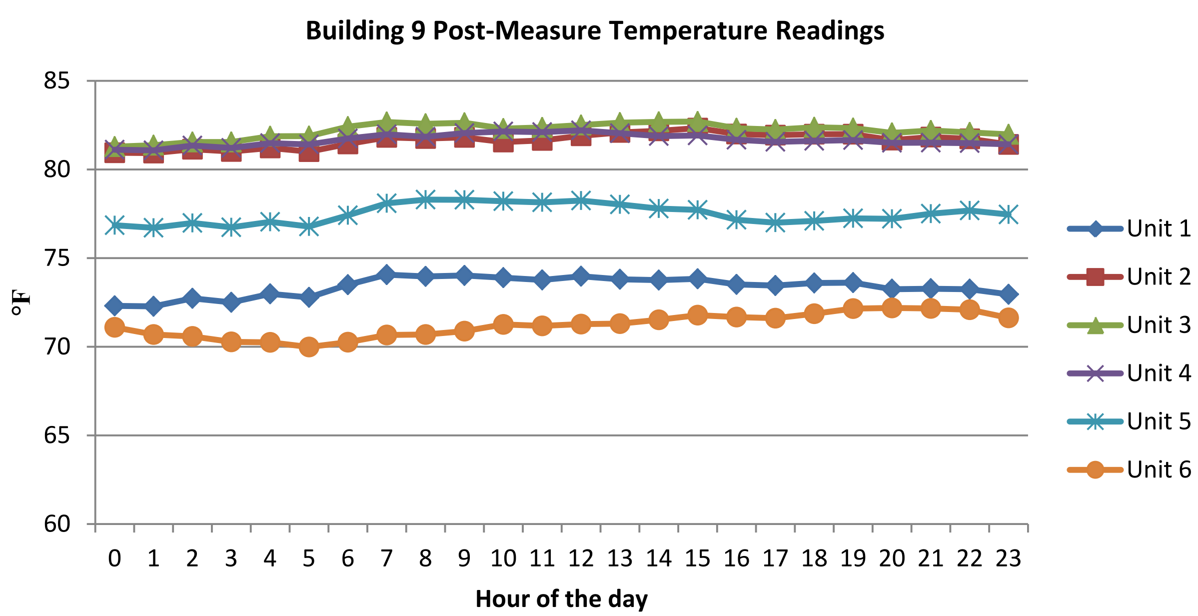


Note: Post-measure data for Unit 1 were unavailable because of limited access to the unit.

Building 9

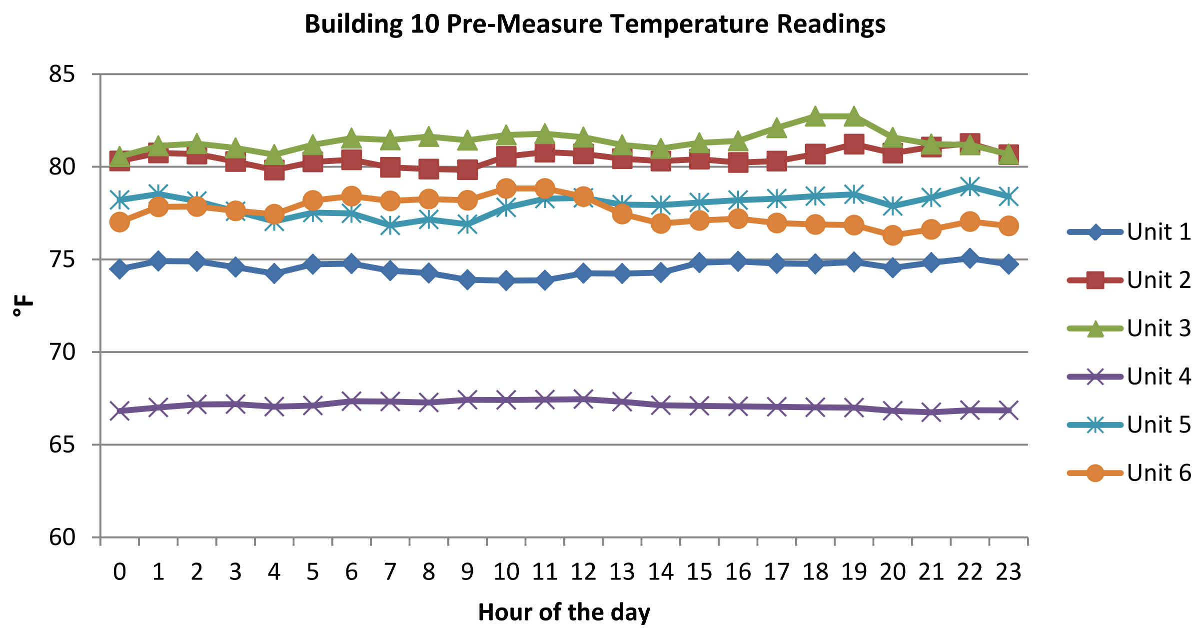


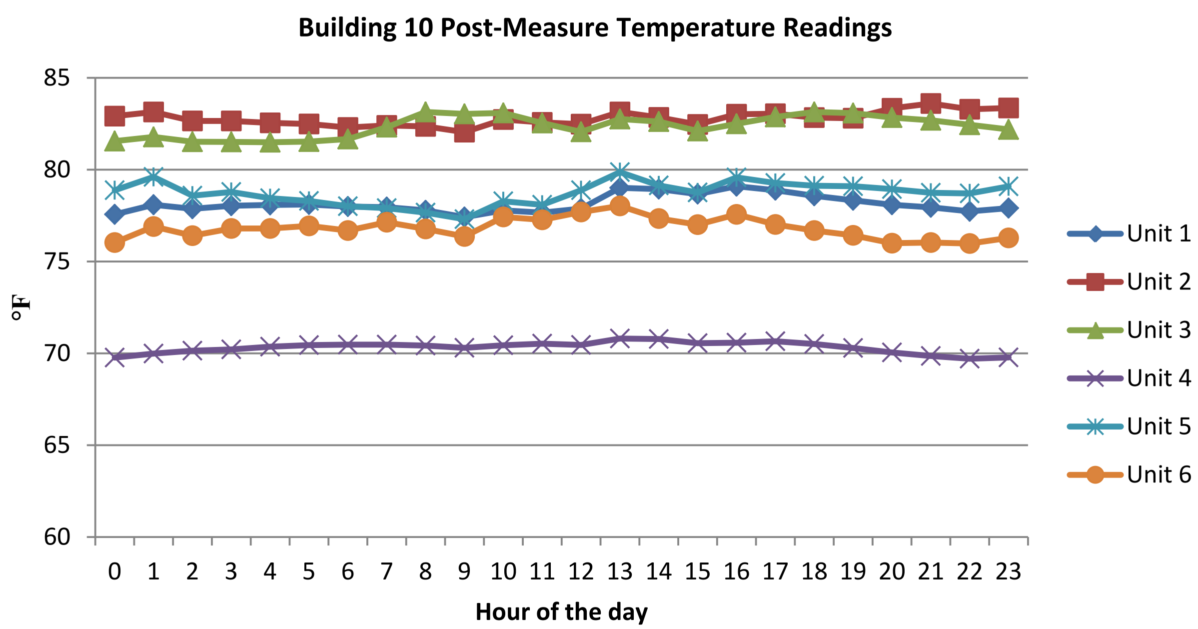
Building 9 Pre-Measure Temperature Readings
85
80
75
70
65
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6



Building 9 Post-Measure Temperature Readings
85
80
75
70
65
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

Building 10


Building 10 Pre-Measure Temperature Readings
85
80
75
70
65
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6


Building 10 Post-Measure Temperature Readings
85
80
75
70
65
60
°F
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the day
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE/GO-102013-4238 ▪ August 2013

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post-consumer waste.