Multifamily Space Heat Thermostat Metering Study

Phases 1 and 2

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2006

Seattle City Light

Multifamily Space Heat Thermostat Metering Study, Phases 1 and 2

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December 2006

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Prepared by the City of Seattle — Seattle City Light Department

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Jeffrey Romberger (SBW Consulting, Inc.), Debra Tachibana (Seattle City Light),

and Randall Birk (SBW Consulting, Inc.).

"The Challenge of Vapor Diaphragm Thermostat Retrofits in Existing Multifamily Buildings."

In Proceedings of the American Council for an Energy-Efficient Economy

2008 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA (pp. 1.223–1.236).

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Space Heat Thermostat Metering Study

Investigating the Energy Impacts of Residential Space Heat Thermostat Retrofits in Multifamily Units

Executive Summary

Combined Phase 1 and Phase 2 Report

This report described two phases of metering research. Phase 1 was conducted in 2004-2005, followed by Phase 2 research in 2005-2006. Following descriptions of each separate phase, this report presents a combined analysis of the two phases of metering research. The executive summary focuses on the combined analyses and identifies differences between the two phases as appropriate. The appendix includes supplemental details about both phases.

Introduction

Seattle City Light (SCL) proposed residential thermostat replacements as an eligible measure in negotiations with the Bonneville Power Administration (BPA) for the Conservation Augmentation contract in 2001. At that time the BPA was not willing to allow this as an eligible measure. Since then, the Regional Technical Forum (RTF) reviewed available data on energy savings from thermostat replacements and established deemed energy savings for a similar measure (electronic line voltage thermostats) under the BPA Conservation and Renewables Discount program, but only for single family homes. Existing research did not convincingly demonstrate energy savings for thermostat replacements in multifamily buildings. There is no current research on vapor diaphragm thermostat replacements in multifamily buildings.

Based on the RTF endorsement of the measure in single-family homes, City Light approached the BPA to ask if multifamily thermostat replacements would be accepted as an eligible measure under the existing Conservation Augmentation contract. BPA agreed to accept multifamily thermostat replacements if City Light could convincingly quantify the energy savings from this measure. This metering study is intended to help answer the question of what energy savings result from multifamily thermostat replacements.

Objectives

The objective of this study is to confirm or dispel the following hypotheses.

1. *Reducing the thermostat temperature setting results in savings of the expected magnitude. The expected magnitude is approximately seven percent of annual space heat for a one-degree reduction in temperature, based on reported savings for single-family housing.*
2. *Equivalent comfort can be achieved at lower temperature settings when hysteresis is reduced.*
3. *Changing bimetal thermostats to vapor diaphragm thermostats, without thermostat pre-sets, labeling, or tenant education, automatically results in energy savings.*

In addition, the following objective was included for Phase 1 of this study.

4. *Critique the "proof of concept" from the metering methodology, and offer recommendations regarding a Phase 2 round of additional metering study.*

..... Hypothesis: How Vapor Diaphragm Thermostats Save Energy

Vapor diaphragm thermostats maintain the temperature in the space closer to the set temperature on the dial (smaller hysteresis) than do bimetal thermostats. The hysteresis, also known as dead-band, refers to the temperature difference range between a thermostat coming on and shutting off (or conversely the range between shutting off and coming on). Typically the hysteresis of a vapor diaphragm thermostat is about 2°F as opposed to a bimetal thermostat at 5°F or above. Occupants can achieve the same or better comfort levels than before while setting the thermostat to a lower average temperature. This action saves space-heating energy. By lowering the thermostat set-point, the same level of comfort can be achieved.

Methodology

The following subtasks were performed to complete the study.

Subject population definition

Basic characteristics were collected for twenty-two candidate multifamily buildings, twelve in Phase 1 and ten in Phase2. Characteristics included year built, floor area, number of living units, energy efficiency upgrade history and bimonthly electric billing histories for each unit. The billing histories were screened to identify units with significant heating energy consumption, resulting in the identification of 418 candidate apartments, 84 in Phase 1 and 334 in Phase 2, for the study. A characteristics binning strategy for Phase 1 was defined and included two divisions for each of the four categories of weatherization, floor area, exterior surface exposure and occupant behavior of heater operating hours. The binning strategy included 16 characteristics bin combinations. The binning strategy was modified for Phase 2 to include two divisions for each of two categories on floor area and exterior surface exposure for only one weatherization category. The Phase 2 strategy included four characteristic bin combinations.

Baseline characteristics data collection and hysteresis confirmation

Interviews were performed with each of the twenty-two resident managers to verify previously identified characteristics and supplement additional characteristics to further categorize the candidate units into the characteristics bins. Residents were also interviewed for recruitment into the study and to obtain further characteristics. The units recruited were also screened by testing the thermostat to verify significant hysteresis.

Final sample selection

Eighteen units were ultimately recruited for the Phase 1 study. Table 1 summarizes the distribution across the characteristics bins.

Table 1: Final Sample Selection, Phase 1

Bin	Weatherization	Floor Area	External Exposure	Heating Hours	
1			Extensive	High	2
2		Large	5	Low	3
3			Minimal	High	1
4	Weatherized	6	1	Low	0
5			Extensive	High	2
6		Small	5	Low	3
7			Minimal	High	0
8	11	5	0	Low	0
9			Extensive	High	1
10		Large	2	Low	1
11			Minimal	High	0
12	Not Weatherized	2	0	Low	0
13			Extensive	High	0
14		Small	3	Low	3
15			Minimal	High	2
16	7	5	2	Low	0
Cases	**18**	**18**	**18**		**18**

Twenty units were recruited for the Phase 2 study and are summarized in Table 2 across the characteristic bins.

Table 2: Final Sample Selection, Phase 2

Bin	Weatherization	Floor Area	External Exposure
A			Extensive
		Large	14
B			Minimal
	Weatherized	15	1
C			Extensive
		Small	5
D			Minimal
	20	5	0
Cases	**20**	**20**	**20**

Detailed on-site measurement using data loggers

Ampere loggers were installed on up to two heat circuits in each the sampled units, (up to three circuits in Phase 2). Temperature loggers were installed at each bimetal thermostat that was to be replaced with a vapor diaphragm thermostat. One temperature logger was installed to obtain outdoor air temperature at each building. The metering equipment remained in place for four weeks, then the thermostats were replaced and an additional four weeks of data were collected.

Post-measurement characteristics data collection

All data channels were downloaded and analyzed. Anomalous data were identified and specific questions were generated to ask the tenants for possible explanation of anomalies. Some tenants were unreachable. The tenants interviewed indicated consistent use of both thermostats and were unaware of pre-post temperature differences observed in the data.

Phase 1 Data Collection

Two units in were dropped from the sample: one due to significant logger data loss and one due to vacating the unit shortly after the thermostat was retrofitted. Two other units in experienced thermostat mechanical failures, which resulted in half the electric heat logger data (one of two channels) being invalid for the failed thermostats. These units were eventually dropped because the failed thermostats affected the operation of the remaining thermostats in the units. General observations of the data included: two living rooms and five bedrooms had insignificant heater use in both the pre- and post-periods; post-period outdoor temperature was about five degrees greater than pre-period outdoor temperature; 17 thermostats had a lower post-period average temperature when the heat was on; and, 11 thermostats had a higher post-period average temperature when the heat was on.

Phase 2 Data Collection

One unit was dropped from the sample because it had very low heat consumption. It was erroneously identified as a high space heat consumption unit due to anomalies in the billing data. General observations included: six bedrooms had insignificant heater use in both the pre- and post-periods; post-period outdoor temperature was about 2 degrees cooler than the pre-period outdoor temperature; 26 thermostats had a lower post-period average temperature when the heat was on: and, 20 thermostats had a lower post-period average temperature when the heat was on.

Energy savings analysis for both phases combined

The energy savings analysis included the three primary tasks of performing a regression analysis, adjusting the data for pre-post outdoor temperature differences and extrapolating the energy savings to an annual basis. The metered data were used to correlate hourly kW heat to outside air temperature for both the pre- and post-periods. The correlations were then applied to Typical Meteorological Data (TMY) hour temperature data to extrapolate pre- and post-consumption to the entire heating season. Anomalous data, which included units where space heat increased at the same time space temperatures decreased (and the reverse condition), were eliminated from the sample. This left eighteen units with a resulting energy savings that

ranged from increased energy use of 2,154 to a decreased energy use of 1,591 kWh per year. The average was an increase energy use of 78 kWh per year. Phase 1 results ranges from an increase of 2,112 kWh per-period year to a decrease of 1,591 kWh per year with an average heat energy reduction of 195 kWh per year. Phase 2 results ranges from an increase of 2,154 kWh per year to a decrease of 1,314 kWh per year with an average heat energy increase of 420 kWh per year.

Energy savings relationship to change in space temperature

The relationship of energy savings to changes in space temperature was developed from the data collected. This resulted in determining that for every one-degree decrease in average unit space temperature, energy consumption would decrease by about 513 kWh per year. The sample sizes were too small to categorize savings by characteristics bins.

Study Findings

The energy savings for each of the 18 units and spaces within each unit (for cases when more than one heat channel was metered, such as bedrooms and living room) are presented in Table 3. The table also includes the space temperature difference between pre- and post-period both while the heat was on and while the heat was off.

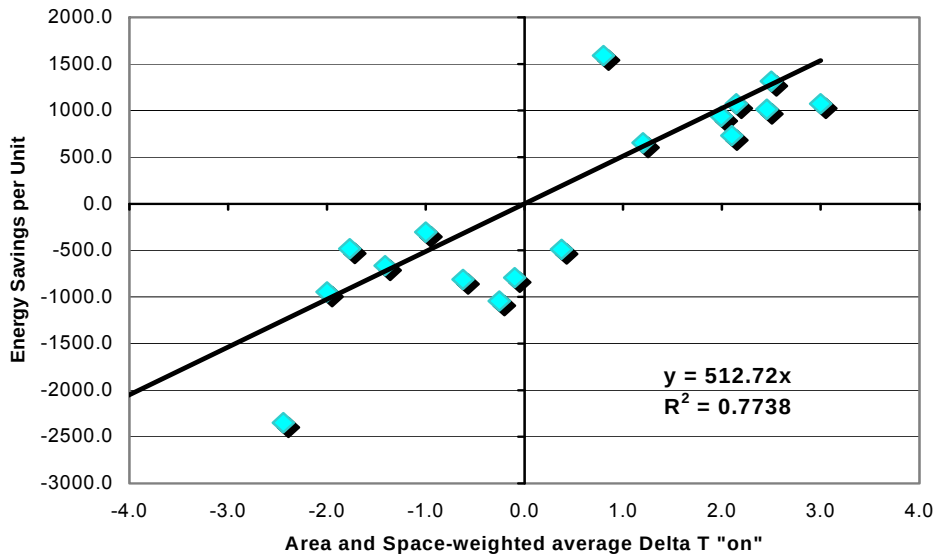
Table 3: Difference in Space Temperatures and Adjusted Annual Energy Savings, by Unit and Space, for Units with Consistent Results, Combined Phases

Building	Unit	Temperature Adjusted Annual kWh Savings	Space	Temperature Adjusted Annual kWh Savings	Delta T 'ON' (Pre - Post)	Delta T 'OFF' (Pre - Post)
1	A302	653	LR	653	1.2	-1.3
			BR1*	**0**		
1	A309	732	LR*	**0**		
			BR1	732	2.1	-0.2
			BR2		-2.2	-3.4
1	B102	-665	LR	225	0.9	-0.2
			BR1	-890	-3.4	-3.1
2	48	938	LR*	**0**		
			BR1	938	0.7	-0.2
			BR2		2.7	1.2
3	15	1,591	LR	1,591	0.8	0.7
3	30	-792	LR	-792	-0.1	0.0
3	32	1,073	LR	1,073	3.0	4.2
10	205	1,013	LR	806	2.4	2.1
			BR1	207	2.7	1.9
10	406	***-2,112***	LR	***-2,112***	-4.1	-1.3
			BR1*	**0**	1.0	-1.6
12	407	-483	LR	-483	-1.8	-1.7
			BR1		-1.7	-1.1
			BR2*	**0**	1.6	-1.0
13	103	-947	LR	-947	-2.0	-1.4
			BR1*	**0**	-3.2	-0.7
			BR2**		missing	missing
14	12	-2,154	LR	-737	-1.6	-3.1
			BR1	-1,417	-0.9	-1.6
			BR2		-4.2	-4.9
14	13	-1,042	LR	-13	0.2	-1.0
			BR1	-1,029	-0.5	-0.8
			BR2		-0.6	-0.9
14	16	-489	LR	-985	-0.1	0.9
			BR1	496	-0.2	0.7
			BR2		1.7	0.6
14	44	1,072	LR	471	1.0	0.0
			BR1	601	4.3	1.3
			BR2*	**0**		0.2
16	214	-810.0	LR	-751	-0.5	0.3
			BR1	-59.0	-0.5	0.0
			BR2		-2.3	-1.7
			Bath		-2.0	0.3
18	301	1,314	LR	1,314	2.5	1.8
18	304	-304	LR	-304	-1.0	-3.4
Average		**-78**			**-0.1**	**-0.5**
Std Dev		1,155				

* Insignificant or no heater use in both pre- and post-periods.
** Thermostat failure in post-period.

Figure 1 summarizes the data to illustrate the relationship between change in space temperature and impact on energy consumption. The slope of the correlation line indicates the sensitivity of the relationship.

Figure 1: Space Heat Energy Change as a Function of Space Temperature Change, Weighted by Area and Space



Discussion

It is difficult to draw firm conclusions regarding the amount of energy savings that can be achieved in multifamily units that are retrofitted from bimetal to vapor diaphragm thermostats. The study purposely instructed the tenants to use the new thermostats as they would the old ones. There was no mention about energy savings to the tenants, so that they would not be consciously or unconsciously trying to skew energy consumption. As a result, there was a large variation in unit energy savings. In general, when the occupants reduced the thermostat set-point temperature, energy consumption decrease and when they set the new thermostat higher, energy consumption increased. This is a similar result to the Lambert study[1] that was conducted on apartment homes using electronic line voltage thermostats to replace bimetal thermostats. The Lambert study similarly instructed tenants that the study was to assess operation and acceptance of the new thermostats. As a result, some apartments experienced an increase in average temperature and some experienced a decrease.

Our study did show that if the new thermostats were set at a lower average temperature, energy savings would be the result. For every degree drop in space temperature, annual space heat consumption will decrease by about 513 kWh. For the 18 units in the combined Phase 1

[1] Lambert, Les. 1996. "Electronic Line Voltage Thermostats: A Worthwhile Retrofit for Baseboard Heat?" In *Proceedings of the ACEEE 1996 Summer Study on Energy Efficiency in Buildings.* Washington, D.C.: American Council for an Energy Efficient Economy. 1:157-168.

and Phase 2 analysis, the average annual electric consumption for space heat was about 3,780 kWh. This was roughly estimated from the utility bills, and a summary by unit is included in a table in the appendix. The resulting energy savings of 513 kWh per degree temperature drop then represents nearly 14% of annual space heat of the multifamily units. This is twice as much as conclude in the EPRI study. However, the EPRI results were based on single-family homes and were not screened to be significantly high space heat users. Across the entire population of multifamily units, the savings will be much closer to the EPRI result because many multifamily units have significantly smaller space heat consumption.

The Lambert Study concluded that for the average decrease in space temperature of 0.88 degrees, that annual energy savings would be about 222 kWh per year. They did not screen the sampled units for high heat consumption as we did, so a lower savings value is expected. Again, across the population of multifamily units, the savings for both studies would likely be quite similar.

Conclusions and Observations

Conclusions regarding the hypotheses listed in the Phase 2 Introduction are as follows:

> *Reducing the thermostat temperature setting results in savings of the expected magnitude. The expected magnitude is approximately seven percent of annual space heat for a one-degree reduction in temperature. Result: Confirmed.*

Multifamily units across the study showed a heat to space temperature relationship of 513 kWh per a one-degree change in temperature. Or, if the space temperature decreases by one degree, annual energy consumption decreases by 513 kWh. Sample size of the non-weatherized category was too small to accurately determine the variation between weatherized and non-weatherized categories. The energy savings for the study sample is greater than the literature suggests, but is also expected to be greater due to the stratification of the sample to high space heat consumers.

> *Equivalent comfort can be achieved at lower temperature settings when hysteresis is reduced. Result: Confirmed.*

Most tenants can't distinguish a one or two degree difference in space temperature. There were many tenants that maintained a slightly higher space temperature in the post-period, and were unaware that there was a difference

> *Changing bimetal thermostats to vapor diaphragm thermostats, without re-sets, labeling, or tenant education, automatically results in energy savings. Result: Inconclusive.*

There was a large variation in results across the sampled units. This was due confirmation of hypothesis 2 above. Since the tenants could not tell if temperature were greater or less during the post-period, some slightly increased temperature and some slightly decreased temperature. This was also compounded since many tenants that did not have thermometers or temperature setting numbers on their old thermostats, and the ones that did may have been out of calibration. This emphasizes the need for an educational component to accompany the new thermostats.

The following observations were also made from combined Phase 1 and Phase 2 analysis:

> *Overall, annual energy consumption increased by 78 kWh.*

This was accompanied by a 0.1°F increase of the average space temperature during the post-period compared to the pre-period.

> *The Phase 2 units tended to have significantly greater space heat consumption based on the billing analysis.*

This may have also been a factor relating to the demographics of the sample. Although we did not collect demographic data, it was observed that the Phase 2 participants tended to be a higher income group. This is also reflected in that a significant number of Phase 2 units were condominiums, presumably owned by the occupant.

> *Short-term measures of space heat in multifamily units are difficult to extrapolate to annual values.*

Establishing a relationship between space heat consumption and outdoor temperature and/or time factors, and extrapolation of annual space heat consumption, was particularly difficult in the Phase 2 units. There were instances of conflicting results in that space heat consumption would increase when the data showed a decrease in space temperatures, or the reverse condition. In the Phase 2 units, this may be due to very cold weather condition during the measurement periods. If there is not enough range in conditions, the extrapolation will not be accurate. This was also substantiated by the Phase 2 annual space heat extrapolation, which tended to be greater than the space heat for the previous year. Conflicting extrapolation data was removed from the sample.

Recommendations

The following recommendations are presented:

> *Energy savings will not be achieved from a thermostat replacement program unless the thermostat installation is accompanied by tenant education.*

Tenants must understand that most people will not notice a small decrease in space temperature, and that the resulting energy savings can be significant for a small decrease in space temperature.

> *Without ongoing education, program savings will likely decrease or not occur with tenant turnover.*

It may be advisable to place an educational sticker on the thermostat or mail an annual educational flyer to program participants.

Phase 1 Metering Research

In-Unit Measurements, Winter 2004-2005

Phase 1 Introduction

Seattle City Light (SCL) proposed residential thermostat replacements as an eligible measure in negotiations with the Bonneville Power Administration (BPA) for the Conservation Augmentation contract in 2001. At that time the BPA was not willing to allow this as an eligible measure. Since then, the Regional Technical Forum (RTF) reviewed available data on energy savings from thermostat replacements and established deemed energy savings for a similar measure (electronic line voltage thermostats) under the BPA Conservation and Renewables Discount program, but only for single family homes. Existing research did not convincingly demonstrate energy savings for thermostat replacements in multifamily buildings. There is no current research on vapor diaphragm thermostat replacements in multifamily buildings.

Based on the RTF endorsement of the measure in single-family homes, City Light approached the BPA to ask if multifamily thermostat replacements would be accepted as an eligible measure under the existing Conservation Augmentation contract. BPA agreed to accept multifamily thermostat replacements if City Light could convincingly quantify the energy savings from this measure. This metering study is intended to help answer the question of what energy savings result from multifamily thermostat replacements.

Objectives

The following are the primary objectives of this study.

1. *Evaluate energy savings from vapor diaphragm thermostats installed in multifamily residential units with electric baseboard space heat, located in the Seattle City Light service area.*
2. *Determine significant building and tenant characteristics that are major determinants of energy savings associated with installing vapor diaphragm thermostats to replace bimetal thermostats.*
3. *Develop a methodology that will support extrapolation of the evaluated savings to the population of multifamily building stock in the Seattle City Light service area.*
4. *Critique the "proof of concept" from the metering methodology, and offer recommendations regarding a Phase 2 round of additional metering study.*

Vapor Diaphragm Thermostats as a Conservation Measure

Most of Seattle's multifamily housing units have electric resistance space heat, which was the lowest-first-cost choice for builders. Baseboard and radiant heaters allow for zonal heating with independent thermostats, which can save energy when unoccupied rooms have lower temperature settings or are operated fewer hours. It is believed that occupants often set thermostats higher than the desired average temperature in order to avoid extended cool periods during times between heater on-cycles, causing the room at times to overheat. It is difficult for traditional bimetallic thermostats to maintain near-constant temperatures in these systems.

Newer design vapor diaphragm and line voltage thermostats offer more precise temperature control than conventional bimetal thermostats. The more accurate calibration and more frequent duty cycles yield increased comfort for occupants. The basis for replacing space-heat thermostats is achieving a tighter 'dead-band' and avoiding excessive temperature 'droop'.

Dead-band (also known as hysteresis) is the difference between the temperatures at which the heater switches off or on. Bimetallic thermostats typically cycle on and off every 90 minutes, have a dead-band of about 5°F, and a droop of about 5°F. Droop occurs when heat builds up from the current passing through wires inside the thermostat. A sensor not insulated from this build-up turns off the heater too soon. Occupants can become uncomfortable from excessive droop, because ambient temperatures do not rise to the expected level. They can also become uncomfortable from a wide dead-band, which leaves the heater off too long between duty cycles and allows the space to cool excessively before rewarming.

Vapor diaphragm and electronic line voltage thermostats have a narrower dead-band, around 2°F, and a commensurately smaller droop of about 2°F. These thermostats come on and off more frequently, responding to smaller changes in room temperature, often operating in 10-15-minute cycles. Thermodynamically, these thermostats by themselves do not save more energy over the bimetallic type. However, occupants can achieve the same or better comfort levels than before while setting the thermostat to a lower average temperature. By lowering the thermostat set-point, space heating is saved and the same level of comfort is achieved. Room temperatures do not need to swing as high as before, while the low point of the cycle remains the same. If the thermostat were set down by only one degree on average, energy savings could be about 7% of space heating; and if by two degrees, savings could be about 14% (according to EPRI, the Electric Power Research Institute[2]).

Additional information on vapor diaphragm thermostats is included in the appendix.

Phase 1 Methodology

The methodology for this study addressed the study objectives and consisted of seven major subtasks. The subtasks support four distinct phases of the study. The first was to select a sample of multifamily units in which to demonstrate the energy savings potential. The second was to collect short-term measurement based performance data before and after

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[2] Gregerson, Joan. 1997. "Advanced Line-Voltage Thermostats for Electric Resistance Heating." *E-Source Tech Update TU-97-1*, January 1997.

installation of the vapor diaphragm thermostats. The next phase was to analyze the data, to obtain annualized energy savings. The fourth phase was to create a methodology to support a sector wide extrapolation to the population. As a result of the study a critique of the "proof of concept" was completed with recommendation concerning methodological improvements for a Phase 2 study to provide a more robust result. Each of the subtasks is described in more detail below.

Subject Population Definition

..... Building Characteristics

Seattle City Light collected basic characteristics for twelve candidate multifamily buildings to represent a diverse and representative group of electrically heated multifamily units that would likely participate in a program that offered an incentive for this thermostat retrofit measure. Besides contacting the building owner/manager to determine interest in the study, the following characteristics of the electrically heated buildings were collected:

- Year built
- Total floor area
- Number of living units in the complex
- History of past participation in SCL programs for energy efficiency upgrade ("weatherization")
- Bimonthly electric billing histories for each living unit

Table 4 summarizes the first four characteristics for the twelve buildings. As seen in the table, four of the buildings have participated in weatherization programs that included window and/or insulation retrofits. Three buildings participated only in common area lighting upgrades. It should be noted that building 6 has not participated in an SCL weatherization program, however the building was built in 1990 and has double pane windows. Therefore it might be considered to be equal to a weatherized building, however for the purpose of this study, it was considered not weatherized (see the Sample Binning Strategy for category definitions). There are a total of 436 living units in the twelve candidate buildings.

Table 4: Characteristics of Candidate Buildings, Phase 1

Building	Year Built	Total SqFt Floor Area	Number of Units	Past SCL Program Participation Year: Measures Installed
1	1978	61,621	82	1996: Windows, Insulation, Lighting
2	1971	44,640	62	None
3	1926	22,284	26	2004: Common area Lighting
4	1976	20,599	20	1993: Windows, Insulation, Lighting
5	1926	33,277	29	None
6	1990	30,110	25	None
7	1978	53,040	60	2003: Common area Lighting
8	1957	8,232	12	None
9	1965	21,469	21	1997: Windows, Lighting
10	1965	37,830	40	2004: Common area Lighting
11	1955	5,610	8	None
12	1978	51,387	51	2002: Windows, Lighting

..... Space Heat Screening

The bimonthly billing records were examined for the 436 apartments. For the purposes of the study, units were only considered if they had the same tenant living in them for at least the last year. Total electric consumption was determined for each unit by summing the most recent six bimonthly bills. The non space-heat component of the annual consumption was determined by multiplying the smallest bimonthly bill by six. This value was then adjusted up by 15% to account for potentially low summer bills due to partial vacation vacancies. The non space-heat consumption was then subtracted from the total annual consumption to obtain the annual space heat electric consumption. Only units that had significant space heat were considered as candidates for the study. Significant space heat was defined as consumption greater than 2,400 kWh per year as determined above. As a result of the analysis of the billing records, 84 apartments remained as candidates for the study (19%).

Regression to the mean

Heat consumption is not only a function of the heat transfer characteristics of the building under variable weather conditions, but it is also a function of occupant behavior. Occupants change the thermostat settings and setback or shut off heat based on a complex behavior model that is very difficult to define. The dwelling units in this study were selected based on units that have high space heat consumption, not average space heat consumption. Therefore with this highly stratified sample, the regression to the mean phenomenon should be mentioned. Regression to the mean simply states that when a sample is purposely selected away from the population mean, that upon retest, the sample is likely to fall closer to the population mean. Therefore, it is likely that the sample of high heat dwelling units may have lower heat consumption upon retest, which could potentially result in less energy savings if the study were to be repeated on the same sample.

..... Sample Binning Strategy

To select a representative sample of housing units for measurement, it was necessary to group the candidate housing units by characteristics that are major determinants of space heat energy consumption. There are a variety of characteristics that influence space heat consumption. They include both physical building characteristics and tenant behavior characteristics. The most important characteristics were hypothesized to include the following:

- **Weatherization**—buildings that have not received shell energy efficiency or have a lower thermal integrity will require more space heat. Two categories were defined as *weatherized* units and *not weatherized* units.

- **Floor area**—larger apartments will require more space heat than small apartments. Two floor area categories were defined as *large* or *small*, with the separation set at 830 square feet.

- **External exposure**—apartments that have more surfaces exposed to the exterior (walls, roof, floor) will have greater heat loss. Two categories were defined as *minimal* having one or two exterior surfaces, and *extensive* as having three or more exterior surfaces.

- **Heating hours**—Tenants who do not set back the thermostat will use more space heat energy. Two heating hour categories were defined as *low* when tenants mostly set back or shut off heat at night and/or when they left the unit, and *high* when tenants left the space temperature nearly constant.

Figure 2 graphically illustrates the sixteen resulting characteristics bins.

Figure 2: Binning Strategy for Sampled Units, Phase 1

Weatherization	Floor Area	External Exposure	Heating Hours
Weatherized	Large	Extensive	***1*** High
			2 Low
		Minimal	***3*** High
			4 Low
	Small	Extensive	***5*** High
			6 Low
		Minimal	***7*** High
			8 Low
Not Weatherized	Large	Extensive	***9*** High
			10 Low
		Minimal	***11*** High
			12 Low
	Small	Extensive	***13*** High
			14 Low
		Minimal	***15*** High
			16 Low

Baseline Characteristics Data Collection and Hysteresis Confirmation

Building characteristics, tenant characteristics and space heating system performance characteristics data were collected to further determine eligibility to participate in the study. The data were collected through resident manager interviews, tenant interviews and thermostat performance testing as described in the following sections.

..... Resident Manager Interview

Interviews were conducted with resident managers to verify/obtain basic building characteristic and tenant contact information. The interview form used is included in the appendix and included the following primary items of interest:

- Number of buildings in complex and number of floors per building
- Total number of housing units
- Location of laundry facilities (common area or in-unit)

- Interior hallways or exterior unit entries
- Verification of electric baseboard heat
- Presence of air conditioning
- Floor area of specific housing units of interest (units identified as significant heat consumers, as described under Space Heat Screening)
- Missing tenant contact information

Resident manager interviews were conducted on all twelve buildings. Two of the building owners/managers, who previously indicated interest in the study, declined participation. Across the ten remaining buildings, 69 candidate units remained.

..... Tenant Interview

Interviews were conducted with as many of the remaining 69 candidates as could be contacted. The tenant interview form is included in the appendix and included the following primary items of interest.

- Residency information—verify past one year and expect to remain for duration of test period
- Apartment characteristics—number of exterior surfaces and number of bedrooms
- Heat use characteristics—typical set-point temperature, fraction of unit that they heat, and thermostat setback operation
- Presence of air conditioning
- Interest in participating in the study

As a result of the interviews, 27 tenants gave preliminary permission to participate in the study. It is noted that the several of the tenants included low income and English as a Second Language (ESL) demographic groups. All efforts were made to recruit and retain these tenants.

..... Hysteresis Testing

Hysteresis is the difference between temperatures at which a heater switches on and off. This is also known as the thermostat dead band. Typically, bimetal thermostats have a dead band of 5°F or more. Vapor diaphragm thermostats have a narrower dead band around 2°F. It was necessary to test the existing thermostat's dead band to ensure that the new vapor diaphragm thermostat would provide a significantly reduced dead band.

Test equipment

A device was developed for hysteresis testing of wall-mounted thermostats. It consisted of a transparent plastic container with dimensions of about 12 inches by 6 inches by 4-1/2 inches.

Two sealable ventilation holes were cut in it. A small fan was installed to circulate air around the thermostat. An air temperature sensor was included to measure the air temperature around the thermostat during testing. And, a switched light bulb was mounted inside as a heat source.

Test procedure

The following steps were used in testing the hysteresis of the thermostats:

- The thermostat was turned up, if off, until it clicked on.
- The test equipment was held in place against the wall covering the thermostat and remained there until the test was completed.
- The fan was turned on and remained on until the test was completed.
- The air vents in the device were closed and the light was switched on. This heated the air circulating around the thermostat in the small enclosed space.
- When the thermostat clicked off from the heated air in the device, the air temperature was noted.
- The light bulb was switched off and the air vents opened. This allowed the air in the device to cool down to room temperature.
- When the thermostat clicked on, again the air temperature in the device was noted.
- The cycle was repeated several times until the readings provided consistent on and off temperatures.
- The difference between the off and on temperatures was considered a strong indicator of the thermostat hysteresis.

Interpreting results

The hysteresis testing device did not provide an exact measurement of the actual thermostat hysteresis; however, it did provide a relative indication of thermostat performance. The test repeatedly showed an off-on temperature difference of about 6°F for the new vapor diaphragm thermostats that were rated at 2°F hysteresis. Therefore, only test results with temperature difference values greater than 15°F in the study were accepted. Most thermostats tested with this device resulted in temperature differences in excess of 20°F. In all, thermostats were tested in 26 units (57 total thermostats), of which 22 were determined to have large hysteresis for all thermostats. Of the 57 total thermostats tested, four were determined to have small hysteresis. This resulted in 93% of bimetal thermostats tested to have significantly large hysteresis.

Final Sample Selection for Metering

The final sample selected for participation included 18 apartments in seven buildings. One building was dropped due to electrical panels being too small to accommodate the metering

equipment. Another building was dropped because the heating equipment was primarily radiant ceiling panels with two-stage thermostats. And a third building was dropped because the owner declined to participate. One apartment that passed the interview screening, was discovered to already have vapor diaphragm thermostats installed. A couple of individual apartments that passed all screening criteria were also dropped because the tenant declined to participate just before equipment installation.

Table 5 shows the distribution of the final sampled apartments across the previously defined characteristic bins. A more detailed listing of apartment characteristics is included in the appendix. Logically, it is expected that smaller units with fewer exposed surfaces and low heating hours would not have significant space heat consumption. This is consistent with zero observations in bins 4, 8, 12 and 16.

Table 5: Final Sample Selection, Phase 1

Bin	Weatherization	Floor Area	External Exposure	Heating Hours	
1			Extensive	High	2
2		Large	5	Low	3
3			Minimal	High	1
4	Weatherized	6	1	Low	0
5			Extensive	High	2
6		Small	5	Low	3
7			Minimal	High	0
8	11	5	0	Low	0
9			Extensive	High	1
10		Large	2	Low	1
11			Minimal	High	0
12	Not Weatherized	2	0	Low	0
13			Extensive	High	0
14		Small	3	Low	3
15			Minimal	High	2
16	7	5	2	Low	0
Cases	**18**	**18**	**18**		**18**

As observed in Table 5, the largest count of units with significant space heat occurred in apartments with a large number of exposed surfaces. Eleven units in the sample were in weatherized buildings while only seven units were in buildings that have not been weatherized.

Detailed On-site Measurement Using Data Loggers

Each of the eighteen residential units in the sample was subject to a series of short-term measurements before and after the installation of the vapor diaphragm thermostats. Measurements included electric consumption, indoor air temperature and outdoor air temperature. The short-term measurements were recorded for approximately four weeks prior to and after thermostat replacement.

..... Installation of Metering Equipment

Electric consumption was measured in each apartment. One four-channel logger was used to measure total electric consumption (two channels) and up to two channels of space heat. The heat circuits were verified by systematically turning on each thermostat and measuring amperage at the circuit breakers. The heat channels were prioritized for measurement as one channel for the living room heat and one channel for bedroom heat, if separately circuited. The loggers were installed inside the electric circuit breaker panel of the apartment, and were used to measured average amperes over either five-minute or ten-minute intervals. Single channel temperature loggers were also placed at each thermostat that was to be replaced to record average air temperature over five-minute intervals coincidentally with electric amp measurements. At each apartment complex, one temperature logger was also placed outside on the north side of the building in the shade to record outdoor air temperature.

During the metering equipment installation site visit, the line voltage of each of the two phases of electrical system was measured using a voltmeter. Building characteristics obtained during the tenant interview, such as number of exterior surfaces and number of bedrooms, were also verified.

Table 6 summarizes the resulting channel configuration for measurement of space temperature and space heat in each unit. As shown in the table, Building 6, unit 207 only had a single heat circuit and therefore was measured as a single channel. Also observed, for Building 12, unit 407, the living room heat was on the same circuit with the heater in one of the bedrooms. Building/apartment orientation regarding sun exposure was expected to be a minor factor on space heat consumption and was not considered in the study.

Table 6: Temperature and Space Heat Data Channels, by Unit and Space, Phase 1

Building	Unit	Space	Temperature Channel	Space Heat Channel
1	A107	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
1	A205	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
1	A302	Living room	1	A
		Bedroom 1	2	B
1	A309	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
1	B102	Living room	1	A
		Bedroom 1	2	B
1	B303	Living room	1	A
		Bedroom 1	2	B
2	48	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
2	61	Living room	1	A
		Bedroom 1	2	B
3	10	Living room	1	A
3	15	Living room	1	A
3	30	Living room	1	A
3	32	Living room	1	A
6	207	Living room	1	A
		Bedroom 1	2	A
		Bedroom 2	3	A
10	205	Living room	1	A
		Bedroom 1	2	B
10	404	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
10	406	Living room	1	A
		Bedroom 1	2	B
11	503	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
12	407	Living room	1	A
		Bedroom 1	2	A
		Bedroom 2	3	B
7	**18**	**Total Count**	**40**	**31**

..... Thermostat Replacement

After approximately four weeks of short-term measurements, the forty thermostats as represented by the space temperature channels in Table 6 were replaced. A licensed electrician was contracted for the thermostat replacements. Either single pole or double pole thermostats were installed as appropriate for each case.

One anomaly was discovered during replacement. This occurred in building 10, unit 406, where it was discovered that one of the two living room heaters had been shorted out and had not been functioning for quite a long time. The bad heater was disconnected. This anomaly had no impact on heat consumption for the living room circuit.

..... Data Equipment Retrieval

Approximately four weeks after the thermostats were replaced, the data logging equipment was removed. Three significant data problems occurred during the post-period.

Upon removal of the equipment in building 1, unit B303, the apartment was discovered to be vacant. The resident manager and maintenance staff indicated that the tenant moved out a few days after the new thermostat was installed. The tenant gave no notice the manager and the unit was discovered vacant by maintenance staff.

During equipment removal, the tenant in building 2, unit 61, indicated that the bedroom thermostat did not function properly. The thermostat was inspected and determined that the control dial was stuck in one position and could not be adjusted. This invalidated the post-period data for the bedroom in this unit. This thermostat was replaced.

Three weeks into the post-period, the tenant in building 1, unit 107, reported that the new living room thermostat was not working and had not worked since installation. This thermostat was inspected and appeared to have a manufacturing flaw causing failure. The thermostat was replaced and the loggers were downloaded at that time. The data logging equipment was left in place for an additional three weeks to capture post-period living room usage with a properly functioning thermostat. However, upon removal of the data loggers, it was discovered that the amp logger had failed, resulting in the loss of data for the additional three-week period.

Additional information about malfunctioning thermostats is included in the appendix on vapor diaphragm thermostats.

Post-Measurement Characteristics Data Collection

All data loggers were downloaded and the data were compiled into spreadsheet workbooks for each apartment. Amperage data were converted into kW values by multiplying the amperage values by the measured voltage in each apartment. Building 3 data were recorded in ten-minute interval averages. All other units had five-minute interval average values. Each workbook then contained the following data in a time series.

- Date and time
- Total apartment kW
- Heat kW by channels defined in Table 6
- Temperature data for each thermostat as defined in Table 6
- Outdoor air temperature

The pre- and post-periods were distinguished based on the date and approximate time that the new vapor diaphragm thermostats were installed.

..... Rejected and Lost Data

Data that were identified as problematic were dropped from the analysis. Three such cases were mentioned in the previous section. An additional case is included in the listing below. In the first two cases the entire apartment was dropped from the sample. In the last two cases, one heat channel in each apartment was dropped from the energy savings analysis; however, the temperature data were retained to explore possible interactions that might confound the consumption characteristics of the remaining heaters.

- Due to the tenant moving out unexpectedly very early in the post-period, building 1, unit B303 was dropped from the sample.
- Amperage logger data were lost in Building 3, unit 10 over the entire study period due to a logger programming failure. Therefore, this apartment was dropped from the analysis.
- The living room thermostat in building 1, unit A107 was dropped from the sample due to thermostat failure during the post-period.
- The bedroom thermostat in building 2, unit 61 was dropped from the sample due to thermostat failure during the post-period

With the dropped data, 35 thermostats remained in the study in 16 buildings.

..... Data Analysis of Individual Units.

The data were analyzed for each apartment based on the resolution of heating-circuit recorded data. When more than one thermostatically controlled heater was on the recorded heat channel, the energy consumption was analyzed as the group of affected heaters. The space temperatures were considered on an individual thermostat level, but could not be used to disaggregate the heat consumption to each thermostat.

Each unit was analyzed to determine pre- and post-period values for the following variables:

- Hours of heat use
- Total heat kWh consumption for each recorded circuit
- Average space temperature when the heat was on for each thermostat.

When more than one thermostat was associated with a single heat circuit, the average “on” temperature for each thermostat was determined by considering any time that the heating occurred on the circuit. For example, bedroom 2 heat may not have been used at all, but since it was on the same circuit as bedroom 1 it was assigned the same on time as bedroom 1.

- Average space temperature when the heat was off for each thermostat

- Pre-period setback temperature (average "on" temperature minus average "off" temperature
- Post-period setback temperature (average "on" temperature minus average "off" temperature
- Pre-period minus post-period "on" temperature
- Pre-period minus post-period kWh heat consumption for each recorded circuit

The average temperatures listed above are only indicators of what is happening with the space heat and not an accurate indicator of temperature set-point. Some tenants used the thermostat as an on/off switch where they would turn the temperature up high for several hours and then turn it off. In these cases, the average temperature cannot be used to determine a heating set-point or a setback temperature.

The analyzed values are presented in Table 7 and Table 8. The following are generalized observations about the table.

- The two black rows with white lettering represent the two faulty thermostats.
- Two living rooms and five bedrooms across six apartments had zero or insignificant heater use in both the pre- and post-periods. Heater use less than 1% of total hours was considered insignificant. See shaded rows in the table.
- The average outdoor temperature was about 5°F warmer during the post-period.
- 17 thermostats had a lower average temperature in the post-period than in the pre-period during heating. This is represented by a positive value in the *Delta T "on", (pre – post)* column.
- 11 thermostats had a higher average temperature in the post-period than in the pre-period during heating (negative *Delta T "on"* value).

..... Tenant Survey

Based on the analysis results in Table 7 and Table 8, tenant specific questions were developed. Multiple attempts to contact the tenants were made. Some were not reachable. For those that were, the primary inquiries were about whether they used the new thermostat any differently than the old one. There was a follow up discussion about average post-period room temperatures that were either greater than or less than average pre-period room temperatures. All respondents indicated that they used the new thermostats no differently than the old ones. Each was surprised to hear about the average temperatures being different in the post-period than in the pre-period. They could not perceive any difference in temperatures. The specific questions and responses are included in the appendix.

One of the tenants in the two apartments that had faulty thermostats during the post-period was not reachable to conduct the survey. Questions to them were to be focused on how the working thermostats were affected by the faulty thermostats.

The one respondent did confirm that they left the bedroom doors open so some of the heat drifted out to the unheated living room. They also mentioned that they spent much more time in the heated bedrooms during the post-period. This confirmed that the living room was being partially heated by the bedroom heater. The living room temperatures were also observed to be only 1.5 degrees cooler during the post-period. Therefore, it was decided that the unit should be dropped from the sample due to this confounding effect.

The apartment with the bedroom thermostat stuck at a high temperature appeared to be heating the living room also. The bedroom averaged 7.6°F warmer in the post-period and the living room was greater than 2°F warmer in the post-period. The tenant was not reachable to confirm this, but based on the data, it was decided that the unit should be dropped from the sample due to this confounding effect.

Each of the remaining 14 sampled units received a separate energy savings analysis. For apartments where electric heat consumption was measured for more than one space in the unit, each space represented by the measurement date received a separate energy savings analysis. Savings were adjusted to account for differences in outdoor air temperature between pre- and post-periods. Savings were also extrapolated to the entire heating season to obtain annualized savings values.

Table 7: Pre-Installation Space Temperatures, Heating Hours, and Heat kWh, by Unit and Space, Phase 1

Building	Unit	Outside Air Temp, F	Space	Heat 'ON' Hours	Heat kWh	Heat 'ON' Temp, F	Heat 'OFF' Temp, F	Setback 'ON'–'OFF' Temp diff
1	A107	45.5	LR**	182	517	74.8	72.3	2.5
			BR1	237	359	74.3	72.1	2.2
			BR2			73.3	71.2	2.1
1	A205	45.5	LR	150	432	79.3	75.6	3.7
			BR1	313	322	76.1	74.9	1.2
			BR2			77.4	74.5	2.9
1	A302	45.0	LR	150	395	74.7	69.6	5.1
			BR1*	**0**			64.8	
1	A309	45.0	LR*	2			63.6	
			BR1	221	178	72.1	69.9	2.2
			BR2			62.6	64.1	-1.5
1	B102		LR	73	207	71.8	68.5	3.3
			BR1	64	99	67.5	64.9	2.6
2	48	45.5	LR*	**0**			74.9	
			BR1	218	253	74.2	72.4	1.8
			BR2			74.4	72.2	2.2
2	61	44.8	LR	170	399	74.1	72.7	1.4
			BR1**	125	107	70.9	71.8	-0.9
3	15	47.4	LR	270	1,988	68.4	68.3	0.1
3	30	47.4	LR	107	1,037	67.1	67.6	-0.5
3	32	47.4	LR	254	1,598	71.3	72.2	-0.9
6	207	45.0	LR	215	210	69.1	65.5	3.6
			BR1			69.5	64.6	4.9
			BR2			68.3	65.6	2.7
10	205	46.3	LR	131	401	74.4	74.3	0.1
			BR1	51	63	72.5	70.8	1.7
10	404	46.5	LR	205	508	73.7	70.7	3.0
			BR1*	**0**				
			BR2*					
10	406	47.2	LR	24	27	66.4	68.1	-1.7
			BR1*	3	4	66.2	66.5	-0.3
11	503	46.3	LR	152	1,534	71.4	71.6	-0.2
			BR1	162	55	69.3	70.0	-0.7
			BR2			71.3	71.7	-0.4
12	407	43.6	LR	232	452	72.2	69.4	2.8
			BR1			69.5	68.3	1.2
			BR2*	2	**0**	58.8	61.1	-2.3
Average* **		**45.9**				**70.7**		

* Insignificant or no heater use in both pre- and post-periods.
** Thermostat failure in post-period.
*** Average excludes Building 1, Unit A107 (Bin 1) and Building 2, Unit 61 (Bin 5)

Table 8: Post-Installation Space Temperatures, Heating Hours, and Heat kWh, by Unit and Space, Phase 1

Building	Unit	Outside Air Temp, F	Space	Heat 'ON' Hours	Heat kWh	Heat 'ON' Temp, F	Heat 'OFF' Temp, F	Setback 'ON'–'OFF' Temp diff
1	A107	52.4	LR**	**0**	**0**		69.9	
			BR1	212	321	72.8	70.7	2.1
			BR2			72.5	69.9	2.6
1	A205	51.7	LR	160	362	77.6	75.7	1.9
			BR1	332	297	76.9	75.4	1.5
			BR2			76.8	74.8	2.0
1	A302	51.7	LR	73	176	73.5	70.9	2.6
			BR1*	1			67.3	
1	A309	51.2	LR*	**0**			67.5	
			BR1	31	27	70.0	70.1	-0.1
			BR2			64.8	67.5	-2.7
1	B102	51.7	LR	45	92	70.9	68.7	2.2
			BR1	105	133	70.9	68.0	2.9
2	48	51.7	LR*	**0**			74.5	
			BR1	73	67	73.5	72.6	0.9
			BR2			71.7	71.0	0.7
2	61	51.7	LR	163	362	76.2	74.4	1.8
			BR1**	125	144	78.5	73.3	5.2
3	15	51.2	LR	105	755	67.6	67.6	0.0
3	30	51.2	LR	91	1,055	67.2	67.6	-0.4
3	32	51.2	LR	124	823	68.3	68.0	0.3
6	207	50.7	LR	118	106	69.8	68.8	1.0
			BR1			68.7	67.8	0.9
			BR2			69.3	68.7	0.6
10	205	50.2	LR	86	209	72.0	72.2	-0.2
			BR1	29	28	69.8	68.9	0.9
10	404	50.2	LR	136	344	74.4	71.8	2.6
			BR1*	1				
			BR2*					
10	406	50.2	LR	249	249	70.5	69.4	1.1
			BR1*	1	1	65.2	68.1	-2.9
11	503	49.9	LR	64	54	68.8	68.9	-0.1
			BR1	207	70	68.2	68.9	-0.7
			BR2			69.0	69.2	-0.2
12	407	50.0	LR	274	490	74.0	71.1	2.9
			BR1			71.2	69.4	1.8
			BR2*	5	3	57.2	62.1	-4.9
Average* **		**51.0**				**70.3**		

* Insignificant or no heater use in both pre- and post-periods.
** Thermostat failure in post-period.
*** Average excludes Building 1, Unit A107 (Bin 1) and Building 2, Unit 61 (Bin 5)

..... Outdoor Air Temperature Adjustment and Annual Extrapolation

The average outdoor temperature in the post-period was greater than five degrees warmer than the pre-period. Therefore, it was necessary to adjust the consumption values to compensate for the difference. This was done using the procedure described below.

The five-minute and ten-minute kW data were averaged to hourly values. Since any annualized extrapolation would be based on hourly temperature data, it was necessary to work with hourly values.

Calculate annual pre-period and post-period heat consumption

Multiple linear regression was used to separately correlate the pre- and post-period hourly kW data with hourly outdoor air temperature, day of the week, and hour of the day. Based on these three correlations, it was determined which of the variables were significantly related to hourly kW (t-statistic greater than 1.96). If any of the three variables were not significantly related, the regression was repeated using only the significant variables.

A list of significant variables and the resulting R-squared values are included in the appendix. Typically, the R-squared correlation values were very poor. This indicates that kWh consumption is only very weakly associated with outdoor temperatures, or with a fixed time schedule.

The resulting regression equations were used with Typical Meteorological Year (TMY) hourly outdoor temperature data for Seattle to calculate hourly electric heat consumption for each corresponding metered heat circuit.

Calculate annual energy savings

Hourly savings were calculated by subtracting hourly post-period consumption from hourly pre-period consumption. Annual savings were calculated by summing the hourly savings values from October through May to reflect the heating season.

..... Impact of Adjacent Units Energy Consumption

It is expected that the heat consumption of units adjacent to the study units play a very minor impact on the heat consumption of the study units. The exception may be if a unit above or below was only occupied for a portion of the study period and had the heat turned off (or back on) during a portion of the study period.

After the metering period was completed, the electric bills were obtained by SCL for the units adjacent to the study units. The bills were analyzed for the units adjacent to several of the study units with the largest and smallest adjusted savings. The analysis showed no significantly different energy use patterns in the adjacent unit to those of the study units.

Phase 1 Findings

A separate analysis of annual energy savings for each sampled housing unit was performed. In addition, spaces within the units, such as bedrooms and living rooms, also received

separate energy savings analysis when short term metering data supported that level of detail. The analysis include an adjustment for differences in outdoor air temperature between the pre-period and post-period. The energy savings analysis results were presented overall in the methodology section above. This section will present the results also as a function of characteristics that were defined by the sample.

Adjusted Annual Energy Savings

The annual energy savings resulting from the analysis described in the preceding Energy Savings Analysis are presented in Table 9. The table also includes previously presented unadjusted savings directly calculated from the metered data. A table comparing the pre-period space heat consumption from the regressions and the billing data is provided in the appendix.

As observed from Table 9, annual energy savings for the whole apartments ranged from –2,112 to 1,591 kWh per year with an average value annual energy saving of 166 kWh per year. The standard deviation of savings was 1076 kWh per year. Values that were more than + or – two standard deviations from the mean were considered outliers. All savings values fell within two standard deviations; therefore no outliers were eliminated. It should be noted that building 10, unit 406 is very close to statistically being an outlier and would significantly increase energy savings if it were removed from the sample. It is likely that with a larger by number of cases, a value of this size would exceed two standard deviations.

Table 9: Difference in Space Temperatures and Adjusted Annual Energy Savings, by Unit and Space, Phase 1

Building	Unit	Temperature Adjusted Annual kWh Savings	Space	Unadjusted Metered kWh Savings	Temperature Adjusted Annual kWh Savings	Delta T 'ON' (Pre - Post)	Delta T 'OFF' (Pre - Post)
1	A205	-1,413	LR	70	-740	1.7	-0.1
			BR1	25	-673	-0.8	-0.5
			BR2			0.6	-0.3
1	A302	653	LR	219	653	1.2	-1.3
			BR1*	**0**	**0**		
1	A309	732	LR*	**0**	**0**		
			BR1	151	732	2.1	-0.2
			BR2			-2.2	-3.4
1	B102	-665	LR	115	225	0.9	-0.2
			BR1	-34	-890	-3.4	-3.1
2	48	938	LR*	**0**	**0**		
			BR1	187	938	0.7	-0.2
			BR2			2.7	1.2
3	15	1,591	LR	1,233	1,591	0.8	0.7
3	30	-792	LR	-18	-792	-0.1	0.0
3	32	1,073	LR	775	1,073	3.0	4.2
6	207	592	LR	104	592	-0.7	-3.3
			BR1			0.8	-3.2
			BR2			-1.0	-3.1
10	205	1,013	LR	191	806	2.4	2.1
			BR1	35	207	2.7	1.9
10	404	416	LR	164	416	-0.7	-1.1
			BR1*	**0**	**0**	**0.0**	**0.0**
			BR2*			**0.0**	**0.0**
10	406	-2,112	LR	-223	***-2,112***	***-4.1***	-1.3
			BR1*	**0**	**0**	1.0	-1.6
11	503	786	LR	1,481	944	2.6	2.7
			BR1	-15	-158	1.1	1.1
			BR2			2.3	2.5
12	407	-483	LR	-38	-483	-1.8	-1.7
			BR1			-1.7	-1.1
			BR2*	**0**	**0**	1.6	-1.0
Average		**166**				**0.4**	**-0.4**
Std Dev		1,076					

* Insignificant or no heater use in both pre- and post-periods.

Energy Savings by Characteristics Bins

The characteristics bins previously defined in the section, Subject Population Definition, group the sample units by their physical and operational characteristics. Table 10 shows the savings results for the final fourteen units with the bin characteristics. The average savings is shown with and without building 10, unit 406. Even though this unit is not statistically an outlier, it has a significant impact on the result and should be considered as an anomaly in evaluating the results of this small sample.

Table 10: Bin Characteristics and Annual Energy Savings Estimates, Phase 1

Build-ing	Unit	Temperature-Adjusted Annual kWh Savings	Space	Temperature-Adjusted Annual kWh Savings	Weatherized?	Floor Area	External Exposure	Heating Hours	Bin
1	A107	-1,413	LR	-740	Wz	Lg	Min	Hi	3
			BR1 BR2	-673					
1	A302	653	LR	653	Wz	Sm	Ext	Lo	6
			BR1	**0**					
1	A309	732	LR	**0**	Wz	Lg	Ext	Lo	2
			BR1 BR2	732					
1	B102	-665	LR	225	Wz	Sm	Ext	Lo	6
			BR1	-890					
2	48	938	LR	**0**	Wz	Lg	Ext	Hi	1
			BR1 BR2	938					
3	10	1,591	LR	1,591	No	Sm	Min	Hi	15
3	15	-792	LR	-792	No	Sm	Min	Lo	14
3	32	1,073	LR	1,073	No	Sm	Min	Hi	15
6	207	592	LR BR1 BR2	592	No	Sm	Ext	Lo	10
10	205	1,013	LR	806	Wz	Sm	Ext	Lo	6
			BR1	207					
10	404	416	LR	416	Wz	Lg	Ext	Lo	2
			BR1 BR2	**0**					
10	406	***-2,112***	LR	***-2,112***	Wz	Sm	Ext	Hi	5
			BR1	**0**					
11	503	786	LR	944	No	Sm	Min	Lo	14
			BR1 BR2	-158					
12	407	-486	LR BR1	-483	Wz	Lg	Ext	Lo	2
			BR2	**0**					
		166		**Average**	**All 14 Buildings**				
		342		**Average**	*Without Building 10, Unit 406*				

* Insignificant or no heater use in both pre- and post-periods.

Table 11 summarized the energy savings by characteristic bin. As can be seen in the table, it is difficult to draw any significant conclusions due to the small sample sizes. However, the non-weatherized units (bins 9 through 16) tend to have greater energy savings than the weatherized units (bins 1 through 8). Further breakdown of the results by bin characteristics are presented in the following subsections.

Table 11: Energy Savings by Bin, Phase 1

Bin	Average kWh Savings	Sample Size
1	998	1
2	222	3
3	-1,413	1
4		0
5	-2,112	1
6	334	3
7		0
8		0
9		0
10	592	1
11		0
12		0
13		0
14	-3	2
15	1,332	2
16		0
Total		**14**

Energy Savings Comparison for Bedrooms and Living Rooms

Energy savings were also compared between bedrooms and living rooms. One apartment had heat energy metering that combined the living room with one bedroom (Building 12, unit 407). However, the post-period metering tenant survey indicated that the tenants did not use the bedroom heat. Therefore, the combined space was assigned to the living room category. Another apartment was metered to include the living room and both bedrooms together (Building 6, unit 207). This unit was assigned to the living room category because, in general, living rooms appear to be the most energy intensive space.

Table 12 compares energy savings between living rooms and bedrooms for both weatherized and not weatherized categories. The not weatherized bedroom category has a sample size of one and shows negative savings (increased energy use) of 158 kWh per year, while the living room category shows significant saving of 682 kWh per year. The weatherized bedrooms show a relatively small savings of 35 kWh per year, while the living room shows increased energy use by 137 kWh per year. Table 12 also presents results with the anomalous unit removed from the sample. With the large negative value removed, living room energy savings were 110 kWh per year and total unit savings increased to 149 kWh per year.

Table 12: Energy Savings by Space Type, Phase 1

	All 14 Cases		Adjusted *	
Category	**Weatherized**	**Not Wz**	**Weatherized**	**Not Wz**
Annual kWh Savings:				
Bedrooms	35	-158	39	-158
Livingrooms	-137	682	110	682
Total Unit	-102	650	149	650
Sample Size:				
Bedrooms	9	1	8	1
Livingrooms	9	5	8	5
Sample Size	9	5	8	5

* Adjusted by excluding Building 10, Unit 406 (Bin 5)

..... Energy Savings Comparison by Floor Area

Housing unit floor area was also anticipated to be a factor in energy savings because typically larger units have larger space heat requirements. Table 13 summarizes savings by large and small floor area categories as well as by weatherized/not weatherized categories. Again the summary is presented both with and without the anomalous apartment.

As seen in the table, smaller floor area is associated with smaller savings in the weatherized units. Only two cases remained in the small floor area category after removing anomalous data, with a slightly negative result (increased energy use). For the not weatherized category, only small units occurred in the sample and those units did have significant energy savings.

Table 13: Energy Savings by Floor Area, Phase 1

	All 14 Cases		Adjusted *	
Category	**Weatherized**	**Not Wz**	**Weatherized**	**Not Wz**
Annual kWh Savings:				
Large Floor Area	201		201	
Small Floor Area	-708	650	-9	650
Total Unit	-102	650	149	650
Sample Size:				
Large Floor Area	6		6	
Small Floor Area	3	5	2	5
Sample Size	9	5	8	5

* Adjusted by excluding Building 10, Unit 406 (Bin 5)

..... Energy Savings Comparison by Exterior Exposure

The number of exterior surfaces exposed to the weather was also anticipated to be a factor in energy savings because typically larger exposure would relate to larger space heat requirements. Table 14 summarizes savings by large and small exterior exposure area categories as well as by weatherized/not weatherized categories. Again the summary is presented both with and without the anomalous apartment.

As expected, the larger exposures also reflect larger energy savings. However, there is only one observation in the weatherized small exposure category.

Table 14: Energy Savings by External Exposure, Phase 1

	All 14 Cases		Adjusted *	
Category	**Weatherized**	**Not Wz**	**Weatherized**	**Not Wz**
Annual kWh Savings:				
Extensive Exposure	62	689	372	689
Minimal Exposure	-1,413	624	-1,413	624
Total Unit	-102	650	149	650
Sample Size:				
Extensive Exposure	8	2	7	2
Minimal Exposure	1	3	1	3
Sample Size	9	5	8	5

* Adjusted by excluding Building 10, Unit 406 (Bin 5)

..... Energy Savings Comparison by Heating Hours

The number of heating hours was also anticipated to be a factor in energy savings because typically a larger number of hours that the space is heated would relate to larger space heat requirements. Table 15 summarizes savings by high and low heating hour categories as well as by weatherized/not weatherized categories. Again the summary is presented both with and without the anomalous apartment.

As expected, higher operating hours correspond to larger energy savings for the case where the anomalous unit is removed.

Table 15: Energy Savings by Heating Hours, Phase 1

	All 14 Cases		Adjusted *	
Category	Weatherized	Not Wz	Weatherized	Not Wz
Annual kWh Savings:				
High Hours	-394	1,332	179	1,332
Low Hours	131	195	131	195
Total Unit	-102	650	149	650
Sample Size:				
High Hours	4	2	3	2
Low Hours	5	3	5	3
Sample Size	9	5	8	5

* Adjusted by excluding Building 10, Unit 406 (Bin 5)

Phase 1 Conclusions and Recommendations

Conclusions

It is difficult to draw firm conclusions from this study because of the small sample size. However, findings from the limited sample lead to the following conclusions based on the study sample analyzed:

> *The study proved the concept of energy savings from replacing bimetal thermostats with vapor diaphragm thermostats, and proved the study methodology for determining savings.*

Overall energy savings per multifamily housing unit falls within the range of 166 and 342 kWh per year as a result of replacing bimetal thermostats with vapor diaphragm thermostats. This represents 6-12% of the November-April space heat. Given the expectation of 7% savings from every one-degree drop in average thermostat temperature settings, this would imply a 1-2 degrees Fahrenheit drop in those settings. The average temperature reading taken near those thermostats only changed by 0.5 degrees. However, this does not necessary equate to the same change in thermostat settings because the average values include significant heat-off hours for those cases where more than one thermostat was associated with the heating circuit.

> *Energy savings are greater in units that have not been weatherized, units with larger floor areas, units with more extensive exterior exposure, in units where the occupants do not set back the thermostats at night or when they leave the unit, and in living room spaces within units.*

- Energy savings are significantly greater in units that have not been weatherized. Savings in these units are on the order of about 650 kWh per year.

- Energy savings in weatherized units is more uncertain and fall in the range of about –100 (increase energy use) to +150 kWh per year. However, it appears likely that the savings value is closer to the 150 kWh per year value.

- Units with larger floor areas use more space heat so the vapor diaphragm thermostat provides greater energy savings. They also require more thermostats, because the units are larger due to more bedrooms in the unit.

- Units with more exterior surface area result in greater energy savings from the thermostat retrofit.

- Vapor diaphragm thermostats installed in living room spaces save more energy than thermostats installed in bedroom spaces.

- Units where the occupants do not set back the thermostats at night or when they leave the unit result in greater energy savings from thermostat retrofit. This results from higher baseline energy use from not setting back temperature.

This last point is useful information in support of tenant education. It should be emphasized that occupants reduced the thermostat setting as much as is comfortable, and that setting back the thermostat when they are away or at night will save even more energy.

> *The hysteresis testing methodology developed for the study was successfully implemented. The tests resulted in determining that 93% (54 of 57) bimetal thermostats had significantly larger hysteresis than the vapor diaphragm thermostats.*

Recommendations

The following recommendations are presented:

> *A Phase 2 Study should be completed to provide more robust energy savings estimates that can be extrapolated to the population.*

> *The study methodology should be modified to reduce data loss and reduce study costs.*

- Complete more rigorous thermostat testing at time of installation to ensure equipment is functioning properly. There was a 5% failure rate of the new vapor diaphragm thermostats.

- Defer hysteresis testing until metering equipment installation site visit. This eliminates one site visit that only resulted in a seven percent rejection of units. Initial recruitment should include 10% more units to compensate for attrition due to hysteresis testing.

- Download data loggers at thermostat replacement. This would identify failed loggers in the pre-period and provide an opportunity to correct and extend the pre-period for a few additional weeks so that the site will not be lost.

- Call each tenant within one week of thermostat replacement to verify equipment is functioning properly.
- Delete heating hours from the characteristics binning strategy. This variable is tenant behavior dependent and not available for population extrapolation.
- Consider vacancy or tenant turnover in units adjacent to the sampled units. This may help explain variations in heat consumption of the sampled units.

Utility thermostat program implementation should consider the following factors.

- There is a possibility of thermostat failure from manufacturing defects.
- Tenant education about thermostat operation will likely provide savings beyond study values. The study did not provide any instruction to the tenant about thermostat operation. Any instruction may be only effective for the duration of tenancy, however the knowledge will carry over to where ever the tenant moves to next.
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Phase 2 Metering Research

In-Unit Measurements, Winter 2005-2006

Phase 2 Introduction

The Phase 2 study was conducted in response to Phase 1 recommendations to increase the sample size of the overall study. In particular, the focus was on increasing sample size in the weatherized building category. This was also deemed important because SCL programs will be aimed at weatherized buildings and will be a better indicator of the measure impact after accounting for interactions with weatherization measures. Also, it was determined from the Phase 1 study, that the tenant behavior characteristic of high heat versus low heat use, had limited value in extrapolation to the population, since that characteristic is not readily available. Therefore, the number of characteristics bins was reduced to only include large and small floor area and large and small exterior surface area. The Phase 1 recommendations to improve the study methodology were also implemented in Phase 2.

Objectives

The objective of this study is to confirm or dispel the following hypotheses.

1. *Reducing the thermostat temperature setting results in savings of the expected magnitude, which is approximately seven percent (7%) of annual space heat for a one-degree (1°F) reduction in temperature, based on reported savings for single family housing.*
2. *Equivalent comfort can be achieved at lower temperature settings when hysteresis is reduced.*
3. *Changing bimetal thermostats to vapor diaphragm thermostats, without thermostat pre-sets, labeling, or tenant education, automatically results in energy savings.*

Phase 2 Methodology

The methodology for Phase 2 is very similar to Phase 1; therefore only deviations from Phase 1 are described in this section.

Subject Population Definition

..... Building Characteristics

Seattle City Light initially identified 14 candidate multifamily sites. Besides contacting the building owner/manager to determine interest in the study, the following characteristics of the electrically heated buildings were collected:

- Year built
- Total floor area
- Number of living units in the complex
- History of past participation in SCL programs for energy efficiency upgrade ("weatherization").
- Bimonthly electric billing histories for each living unit

During the owner/manager discussions, it was determined that four of the buildings were not suitable, because the windows were in very poor condition and were scheduled for replacement.

Table 16 summarizes the first four characteristics for the ten remaining buildings. As seen in the table, all but two of the buildings have participated in weatherization programs. All the buildings that participated have replaced windows. The two buildings, which did not participate, were built after the 1980 energy code, which required double pane windows and improved insulation levels. Therefore, they were both assumed to have thermal integrity equal to the weatherized buildings. It should be noted that the windows in building 14 are 20 years old and not up to the standards of newer windows that are used in the weatherization programs.

Table 16: Characteristics of Candidate Buildings, Phase 2

Building	Year Built	Total SqFt Floor Area	Number of Units	Past SCL Program Participation Year: Measures Installed
13	1968	13,495	11	1999-2000: Windows, Lighting
14	1985	32,996	28	None. Good condition double pane windows
15	1960	17,778	23	2003: Windows, Insulation
16	1965	50,216	49	2002: Windows, Lighting
17	1999	71,510	49	None. Good condition double pane windows
18	1926	16,512	21	1997-1998: Windows, Lighting
19	1923	22,400	34	1996-1997: Windows
20	1959	6,626	9	1995: Windows, Lighting
21	1962	10,614	10	1995: Windows, Lighting
22	1982	86,804	102	None. Poor condition double pane windows

..... Space Heat Screening

The bimonthly billing records were examined for the 334 apartments. For the purposes of the study, units were only considered if they had the same tenant living in them for at least the last year. Total electric consumption was determined for each unit by summing the most recent six bimonthly bills. The non space-heat component of the annual consumption was determined by multiplying the smallest bimonthly bill by six. This value was then adjusted up by 15% to account for potentially low summer bills due to partial vacation vacancies. The non space-heat consumption was then subtracted from the total annual consumption to obtain the annual space heat electric consumption. Only units that had significant space heat were considered as candidates for the study. Significant space heat was defined as consumption greater than 2,400 kWh per year as determined above. As a result of the analysis of the billing records, 142 apartments remained as candidates for the study (43%).

..... Sample Binning Strategy

The Phase 2 sample of housing units consisted of a focused subset of the Phase 1 binning strategy. It was limited to weatherized buildings only and there was no attempt to divide into high and low heating hours. Weatherized buildings were defined as having received shell energy efficiency improvements or building that were built after the 1980 Seattle energy code took affect. The bin characteristics were then defined as follows:

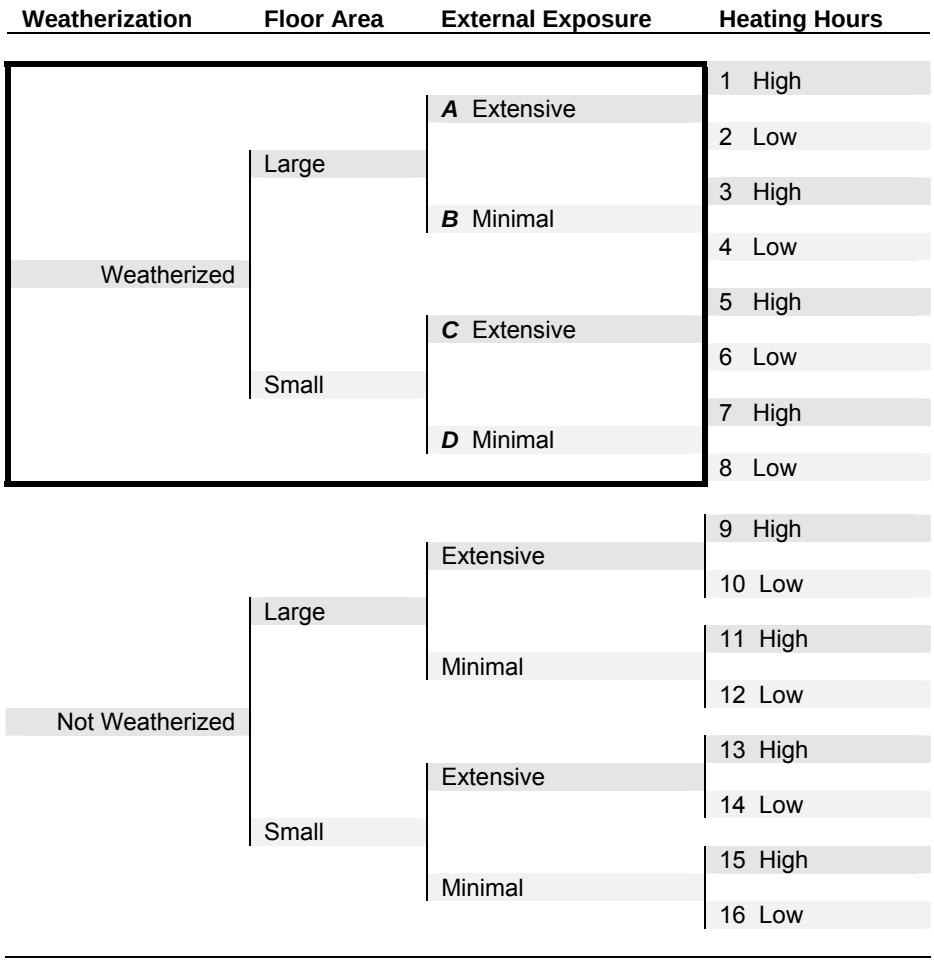
- **Floor area**—larger apartments will require more space heat than small apartments. As in Phase 1, two floor area categories were defined as *large* or *small*, with the separation set at 830 square feet.

- **External exposure**—apartments that have more surfaces exposed to the exterior (walls, roof, floor) will have greater heat loss. As in Phase 1, two categories were

defined as *minimal* having one or two exterior surfaces, and *extensive* as having three or more exterior surfaces.

Figure 3 graphically illustrates the resulting four characteristics bins, A through D. They are presented in relationship to the Phase 1 binning strategy.

Figure 3: Binning Strategy of Sampled Units, Phase 2



Baseline Characteristics Data Collection and Hysteresis Confirmation

Building, tenant and space heating system characteristics data were collected to further determine eligibility to participate in the study. The data were collected through resident manager and tenant interviews as in the Phase 1 study. Thermostat performance testing (hysteresis testing) was deferred to the time of data logger installation. This was determined to be a labor saving modification to the methodology based on the low unit rejection rate from hysteresis testing during the Phase 1 study.

One of the buildings in Phase 2 sample consisted of owner occupied condominiums (building 14). The remaining buildings were rented apartments, as were all the buildings in the Phase 1 study.

..... Resident Manager Interview

Resident manager interviews were conducted on all ten buildings. Two of the buildings were dropped due to discovering characteristic that made them ineligible for the study. One building was dropped because the heating equipment consisted primarily of radiant ceiling panels. Another building was dropped because it did not have wall thermostats. Across the remaining eight buildings, 74 candidate units remained.

..... Tenant Interview

Interviews were conducted with as many of the remaining candidates as could be contacted. As a result of the interviews, 20 tenants gave preliminary permission to participate in the study. All efforts were made to recruit and retain these tenants.

Final Sample Selection for Metering

The final sample selected for participation included 20 apartments in six buildings. Two buildings dropped out because no tenants could be recruited for participation.

Table 17 shows the distribution of the final sampled apartments across the previously defined characteristic bins. A more detailed listing of apartment characteristics is included in the appendix. Logically, it is expected that units with fewer exposed surfaces would not have significant space heat consumption. This is consistent with zero observations in bin D and only 1 observation in bin B.

Table 17: Final Sample Selection, Phase 2

Bin	Weatherization	Floor Area	External Exposure
A	Weatherized	Large	Extensive 14
B		15	Minimal 1
C		Small	Extensive 5
D	20	5	Minimal 0
Cases	**20**	**20**	**20**

As observed in the table above, the largest count of units with significant space heat occurred in apartments with a large floor area and a large number of exposed surfaces, Bin A. Small units with large floor area were more difficult to find as shown with only five observations in bin C.

Detailed On-site Measurement Using Data Loggers

Each of the twenty residential units in the sample was subjected to a series of short-term measurements before and after the installation of the vapor diaphragm thermostats. Measurements included electric consumption, indoor air temperature and outdoor air

temperature. The short-term measurements were recorded for approximately six weeks prior to and after thermostat replacement.

..... Hysteresis Testing

Prior to installing the short term metering equipment in each dwelling unit, hysteresis testing was performed on one or more thermostats in the unit. All living room thermostats were tested and some of the bedroom thermostats were tested. Only one thermostat test resulted in a hysteresis less than 15 degrees (it tested at 13 degrees), which was the elimination point for the Phase 1 Study, (see Interpreting Results). However, the other thermostats in that unit had tested hysteresis significantly greater than 15 degrees, so it was decided to retain the unit in the study.

..... Installation of Metering Equipment

Electric consumption was measured in each apartment. One four-channel logger was used to measure up to three channels of space heat (maximum number of heat circuits found). The heat circuits were verified by systematically turning on each thermostat and measuring amperage at the circuit breakers. The loggers were installed inside the electric circuit breaker panel of the apartment, and were used to measure average amperes over either five-minute or ten-minute intervals. Single channel temperature loggers were also placed at each thermostat that was to be replaced to record average air temperature over five-minute intervals coincidentally with electric amp measurements. At each apartment complex, one temperature logger was also placed outside on the north side of the building in the shade to record outdoor air temperature.

During the metering equipment installation site visit, the line voltage of each of the two phases of electrical system was measured using a voltmeter. Building characteristics obtained during the tenant interview, such as number of exterior surfaces and number of bedrooms, were also verified.

Table 18 summarizes the resulting channel configuration for measurement of space temperature and space heat in each unit. As shown in the table, two studio apartments only had a single heat circuit and therefore were measured as a single channel, three units had three heat circuits, and the remaining 15 units had only two heat circuits.

Table 18: Temperature and Space Heat Data Channels, by Unit and Space, Phase 2

Building	Unit	Space	Temp. Channel	Space Heat Channel
13	103	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	11	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	12	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	13	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	16	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	17	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	22	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	23	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	36	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
14	42	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	C
14	44	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	C
15	16	Living room	1	A
		Bedroom 1	2	B
		Bath room	3	B

Table 18 Temperature and Space Heat Data Channels, by Unit and Space, Phase 2 (continued)

Building	Unit	Space	Temp. Channel	Space Heat Channel
16	106	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
16	107	Living room	1	A
		Dining room	2	B
		Bedroom 1	3	B
		Bedroom 2	4	C
		Bedroom 3	5	C
16	210	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
		Bath room	4	B
16	214	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
		Bath room	4	B
17	304	Living room	1	A
		Bedroom 1	2	B
		Bedroom 2	3	B
18	4	Living room	1	A
		Bedroom 1	2	B
18	301	Living room	1	A
18	304	Living room	1	A
		Total Count	**59**	**41**

..... Thermostat Replacement

After approximately six weeks of short-term measurements, the 59 thermostats as represented by the space temperature channels in Table 18 were replaced. A licensed electrician was contracted for the thermostat replacements. Either single pole or double pole thermostats were installed as appropriate for each case.

Prior to thermostat replacement, the data loggers were downloaded to verify that pre-period data had been successfully recorded. It was discovered that one of the electric consumption loggers had failed (building 14, unit 12) and collected no pre-period data. The logger was replaced and the thermostats were left in place for an additional three weeks to obtain three weeks of pre-period data before thermostat replacement. Temperature data was also lost for two bedrooms, building 13, unit 103, bedroom 2 and building 18, unit 4. The thermostats in these units were replaced as scheduled. One of these bedrooms had no heat consumption during the pre-period and the other had low heat consumption, so it was determined that a full post-period was more important than extending the pre-period another three weeks.

All loggers recorded data at five-minute intervals during the pre-period. It was discovered that for two units, building 12, units 12 and 42, the electric consumption loggers had limited memory and only recorded about 25 days of pre-period data in the six-week period. These loggers were reset to record data at ten-minute intervals to capture the entire six-week post-period.

One tenant, building 14, unit 36, informed us that he would be leaving for an extended vacation three weeks after thermostat replacement.

..... Data Equipment Retrieval

Approximately six weeks after the thermostats were replaced (three weeks for building 14, unit 12), the data logging equipment was removed. One bedroom temperature logger failed two days into the post-period, building 16, unit 107. One electric consumption logger had no post-period data (building 13, unit 103) Therefore, the logger was reset and left in for another two weeks to obtain at least two weeks of post-period data. No other data problems occurred during the post-period.

Post-Measurement Characteristics Data Collection

All data loggers were downloaded and the data were compiled into spreadsheet workbooks for each apartment. Amperage data were converted into kW values by multiplying the amperage values by the measured voltage in each apartment. Each workbook then contained the following data in a time series.

- Date and time
- Total apartment kW
- Heat kW by channels defined in Table 18
- Temperature data for each thermostat as defined in Table 18
- Outdoor air temperature

The pre- and post-periods were distinguished based on the date and approximate time that the new vapor diaphragm thermostats were installed.

..... Rejected and Lost Data

Data that were identified as problematic were dropped from the analysis. Three such cases of bedroom temperature data were mentioned in the previous section, however the energy savings analysis was carried forward in all three cases. The missing temperature data only provides a slightly less informed assessment of the savings analysis results.

..... Data Analysis of Individual Units.

The data were analyzed for each apartment based on the resolution of heating-circuit recorded data. When more than one thermostatically controlled heater was on the recorded heat channel, the energy consumption was analyzed as the group of affected heaters. The space temperatures were considered on an individual thermostat level, but could not be used to disaggregate the heat consumption to each thermostat.

Each unit was analyzed to determine pre- and post-period values for the following variables:

- Hours of heat use
- Total heat kWh consumption for each recorded circuit
- Average space temperature when the heat was on for each thermostat.

When more than one thermostat was associated with a single heat circuit, the average "on" temperature for each thermostat was determined by considering any time that the heating occurred on the circuit. For example, bedroom 2 heat may not have been used at all, but since it was on the same circuit as bedroom 1 it was assigned the same on time as bedroom 1.

- Average space temperature when the heat was off for each thermostat
- Pre-period setback temperature (average "on" temperature minus average "off" temperature
- Post-period setback temperature (average "on" temperature minus average "off" temperature
- Pre-period minus post-period "on" temperature
- Pre-period minus post-period kWh heat consumption for each recorded circuit

The average temperatures listed above are only indicators of what is happening with the space heat and not an accurate indicator of temperature set-point. Some tenants used the thermostat as an on/off switch where they would turn the temperature up high for several hours and then turn it off. In these cases, the average temperature cannot be used to determine a heating set-point or a setback temperature.

The analyzed values are presented in in Table 19 and Table 20. The following are generalized observations about the tables.

- The three <u>black rows with white lettering</u> represent the three temperature data logging failures.
- Seven bedrooms across five apartments had zero or insignificant heater use in both the pre- and post-periods. Heater use less than 1% of total hours was considered insignificant. See shaded rows in the table.
- One bedroom in one unit had zero heater use in the pre-period, but consumption increased during the post-period. <u>See shaded pre-installation half of row in the table.</u>
- The average outdoor temperature was about 2°F cooler during the post-period.
- 27 thermostats had a lower average temperature in the post-period than in the pre-period during heating. This is represented by a positive value in the non-shaded cells of the *Delta T "on", (pre – post)* column.
- 21 thermostats had a higher average temperature in the post-period than in the pre-period during heating (negative *Delta T "on"* value).

The apartment, building 16, unit 106, has very low heat use at less than 2% of the hours on in the living room and less than 1% of the hours on in the bedrooms. The electric utility bills were reviewed and found to contain a very high consumption month followed by a very low consumption month, which was possibly a billing system error. This appears to have falsely identified the unit as a high heat consumer in the bill screening process. This unit is a low heat consumption unit and was dropped from further analysis.

..... Tenant Survey

Based on the analysis results in Table 19 and Table 20, tenant specific questions were developed. The primary inquiries were about whether they used the new thermostat any differently than the old one. There was a follow up discussion about average post-period room temperatures that were either greater than or less than average pre-period room temperatures. Most respondents indicated that they used the new thermostats no differently than the old ones. One tenant (building 14, unit 12) indicated that he used the old thermostat like an on/off switch, but he left the new one in one position when he was home. He turns the new one back when he leaves, but not as far as he did with the old one. Another tenant (building 14, unit 23 indicated that they turned the bedroom thermostat up more at night than they did with the old thermostat. Most were surprised to hear about the average temperatures being different in the post-period than in the pre-period, however one occupant (building 17, unit 304) mentioned that they noticed that the temperature seemed cooler and they eventually started setting the temperature higher, but it took several weeks to notice it. They could not perceive any difference in temperatures. The specific questions and responses are included in the appendix.

Table 19: Pre-Installation Space Temperatures, Heating Hours, and Heat kWh, by Unit and Space, Phase 2

Building	Unit	Outside Air Temp, F	Space	Heat 'ON' Hours	Heat kWh	Heat 'ON' Temp, F	Heat 'OFF' Temp, F	Setback 'ON'–'OFF' Temp diff
13	103	44.4	LR	281	880	75.2	72.7	2.5
			BR1*	1	1	67.2	70.4	-3.2
			BR2**			Missing		
14	11	46.9	LR	264	851	69.7	68.3	1.4
			BR1	318	316	66.7	61.0	5.7
			BR2			65.4	58.2	7.2
14	12	43.8	LR	101	238	66.7	64.6	2.1
			BR1	134	172	64.3	63.3	1.0
			BR2			63.5	61.7	1.8
14	13	46.9	LR	220	732	68.3	65.9	2.4
			BR1	310	528	66.8	65.4	1.4
			BR2			65.1	63.7	1.4
14	16	46.9	LR	164	396	73.4	73.1	0.3
			BR1	327	419	63.7	63.9	-0.2
			BR2			71.5	70.3	1.2
14	17	47.7	LR	248	1,104	72.8	69.6	3.2
			BR1	611	1,034	68.7	68.0	0.7
			BR2			68.2	68.7	-0.5
14	22	47.6	LR	142	452	72.4	72.4	0.0
			BR1**	**0**	**0**		Missing	
			BR2*				69.0	
14	23	46.6	LR	280	796	71.1	69.1	2.0
			BR1	26	41	59.6	60.4	-0.8
			BR2			64.5	62.0	2.5
14	36	47.2	LR	137	324	70.7	69.1	1.6
			BR1	150	191	65.8	67.2	-1.4
			BR2			69.7	70.5	-0.8
14	42	48.9	LR	159	519	74.3	71.6	2.7
			BR1	69	111	72.2	70.0	2.2
			BR2*	**0**	**0**		64.5	
14	44	47.2	LR	357	144	72.5	71.0	1.5
			BR1	135	228	70.6	69.2	1.4
			BR2*	**0**	**0**		69.0	
15	16	48.4	LR	135	449	71.1	69.3	1.8
			BR1	336	368	69.6	67.9	1.7
			Bath			70.1	70.5	-0.4

Table 19 Pre-Installation Space Temperatures, Heating Hours, and Heat kWh, by Unit and Space, Phase 2 (continued)

Building	Unit	Outside Air Temp, F	Space	Heat 'ON' Hours	Heat kWh	Heat 'ON' Temp, F	Heat 'OFF' Temp, F	Setback 'ON'–'OFF' Temp diff
16	106	43.8	LR	16	67	71.9	71.4	0.5
			BR1*	**0**	**0**		69.1	
			BR2*				69.8	
16	107	44.1	LR	101	265	73.5	70.8	2.7
			Dine	853	1,937	72.9	71.2	1.7
			BR1			74.6	74.9	-0.3
			BR2	211	276	74.9	68.2	6.7
			BR3			70.3	69.6	0.7
16	210	43.1	LR	380	764	71.2	69.7	1.5
			BR1	66	63	60.4	61.6	-1.2
			BR2			61.1	63.6	-2.5
			Bath			70.2	68.4	1.8
16	214	43.8	LR	323	730	73.7	73.4	0.3
			BR1	183	67	64.2	64.9	-0.7
			BR2			64.2	64.9	-0.7
			Bath			71.8	70.4	1.4
17	304	46.5	LR	302	879	74.7	71.9	2.8
			BR1	58	70	75.3	73.7	1.6
			BR2			69.9	70.0	-0.1
18	4	44.1	LR	392	992	68.9	67.7	1.2
			BR1**	40	51	Missing		
18	301	44.1	LR	459	883	71.5	68.8	2.7
18	304	44.1	LR	381	766	68.7	65.0	3.7
Average		**45.8**				**69.3**		

* Insignificant or no heater use in both pre- and post-periods.

** Thermostat failure in post-period.

Table 20: Post- Installation Space Temperatures, Heating Hours, and Heat kWh, by Unit and Space, Phase 2

Building	Unit	Outside Air Temp, F	Space	Heat 'ON' Hours	Heat kWh	Heat 'ON' Temp, F	Heat 'OFF' Temp, F	Setback 'ON'–'OFF' Temp diff
13	103	44.3	LR	107	327	77.2	74.1	3.1
			BR1*	14	9	70.4	71.1	-0.7
			BR2*			70.1	71.2	-1.1
14	11	44.7	LR	265	699	70.2	68.2	2.0
			BR1	505	574	67.6	68.4	-0.8
			BR2			69.4	68.4	1.0
14	12	45.6	LR	145	305	68.3	67.7	0.6
			BR1	252	283	65.2	64.9	0.3
			BR2			67.7	66.6	1.1
14	13	44.7	LR	307	771	68.1	66.9	1.2
			BR1	436	737	67.3	66.2	1.1
			BR2			65.7	64.6	1.1
14	16	44.7	LR	305	616	73.5	72.2	1.3
			BR1	265	316	63.9	63.2	0.7
			BR2			69.8	69.7	0.1
14	17	44.7	LR	247	874	70.2	69.0	1.2
			BR1	746	1,424	68.7	67.0	1.7
			BR2			67.9	67.3	0.6
14	22	44.7	LR	421	469	72.2	70.7	1.5
			BR1*	**0**	**0**		67.0	
			BR2*				68.7	
14	23	44.6	LR	363	827	71.4	71.4	0.0
			BR1	273	432	62.8	63.6	-0.8
			BR2			67.2	66.2	1.0
14	36	43.7	LR	111	233	69.4	68.5	0.9
			BR1	138	186	65.3	65.6	-0.3
			BR2			67.7	69.2	-1.5
14	42	44.7	LR	351	372	71.5	69.7	1.8
			BR1	184	113	69.6	68.7	0.9
			BR2	75	17	64.5	62.8	1.7
14	44	44.7	LR	382	161	71.5	71.0	0.5
			BR1	114	155	66.3	67.9	-1.6
			BR2*	**0**	**0**		68.8	

* Insignificant or no heater use in both pre- and post-periods.

** Thermostat failure in post-period.

Table 20 Post- Installation Space Temperatures, Heating Hours, and Heat kWh, by Unit and Space, Phase 2 (continued)

Building	Unit	Outside Air Temp, F	Space	Heat 'ON' Hours	Heat kWh	Heat 'ON' Temp, F	Heat 'OFF' Temp, F	Setback 'ON'–'OFF' Temp diff
15	16	45.5	LR	66	183	69.8	67.2	2.6
			BR1	442	525	67.9	67.4	0.5
			Bath			67.1	69.4	-2.3
16	106	43.0	LR	20	73	72.5	71.9	0.6
			BR1	11	13	67.6	68.7	-1.1
			BR2			70.7	68.7	2.0
16	107	43.0	LR	82	262	73.2	70.1	3.1
			Dine	656	1,422	72.0	71.1	0.9
			BR1**			Missing		
			BR2	277	361	73.4	68.7	4.7
			BR3			68.4	69.4	-1.0
16	210	42.7	LR	363	820	70.2	69.0	1.2
			BR1	48	45	60.4	62.1	-1.7
			BR2			62.0	63.9	-1.9
			Bath			69.7	68.5	1.2
16	214	43.0	LR	353	787	74.2	73.1	1.1
			BR1	153	67	64.7	64.9	-0.2
			BR2			66.5	66.6	-0.1
			Bath			73.8	70.1	3.7
17	304	44.1	LR	329	740	71.0	70.1	0.9
			BR1	195	242	73.3	72.7	0.6
			BR2			68.0	67.6	0.4
18	4	41.7	LR	503	1,236	67.4	66.4	1.0
			BR1	60	74	66.8	62.8	4.0
18	301	41.7	LR	400	684	69.0	67.0	2.0
18	304	41.7	LR	491	880	69.7	68.4	1.3
Average		**43.9**				**68.9**		

* Insignificant or no heater use in both pre- and post-periods.
** Thermostat failure in post-period.

The tenant in building 14, unit 42 was asked about the bedroom heat use in the post-period where there was none in the pre-period. They said that they rarely used that bedroom and that the thermostat had not been adjusted after installation by the electrician. This bedroom was dropped from further analysis and considered an unheated room.

Energy Savings Analysis

Each of the remaining 19 sampled units received a separate energy savings analysis. For apartments where electric heat consumption was measured for more than one space in the unit, each space represented by the measurement data received a separate energy savings analysis. Savings were adjusted to account for differences in outdoor air temperature between pre- and post-periods. Savings were also extrapolated to the entire heating season to obtain annualized savings values.

..... Outdoor Air Temperature Adjustment and Annual Extrapolation

The average outdoor temperature in the post-period was about 2 degrees cooler than the pre-period. Therefore, it was necessary to adjust the consumption values to compensate for the difference. This was done using the procedure described below.

The five-minute and ten-minute kW data were averaged to hourly values. Since any annualized extrapolation would be based on hourly temperature data, it was necessary to work with hourly values.

Calculate annual pre-period and post-period heat consumption

Multiple linear regression was used to separately correlate the pre-and post-period hourly kW data with hourly outdoor air temperature, day of the week, and hour of the day. Based on these three correlations, it was determined which of the variables were significantly related to hourly kW (t-statistic greater than 1.96). If any of the three variables were not significantly related, the regression was repeated using only the significant variables.

A list of significant variables and the resulting R-squared values are included in the appendix. Typically, the R-squared correlation values were very poor. This indicates that kWh consumption is very difficult to clearly define in relationship with outdoor temperatures, or with a fixed time schedule. Other random factors, such as irregularly scheduled thermostat setback by the occupant, are likely confounding factors.

The resulting regression equations were used with Typical Meteorological Year (TMY) hourly outdoor temperature data for Seattle to calculate hourly electric heat consumption for each corresponding metered heat circuit.

Calculate annual energy savings:

Hourly savings were calculated by subtracting hourly post-period consumption from hourly pre-period consumption. Annual savings were calculated by summing the hourly savings values from October through May to reflect the heating season.

Phase 2 Findings

A separate analysis of annual energy savings for each sampled housing unit was performed. In addition, spaces within the units, such as bedrooms and living rooms, also received separate energy savings analysis when short term metering data supported that level of detail. The analysis include an adjustment for differences in outdoor air temperature between the pre-period and post-period. The energy savings analysis results were presented overall in the methodology section above. This section will present the results also as a function of characteristics that were defined by the sample.

Adjusted Annual Energy Savings

The annual energy savings resulting from the analysis described in the Energy Savings Analysis section are presented in Table 21. The table also includes previously presented unadjusted savings directly calculated from the metered data. A table comparing the pre-

period space heat consumption from the regressions and the billing data is provided in the appendix. In general, the predicted annual heat consumption is greater than the billing data analysis heat consumption for the previous year. This is likely a result of the low outdoor temperatures that were experienced during the study period. The resulting correlations likely did not capture enough moderate and warmer outdoor temperatures to accurately predict annual heat consumption.

Several different alternative correlations were tried which included nonlinear regression, time lag of space heat consumption to outdoor air temperature, and dropping data during periods of extreme low outdoor temperature. None of these improved the results.

As observed from the Table 21, annual energy savings for the whole apartments ranged from –2,154 to 2,733 kWh per year with an average value annual energy saving of eight kWh per year. The standard deviation of savings was 1,277 kWh per year. Values that were more than + or – two standard deviations from the mean were considered outliers. All savings values fell within two standard deviations; therefore no outliers were eliminated.

The lightly shaded rows in the table have regression results contrary to what makes sense with the temperature data. For example, one of the worst cases and most obvious illustrations is building 15, unit 16, where the bedroom temperatures are lower in the post-period by about 1.7 and 3.0 degrees during heater on time and by 0.5 and 1.1 degrees during heater off time. However the regression results shows a significant increase in heater consumption. Similar occurrences happen for 12 of the 35 regressions to various degrees. This is a result of correlating data without adequate variables to describe irregular use. Some residential occupants have unpredictable use schedules of space heat. They turn the heat up and down as they feel cold or warm and setback the temperature at different times of the day or night based on an unpredictable schedule of being home and/or when they go to bed. This is in contrast to commercial buildings that are on a regular schedule of use for heating/cooling systems. With commercial buildings, the heat consumption generally correlates very well with outside temperature, day of week and hour of the day due to the regular use schedule.

Table 21: Difference in Space Temperatures and Adjusted Annual Energy Savings, by Unit and Space, Phase 2

Building	Unit	Temperature Adjusted Annual kWh Savings	Space	Unadjusted Metered kWh Savings	Temperature Adjusted Annual kWh Savings	Delta T 'ON' (Pre - Post)	Delta T 'OFF' (Pre - Post)
13	103	-947	LR	553	-947	-2.0	-1.4
			BR1*	-8	0	-3.2	-0.7
			BR2**			missing	missing
14	11	-510	LR	152	928	-0.5	0.1
			BR1	-258	-1,438	-0.9	-7.4
			BR2			-4.0	-10.2
14	12	-2,154	LR	-67	-737	-1.6	-3.1
			BR1	-111	-1,417	-0.9	-1.6
			BR2			-4.2	-4.9
14	13	-1,042	LR	-39	-13	0.2	-1.0
			BR1	-209	-1,029	-0.5	-0.8
			BR2			-0.6	-0.9
14	16	-489	LR	-220	-985	-0.1	0.9
			BR1	103	496	-0.2	0.7
			BR2			1.7	0.6
14	17	346	LR	230	1,328	2.6	0.6
			BR1	-390	-982	0.0	1.0
			BR2			0.3	1.4
14	22	-111	LR	-18	-111	0.2	1.7
			BR1*	**0**	**0**		
			BR2*				
14	23	-1,432	LR	-31	783	-0.3	-2.3
			BR1	-391	-2,215	-3.2	-3.2
			BR2			-2.7	-4.2
14	36	-759	LR	91	-215	1.3	0.6
			BR1	5	-544	0.5	1.6
			BR2			2.0	1.3
14	42	2,733	LR	147	2,877	2.8	1.9
			BR1	-1	-144	2.6	1.3
			BR2*	-17	**0**		1.7
14	44	1,072	LR	-17	471	1.0	0.0
			BR1	73	601	4.3	1.3
			BR2*	**0**	**0**		0.2

Table 21 Difference in Space Temperatures and Adjusted Annual Energy Savings, by Unit and Space, Phase 2 (continued)

Building	Unit	Temperature Adjusted Annual kWh Savings	Space	Unadjusted Metered kWh Savings	Temperature Adjusted Annual kWh Savings	Delta T 'ON' (Pre - Post)	Delta T 'OFF' (Pre - Post)
15	16	1,088	LR	266	2,044	1.3	2.1
			BR1	-157	-956	1.7	0.5
			Bath			3.0	1.1
16	107	2,304	LR	3	-137	0.3	0.7
			Dine	515	2,339	0.9	0.1
			BR1**			missing	missing
			BR2	-85	102	1.5	-0.5
			BR3			1.9	0.2
16	210	-286.0	LR	-56	-401	1.0	0.7
			BR1	17.8	115.0	0.0	-0.5
			BR2			-0.9	-0.3
			Bath			0.5	-0.1
16	214	-810.0	LR	-58	-751	-0.5	0.3
			BR1	-0.9	-59.0	-0.5	0.0
			BR2			-2.3	-1.7
			Bath			-2.0	0.3
17	304	1,012	LR	139	1,795	3.7	1.8
			BR1	-171	-783	2.0	1.0
			BR2			1.9	2.4
18	4	-880	LR	-245	-752	1.5	1.3
			BR1**	-22	-128	missing	missing
18	301	1,314	LR	199	1,314	2.5	1.8
18	304	-304	LR	-114	-304	-1.0	-3.4
Average		**8**					
Std Dev		1,277					

* Insignificant or no heater use in both pre- and post-periods.
** Thermostat failure in post-period.

Adjusted Annual Energy Savings with Consistent Results

The adjusted annual energy savings for only the units that have consistency between the predicted savings and the reduction/increase in space temperature zones are presented in Table 22. Units with any values that were inconsistent, even if only one of two or three zones, were removed from the results.

As observed, only eight of the 19 units remain. Annual energy savings for the whole apartments ranged from –2,154 to 1314 kWh per year with an average annual increase in space heat of 420 kWh. This is consistent with an average increased space temperature of 0.5°F. All savings values fell within two standard deviations of the average; therefore no outliers were eliminated.

Table 22: Difference in Space Temperatures and Adjusted Annual Energy Savings, by Unit and Space, for Units with Consistent Results, Phase 2

Building	Unit	Temperature Adjusted Annual kWh Savings	Space	Unadjusted Metered kWh Savings	Temperature Adjusted Annual kWh Savings	Delta T 'ON' (Pre - Post)	Delta T 'OFF' (Pre - Post)
13	103	-947	LR	553	-947	-2.0	-1.4
			BR1*	-8	**0**	-3.2	-0.7
			BR2**			missing	missing
14	12	-2,154	LR	-67	-737	-1.6	-3.1
			BR1	-111	-1,417	-0.9	-1.6
			BR2			-4.2	-4.9
14	13	-1,042	LR	-39	-13	0.2	-1.0
			BR1	-209	-1,029	-0.5	-0.8
			BR2			-0.6	-0.9
14	16	-489	LR	-220	-985	-0.1	0.9
			BR1	103	496	-0.2	0.7
			BR2			1.7	0.6
14	44	1,072	LR	-17	471	1.0	0.0
			BR1	73	601	4.3	1.3
			BR2*	**0**	**0**		0.2
16	214	-810.0	LR	-58	-751	-0.5	0.3
			BR1	-0.9	-59.0	-0.5	0.0
			BR2			-2.3	-1.7
			Bath			-2.0	0.3
18	301	1,314	LR	199	1,314	2.5	1.8
18	304	-304	LR	-114	-304	-1.0	-3.4
Average		**1,139**				**-0.05**	**-0.07**
Std Dev		-420					

* Insignificant or no heater use in both pre- and post-periods.
** Thermostat failure in post-period.

Energy Savings by Characteristics Bin

The characteristics bins previously defined in the section on Subject Population Definition group the sample units by their physical and operational characteristics. Table 23 shows the savings results for the final eight units with the bin characteristics. As observed, all units

have large exterior exposure area. Five of the units have large floor areas and three have small floor areas.

Table 23: Bin Characteristics and Annual Energy Savings Estimates, Phase 2

Build-ing	Unit	Temperature-Adjusted Annual kWh Savings	Space	Temperature-Adjusted Annual kWh Savings	Weatherized?	Floor Area	External Exposure	Bin
13	103	-947	LR	-947	Wz	Sm	Ext	C
			BR1*	**0**				
			BR2*					
14	12	-2,154	LR	-737	Wz	Lg	Ext	A
			BR1	-1,417				
			BR2					
14	13	-1,042	LR	-13	Wz	Lg	Ext	A
			BR1	-1,029				
			BR2					
14	16	-489	LR	-985	Wz	Lg	Ext	A
			BR1	496				
			BR2					
14	44	1,072	LR	471	Wz	Lg	Ext	A
			BR1	601				
			BR2*	**0**				
16	214	-810.0	LR	-751	Wz	Lg	Ext	A
			BR1	-59.0				
			BR2					
			Bath					
18	301	1,314	LR	1,314	Wz	Lg	Ext	C
18	304	-304	LR	-304	Wz	Lg	Ext	C
		420		**Average**				

* Insignificant or no heater use in both pre- and post-periods.

Table 24 summarizes the energy savings by characteristic bin. It is difficult to draw any conclusions since the savings are dependent on the increase or decrease in space temperature as seen in Table 23. Further summaries of the results were deferred to the next section describing the combined Phase 1 and Phase 2 analysis.

Table 24: Energy Savings by Bin, Phase 2

Bin	Average kWh Savings	Sample Size
A	-685	5
B		
C	21	3
D		
Total		**8**

Phase 2 Conclusions and Recommendations

Conclusions

It is difficult to draw firm conclusions concerning energy savings resulting from installing vapor diaphragm thermostats in weatherized multifamily units based on the Phase 2 results. However, the following conclusions are offered.

- Overall annual energy consumption increased by 420 kWh. This value is based on an average overall increase in space temperature of 0.5°F during the post-period compared to the pre-period. This may be due to the colder post-period average outdoor temperature, which may have prompted tenants to keep their units slightly warmer.
- Based on post-period study tenant interviews, the average person could not distinguish a small change in average space temperature between the pre-and post-periods.
- Units with small exterior surfaces do not have significant heat consumption. No sample units in these categories were found in the recruiting process.
- The recommended changes in Phase 1 methodology significantly reduced data collection losses.
- It is more difficult to correlate and extrapolate annual heat consumption based on data collected during very cold periods.
- No thermostat failures occurred in the Phase 2 study.

Recommendations

The following recommendations are offered:

> *Instead of focusing on absolute savings for the sampled units in the study, the area of focus should be on determining the impact of thermostat set-point on space heat.*

This change in focus is appropriate primarily due to the comments from the post-period data collection tenant interviews that indicated respondents where not able to determine that they were maintaining the spaces at different average temperatures.

> *Tenant education should be a significant emphasis in thermostat use.*

It would be beneficial to have the new thermostats labeled such that the ideal temperature set-point, say 68°F is at the top center of the thermostat dial with an arrow or mark indicating the setting. This would indicate to people that this is the normal or best setting. It also provides the installer with an initial set-point. However, if an installer finds an old thermostat in the low or off position, the new thermostat should be set to the minimum position. Occupants may not know what temperature there old thermostat is set at because it may only have low to high labels or may be significantly out of calibration.

Combined Phases Analysis

Changing from Bimetal to Vapor Diaphragm Thermostats in Multifamily Units

Phase 1 and Phase 2 Combined Analysis

Based on the first recommendation in the previous section, the focus of the combined analysis is to determine the effect of space temperature on space heat consumption. Energy savings from the two phases was also examined.

Adjusted Annual Energy Savings

The values from Table 9 were further analyzed for inconsistencies between adjusted annual savings and space temperature differences between the pre-and post-periods. Four Phase 1 units were found to have either increased heat consumption with decreased space temperatures or decreased heat consumption with increased space temperatures. These four units were removed from the sample. Table 25 shows the results with only the remaining unit with consistent space temperature differences and savings.

As can be seen from the table the average energy savings is 195 kWh with a standard deviation of 1,152. Values that were more than + or – two standard deviations from the mean were considered outliers. All savings values fell within two standard deviations; therefore no outliers were eliminated.

Table 25: Difference in Space Temperatures and Adjusted Annual Energy Savings, by Unit and Space, for Units with Consistent Results, Phase 1

Building	Unit	Temperature Adjusted Annual kWh Savings	Space	Temperature Adjusted Annual kWh Savings	Delta T 'ON' (Pre - Post)	Delta T 'OFF' (Pre - Post)
1	A302	653	LR	653	1.2	-1.3
			BR1*	**0**		
1	A309	732	LR*	**0**		
			BR1	732	2.1	-0.2
			BR2		-2.2	-3.4
1	B102	-665	LR	225	0.9	-0.2
			BR1	-890	-3.4	-3.1
2	48	938	LR*	**0**		
			BR1	938	0.7	-0.2
			BR2		2.7	1.2
3	15	1,591	LR	1,591	0.8	0.7
3	30	-792	LR	-792	-0.1	0.0
3	32	1,073	LR	1,073	3.0	4.2
10	205	1,013	LR	806	2.4	2.1
			BR1	207	2.7	1.9
10	406	***-2,112***	LR	***-2,112***	-4.1	-1.3
			BR1*	**0**	1.0	-1.6
12	407	-483	LR	-483	-1.8	-1.7
			BR1		-1.7	-1.1
			BR2*	**0**	1.6	-1.0
Average		**195**			**0.3**	**-0.3**
Std Dev		1,152				

* Insignificant or no heater use in both pre- and post-periods.

Table 26 is a combination of results from Table 25and Table 24. This new table includes all units from both Phase 1 and 2 that have consistent energy savings and space temperature differences.

Table 26: Difference in Space Temperatures and Adjusted Annual Energy Savings, by Unit and Space, for Units with Consistent Results, Combined Phases

Building	Unit	Temperature Adjusted Annual kWh Savings	Space	Temperature Adjusted Annual kWh Savings	Delta T 'ON' (Pre - Post)	Delta T 'OFF' (Pre - Post)
1	A302	653	LR	653	1.2	-1.3
			BR1*	**0**		
1	A309	732	LR*	**0**		
			BR1	732	2.1	-0.2
			BR2		-2.2	-3.4
1	B102	-665	LR	225	0.9	-0.2
			BR1	-890	-3.4	-3.1
2	48	938	LR*	**0**		
			BR1	938	0.7	-0.2
			BR2		2.7	1.2
3	15	1,591	LR	1,591	0.8	0.7
3	30	-792	LR	-792	-0.1	0.0
3	32	1,073	LR	1,073	3.0	4.2
10	205	1,013	LR	806	2.4	2.1
			BR1	207	2.7	1.9
10	406	***-2,112***	LR	***-2,112***	-4.1	-1.3
			BR1*	**0**	1.0	-1.6
12	407	-483	LR	-483	-1.8	-1.7
			BR1		-1.7	-1.1
			BR2*	**0**	1.6	-1.0
13	103	-947	LR	-947	-2.0	-1.4
			BR1*	**0**	-3.2	-0.7
			BR2**		missing	missing
14	12	-2,154	LR	-737	-1.6	-3.1
			BR1	-1,417	-0.9	-1.6
			BR2		-4.2	-4.9
14	13	-1,042	LR	-13	0.2	-1.0
			BR1	-1,029	-0.5	-0.8
			BR2		-0.6	-0.9
14	16	-489	LR	-985	-0.1	0.9
			BR1	496	-0.2	0.7
			BR2		1.7	0.6
14	44	1,072	LR	471	1.0	0.0
			BR1	601	4.3	1.3
			BR2*	**0**		0.2
16	214	-810.0	LR	-751	-0.5	0.3
			BR1	-59.0	-0.5	0.0
			BR2		-2.3	-1.7
			Bath		-2.0	0.3
18	301	1,314	LR	1,314	2.5	1.8
18	304	-304	LR	-304	-1.0	-3.4
Average		**-78**			**-0.1**	**-0.5**
Std Dev		1,155				

* Insignificant or no heater use in both pre- and post-periods.
** Thermostat failure in post-period.

As observed from Table 26, annual energy savings for the whole apartments ranged from -2,154 to 1,591 kWh per year with an average value annual energy increase of 78 kWh per year. The average annual energy increase relates to an average space temperature increase of 0.1°F during periods that the heat was on and an average increase of 0.5°F when the heat was off. The standard deviation of savings was 1,155 kWh per year. All savings values fell within two standard deviations; therefore no outliers were eliminated.

The average space temperature difference, Delta T "off", is somewhat ambiguous because it is a measure of only the difference in space temperature while the heaters are off. This can be an indication of difference in the amount of temperature setback between pre-and post-periods based on how far the tenant turned the thermostat back when they left or went to bed. It can also be a function of how far the temperature drifted down when they turned it back based on how cold or warm the outside air temperature was. Therefore, it has limited value in determining actual differences in the amount of tenant setback.

Figure 4.A. shows the 18 unit's savings values in graphical form for visualization purposes.

Figure 4.A.: Adjusted Annual Energy Savings, Combined Phases

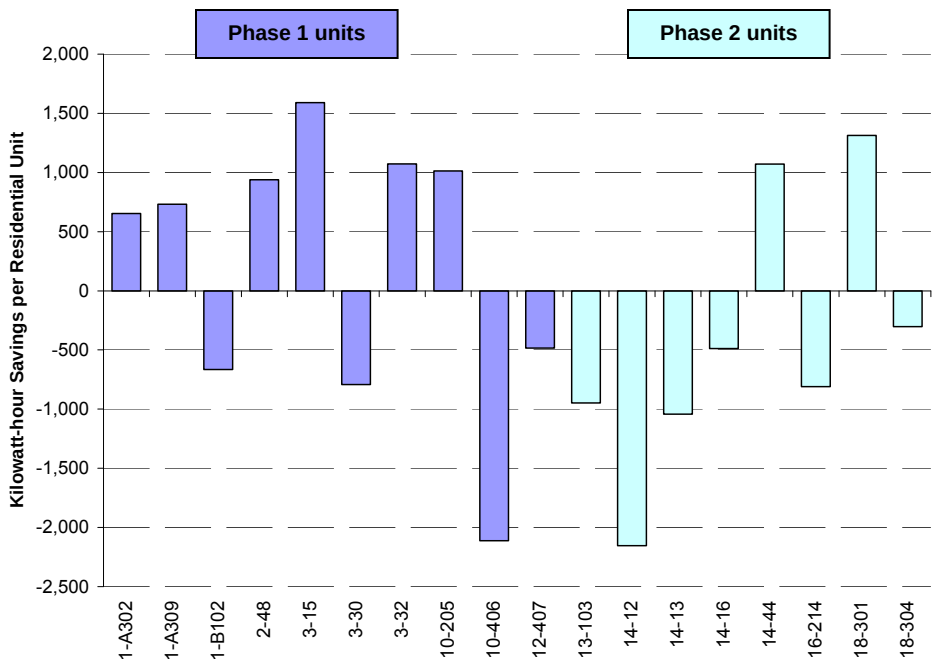
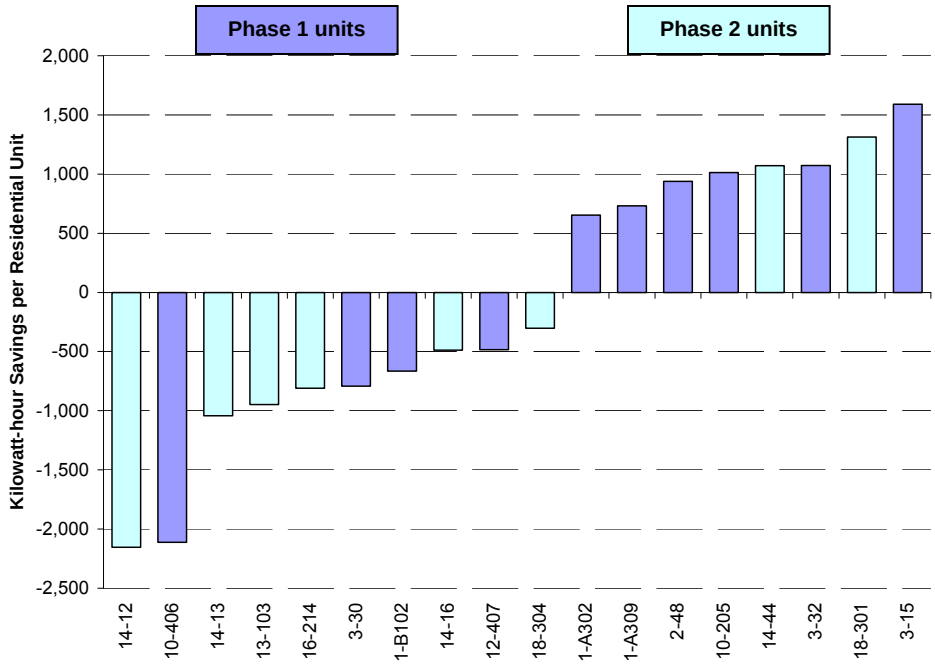


Figure 4.B.: Adjusted Annual Energy Savings, Combined Phases



Included in the appendix is a table showing the attrition of units for both study phases from the point of initial sampling pool identification to the final 18 units included in this section.

Energy Savings by Characteristics Bin

The adjusted annual savings are summarized by characteristics bin in Table 27. The summary table also shows the sample size for each characteristics bin. Values are presented for Phase 1, Phase 2 and the combined analysis. The table shows negative savings (increased space heat) for both the sampled bins in the combined study for weatherized buildings (bins A and C). The Phase 2 negative values in bin A offset the Phase 1 positive values, and the negative values in Phase 1 offset the positive Phase 2 savings values in bin C.

Table 27: Energy Savings by Bin, Combined Phases

Bin		Average kWh Savings			Sample Size		
Phase 1	Phase 2	Phase 1	Phase 2	Combined	Phase 1	Phase 2	Combined
1	A	938	-685	-280	1	5	8
2		128			2		
3	B						
4							
5	C	-2,112	21	-150	1	3	7
6		334			3		
7	D						
8							
9							
10							
11							
12							
13				624			3
14		-792			1		
15		1,332			2		
16							
Total					**10**	**8**	**18**

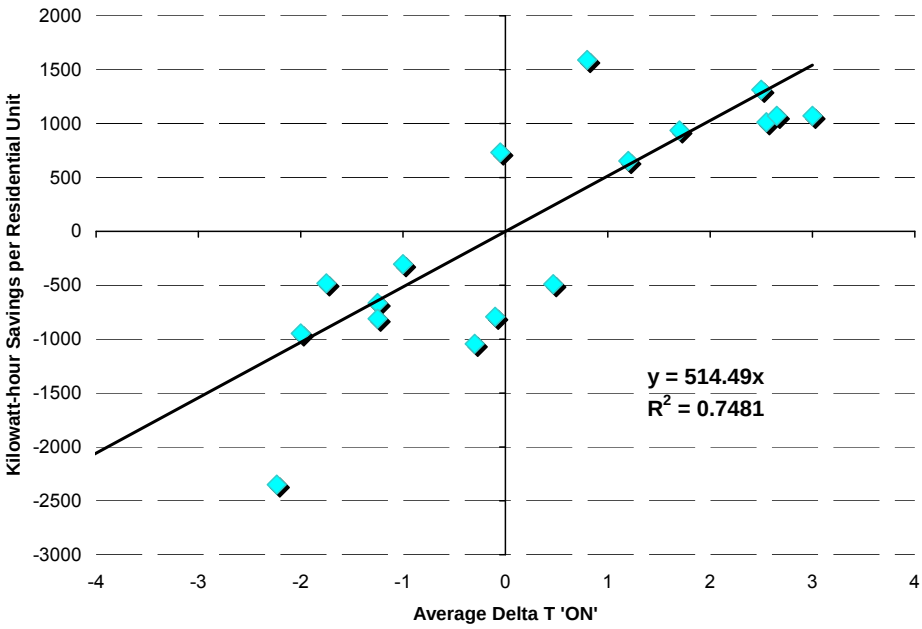
Space Heat Savings and Space Temperature Analysis

An important aspect of the data collected in the study is that the relationship between energy consumption and space temperature can be determined. This section provides that analysis and adjustments to best represent the data on a multifamily dwelling unit level.

..... Unit Savings Relationship to Space Temperature Change

As the space temperature is increased or decreased, the space heat consumption correspondingly increased or decreased. Using the Delta T "on" and the annual kWh savings values from Table 26, this relationship is shown in the Figure 5. The Delta T values are simple averages of all temperatures within the unit associated with space heat savings. The correlation line through the data has a good statistical fit with an R-squared of 0.748. The slope of the line shows that for every 1°F change in average room temperature, the annual space heat changes by 514 kWh.

Figure 5: Space Heat Energy Change as a Function of Space Temperature Change

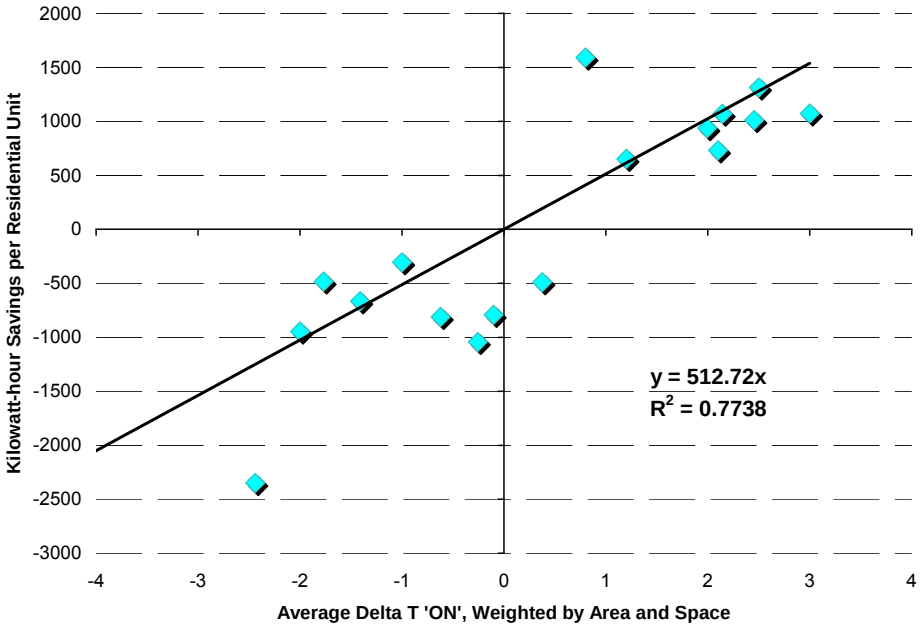


..... Unit Savings Relationship to Space Temperature Change Adjustments

Using the average space temperature change to represent the total unit savings introduces bias in the relationship because each space temperature represents a different sized unit and other factors such as different room temperatures based on occupant temperature preferences. To reduce the bias, the average temperature change values were weighted by approximate floor area of each space to normalize the unit size. The values were also weighted to the magnitude of the energy savings of each space to further normalize to other factors that effect energy savings such as the variations in preferred space temperature. A detailed table of the weighted average values is included in the appendix with a detailed description of the weighting process used.

The weighted values are shown in Figure 6. Even though the values are somewhat different due to the weighted averages, the results are almost the same (less than 1% different) as the correlation presented in the preceding section. The correlation line through the data has a good statistical fit with an R-squared of 0.774. The slope of the line shows that for every 1°F change in average room temperature, the annual space heat changes by 513 kWh.

Figure 6: Space Heat Energy Change as a Function of Space Temperature Change, Weighted by Area and Space



..... Unit Savings Relationship to Space Temperature Change by Weatherization Category

The weighted values shown in Figure 6 are shown separately in Figure 7 and Figure 8, by weatherized and non-weatherized categories. All the units in the weatherized category are in bins A and C, which are the large exposure characteristics bins. Only one small exposure unit occurred in Phase 1, which was eliminated because of conflicting temperature/savings correlation. No small exposure units were found in Phase 2.

As seen in the figures, the weatherized data show a good correlation with an R-squared of 0.830 and a sensitivity of 519 kWh savings per degree temperature change. The non-weatherized data have a much poorer correlation with an R-squared of 0.317 and a sensitivity of 474 kWh per degree temperature change. This is opposite to what is expected because the weatherized units should have a lower sensitivity to savings, due to more thermal integrity. However, the result is likely due to the low sample size in the non-weatherized category. Also, the weatherized units in Phase 2 of the study had significantly greater annual space heat consumption, based on the billing data analysis, than the non-weatherized units in Phase I. The non-weatherized category only has three data points

Figure 7: Space Heat Energy Change in Weatherized Units, as a Function of Space Temperature Change, Weighted by Area and Space

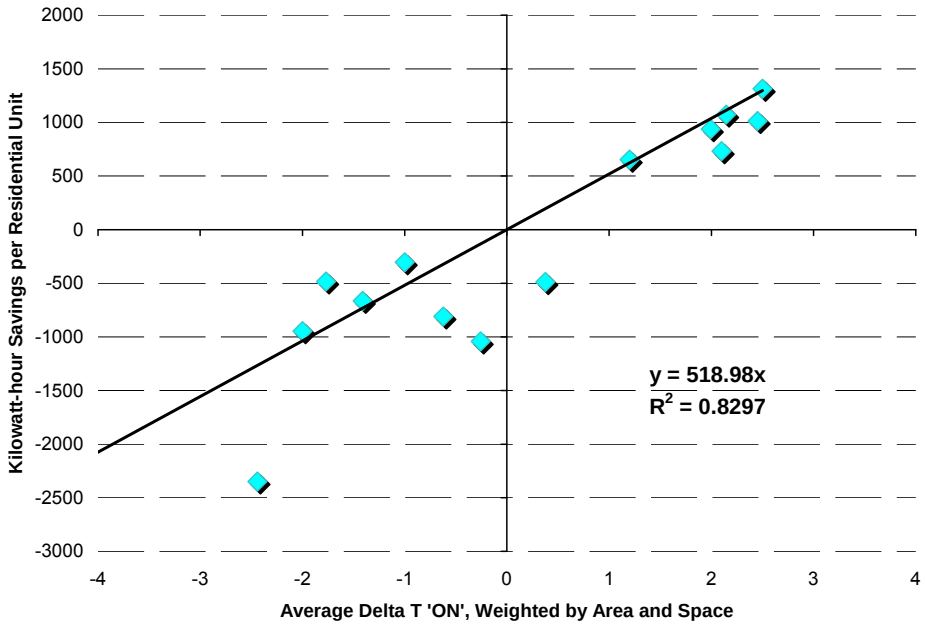
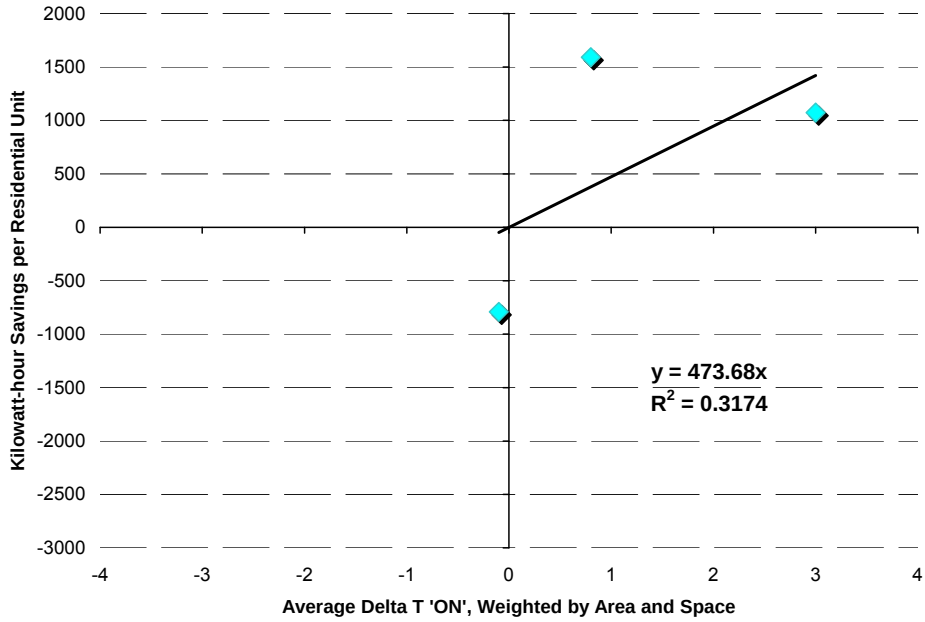


Figure 8: Space Heat Energy Change in Non-Weatherized Units, as a Function of Space Temperature Change, Weighted by Area and Space



Discussion, Conclusions and Recommendations

Discussion

It is difficult to draw firm conclusions regarding the amount of energy savings that can be achieved in multifamily units that are retrofitted from bimetal to vapor diaphragm thermostats. The study purposely instructed the tenants to use the new thermostats as they would the old ones. There was no mention about energy savings to the tenants, so that they would not be consciously or unconsciously trying to skew energy consumption. As a result, there was a large variation in unit energy savings. In general, when the occupants reduced the thermostat set-point temperature, energy consumption decrease and when they set the new thermostat higher, energy consumption increased. This is a similar result to the Lambert study that was conducted on apartment homes using electronic thermostats to replace bimetal thermostats. The Lambert study similarly instructed tenants that the study was to assess operation and acceptance of the new thermostats. As a result, some apartments experienced an increase in average temperature and some experienced a decrease.

Our study did show that if the new thermostats were set at a lower average temperature, then energy savings would be the result. For every degree drop in space temperature, annual space heat consumption will decrease by about 513 kWh. For the 18 units in the combined Phase 1 and Phase 2 analysis, the average annual electric consumption for space heat was about 3,780 kWh. This was roughly estimated from the utility bills, and a summary by unit is included in a table in the appendix. The resulting energy savings of 513 kWh per degree temperature drop then represents nearly 14% of annual space heat of the multifamily units. This is twice as much as conclude in the EPRI study. However, the EPRI results were based on single-family homes and were not screened to be significantly high space heat users. Across the entire population of multifamily units, the savings will be much closer to the EPRI result because many multifamily units have significantly smaller space heat consumption.

The Lambert study concluded that for the average decrease in space temperature of 0.88 degrees, that annual energy savings would be about 222 kWh per year. They did not screen the sampled units for high heat consumption as we did, so a lower savings value is expected. Again, across the population of multifamily units, the savings for both studies would likely be quite similar.

Conclusions and Observations

Conclusions regarding the hypotheses listed in the Phase 1 Introduction section are as follows.

> *Reducing the thermostat temperature setting results in savings of the expected magnitude. The expected magnitude is approximately seven percent of annual space heat for a one-degree reduction in temperature. Result: Confirmed.*

Multifamily units across the study showed a heat to space temperature relationship of 513 kWh per a one-degree change in temperature. Or, if the space temperature decreases by one degree, annual energy consumption decreases by 513 kWh. Sample size of the non-weatherized category was too small to accurately determine the variation between weatherized and non-weatherized categories. The energy savings for the study sample is

greater than the literature suggests, but is also expected to be greater due to the stratification of the sample to high space heat consumers.

> *Equivalent comfort can be achieved at lower temperature settings when hysteresis is reduced. Result: Confirmed.*

Most tenants can't distinguish a one or two degree difference in space temperature. There were many tenants that maintained a slightly higher space temperature in the post-period, and were unaware that there was a difference

> *Changing bimetal thermostats to vapor diaphragm thermostats, without re-sets, labeling, or tenant education, automatically results in energy savings. Result: Inconclusive.*

There was a large variation in results across the sampled units. This was due confirmation of hypothesis 2 above. Since the tenants could not tell if temperature were greater or less during the post-period, some slightly increased temperature and some slightly decreased temperature. This was also compounded since many tenants that did not have thermometers or temperature setting numbers on their old thermostats, and the ones that did may have been out of calibration. This emphasizes the need for an educational component to accompany the new thermostats.

The following observations were also made from combined Phase 1 and Phase 2 analysis:

- Overall, annual energy consumption increased by 78 kWh. This was accompanied by a 0.1°F increase of the average space temperature during the post-period compared to the pre-period.

- The Phase 2 units tended to have significantly greater space heat consumption based on the billing analysis. This may have also been a factor relating to the demographics of the sample. Although we did not collect demographic data, it was observed that the Phase 2 participants tended to be a higher income group. This is also reflected in that a significant number of Phase 2 units were condominiums, presumably owned by the occupant.

- Short-term measures of space heat in multifamily units are difficult to extrapolate to annual values. Establishing a relationship between space heat consumption and outdoor temperature and/or time factors, and extrapolation of annual space heat consumption, was particularly difficult in the Phase 2 units. There were instances of conflicting results in that space heat consumption would increase when the data showed a decrease in space temperatures, or the reverse condition. In the Phase 2 units, this may be due to very cold weather condition during the measurement periods. If there is not enough range in conditions, the extrapolation will not be accurate. This was also substantiated by the Phase 2 annual space heat extrapolation, which tended to be greater than the space heat for the previous year. Conflicting extrapolation data was removed from the sample.

Recommendations

The following recommendations are presented:

> *Energy savings will not be achieved from a thermostat replacement program unless the thermostat installation is accompanied by tenant education.*

- Tenants must understand that most people will not notice a small decrease in space temperature, and that the resulting energy savings can be significant for a small decrease in space temperature.

> *Without ongoing education, program savings will likely decrease or not occur with tenant turnover.*

- It may be advisable to place an educational sticker on the thermostat or mail an annual educational flyer to program participants.

References

Gregerson, Joan. 1997. "Advanced Line-Voltage Thermostats for Electric Resistance Heating." E-Source Tech Update TU-97-1, January 1997

Honeywell – Seattle City Light Interoffice Communication, April 18, 2006.

Lambert, Les. 1996. "Electronic Line Voltage Thermostats: A Worthwhile Retrofit for Baseboard Heat?" In Proceedings of the ACEEE 1996 Summer Study on Energy Efficiency on Buildings, 1:157-168. Washington, D.C.: American Council for an Energy-Efficient Economy.

Suggested Reading

Bobker, Michael, Da-Wei Huang and Daniel Harris. 2006. "The Parable of the Frog: Introducing New Temperature Regimes in Multifamily Housing." In Proceedings of the ACEEE 2006 Summer Study on Energy Efficiency on Buildings, 7:13-22. Washington, D.C.: American Council for an Energy-Efficient Economy.

Johnson, Russ, Dinesh Bhagani and Steven W. Carlson. 2000. "Measured Impact of Mechanical Thermostat Replacement." In Proceedings of the ACEEE 2000 Summer Study on Energy Efficiency on Buildings, 1:137-148. Washington, D.C.: American Council for an Energy-Efficient Economy.

Woods, James. 2006. "Fiddling with Thermostats: Energy Implications of Heating and Cooling Set Point Behavior." In Proceedings of the ACEEE 2006 Summer Study on Energy Efficiency on Buildings, 7:278-287. Washington, D.C.: American Council for an Energy-Efficient Economy.

Appendices

Appendix A. Vapor Diaphragm Thermostats

"Like bimetal thermostats, the vapor-filled diaphragm thermostat is an electromechanical technology. However, instead of using the bending motion of a bimetal strip to make and break the contact, this technology uses an expanding and contracting vapor-filled diaphragm. Its faster response to temperature changes can result in more frequent cycling than bimetal thermostats, which yields smaller temperature swings than bimetal thermostats (but not as small as for electronic models)." [3]

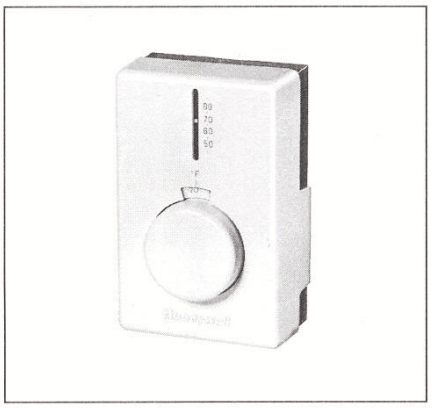
Honeywell manufactured the thermostats used in this study: model number T4398. Below are the manufacturer's product cut sheet and specifications.

[3] Honeywell – Seattle City Light Interoffice Communication, April 18, 2006.

Honeywell

T4398A,B High Performance Electric Heat Thermostats

PRODUCT DATA



FEATURES

- Controls both fan-forced and baseboard electric heaters.
- Temperature-responsive, vapor-filled dual diaphragm sensing element provides 2°F (1°C) sensitivity with minimum droop.
- UL listed up to 5 kW at 277 Vac.
- Replaces virtually all standard wall-mounted line voltage thermostats.
- Includes long-lasting Micro Switch™ mechanism.
- Color-coded leads for easy installation.
- Cover thermometer indicates room temperature.
- Rugged, plastic mounting base.
- Contemporary white finish complements almost any decor.

GENERAL

The T4398A,B High Performance Electric Heat Thermostats provide precise line voltage control of resistance-rated electric heating equipment. Snap action switch makes heating circuit on temperature fall; T4398B models make double line break with setting knob at OFF position.

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68-0147-2

T4398A,B HIGH PERFORMANCE ELECTRIC HEAT THERMOSTATS

SPECIFICATIONS

IMPORTANT

The Specifications given in this publication do not include normal manufacturing tolerances. Therefore, this unit may not exactly match the listed specifications. Also, this product is tested and calibrated under closely controlled conditions, and some minor differences in performance can be expected if those conditions are changed. For exact engineering specifications, contact your Honeywell sales representative.

TRADELINE® MODELS
TRADELINE models are selected and packaged to provide ease of stocking and handling and also maximum replacement value. TRADELINE model specifications are listed in Table 1.

Electrical Ratings (Noninductive Resistive Loads):
22A at 120/208/240 Vac; 19A at 277 Vac, 60 Hz.

Wiring Connections:
6 in. (150 mm) copper leadwires, suitable for connecting to aluminum wiring if approved special service CO/ALR connectors are used.

Sensing Element:
Vapor-filled dual diaphragm.

Temperature Setting Range:
50° to 80°F (10° to 25°C).

Thermometer Temperature Range:
50° to 90°F (10° to 30°C).

Differential:
2°F (1°C), nonadjustable.

Setpoint Adjustment:
Dial on front of thermostat.

Dimensions:
See Fig. 1.

Barometric Sensitivity:
1°F /500 ft (0.5°C/kPa).

Mounting:
Mount directly on vertical 2 x 4 in. outlet box, or on 4 x 4 in. outlet box with ring adapter (ordered separately), using 6-32 Robertson slotted screws.

Approvals:
Underwriters Laboratories Listed: File no. E47434, guide no. XAPX.
Canadian Standards Association Listed: File no. LR1322.

Accessories:
272804A Range Stop and Locking Screw Assembly: Includes locking cover screws, Tinnerman cilps, wrench and range stops—two plastic pins to insert inside cover for field-selection of minimum and maximum temperature settings.

Table 1. Thermostat Specifications.

Model Number	Switching	Temperature Rating °F (°C)	Finish	Includes
T4398A	Spst; makes single line break on temperature fall.	50 to 80 (10 to 25)	White	Cover thermometer, temperature range stops and locking cover.
T4398B	Dpst; makes double line break with setting knob at OFF position.	50 to 80 (10 to 25)	White	Cover thermometer, temperature range stops and locking cover.

..... About Thermostat Failures

During the Phase 1 study, two thermostats failures were observed. The failures should have been detected during installation, but were not detected until after the installer left the site. During the Phase 2 study, several more thermostats were found to be defective and not installed. All failed thermostats were returned to SCL. SCL returned the thermostats to the suppler with others that they found defective in the course of distributing thermostats during program implementation. Honeywell investigated the returned thermostats and issued a report of their findings.[4] The findings were shared with SCL. Honeywell acknowledged some manufacturing flaws, but assumed that most problems occurred from damage during recalibration at installation. However, based on the Phase 1 and Phase 2 study experience, the thermostats did not require field recalibration. Honeywell has now submitted a Power Point presentation and videos to their marketing department and sales reps for distribution with installers.

[4] Honeywell – Seattle City Light Interoffice Communication, April 18, 2006.

Appendix B. Resident Manager Interview

Multi-family Thermostat Study: Resident Manager Interview Questions

May I please speak with (INSERT CONTACT NAME)?

My name is [_____]. My company has a contract with Seattle City Light to help them with a metering project. The project manager at City Light has talked with your (building owner/property manager, INSERT NAME), who has given permission for us to do some metering in your building. (INSERT NAME) told us to contact you directly to make further arrangements.

What we will want to do is put some small metering devices in a few units of your building. A month from now we will install a new type of thermostat in those units. And a month after that, we will return to remove the metering devices. This is a project to test the performance the thermostats.

To see if any of the housing units in your building qualify for the project, we need to ask you a few questions about the building. Do you have 15 minutes to answer a few questions?

Yes [CONTINUE]

No [make an appointment for a more convenient time]

1. How long have you been the manager of this building? _____ (months/years)

2. We have a little information about your building, supplied by Seattle City Light, and we want to confirm some of these facts. How many buildings are in your complex? How many floors and housing units are in each building?

Building Number/Name	Number of floors	Number of housing units

3. Does your facility have laundries in the common area or in each unit? (common/in-unit)

4. Does your facility have interior hallways or do units enter directly from the outside? (interior hallways/exterior unit entries)

5. Are the units heated by electric baseboards? (yes/no)

   If not, what is the space heating type? _____

6. Are some or all of the housing units air-conditioned? (yes/no/partial)

   If partial, which buildings/floors/units are air-conditioned? _____

7. What is the floor area of the following specific housing units?

Unit number (from SCL records)	Floor area (sq ft)

Tenant change in last 3 months (from SCL records: yes/no)

8. Can you tell us what is the make and model number of the existing thermostats in the housing units? _____

Thank you for your time.

We will pass the information that you gave us on to the project manager at Seattle City Light. They will decide if we need to follow up on any of the housing units in your building. There are a few more steps we have to go through before project meters can be installed.

First, we will need to interview the tenants in the specific units we asked about. Based on their answers, we may need to take some preliminary measurements in their units. If they are interested in taking part in the project, and their unit qualifies based on the measurements, then we will make appointments to install the metering equipment for two months.

Half-way through the two months, we will return to replace the thermostats. At the end of the project we will remove the metering equipment. The new thermostat will be left in place unless the owner or tenant does not like its performance.

Seattle City Light has supplied us with telephone numbers for tenants in the specific units we asked about. Do you have any concerns about us contacting them directly, or would you rather talk with them first about the project? _____

(AS NEEDED: For the tenants in unit (UNIT #), City Light did not have a telephone number. What would be the best way to contact them? _____)

If you have any questions about this project, let me give you the business card for our project manager at Seattle City Light. (GIVE DEBRA TACHIBANA'S CARD)

Thanks again for your time.

Appendix C. Tenant Interview

Multi-family Thermostat Study: Tenant Interview Questions

May I please speak with (INSERT CONTACT NAME)?

My name is [_____]. My company has a contract with Seattle City Light to help them with a metering project. The project manager at City Light has talked with your (building owner/property manager, INSERT NAME), who has given permission for us to do some metering in your building. We have also talked with your on-site manger, (INSERT NAME).

What we will want to do is put some small metering devices in a few units of your building. To see if your housing unit qualifies for the project, we need to ask you a few questions about living in this unit. Do you have 15 minutes to answer a few questions?

Yes [CONTINUE]

No [make an appointment for a more convenient time]

1. We have a little information about your building and unit, supplied by Seattle City Light, and we want to confirm some of these facts. According to their records, you have had the account and lived in this unit during all of 2004. Is that correct? (yes/no)

2. Because this project will take place between now and the end of March, we need to ask: Will you be living in this unit for the next 3 months? (yes/no)

   (If no, end interview and thank them for their time.)

3. The records show that you live in unit (UNIT#). What floor is this on? _____

   Is this the top floor of the building? (yes/no)

   If not, is this the bottom floor? (yes/no)

   If you live on the bottom floor, is there parking below your unit? (yes/no)

4. How many of your walls are exposed to the outside? (1 / 2 / 3)

5. How many bedrooms do you have? (1 / 2 / 3/ 4)

6. City Light's metering project involves testing the thermostats in this building. For that reason, we need to ask a few questions about how you use the thermostat to control the space heat. What temperature do you set your thermostat to, when your heat is on? _____F or low/high

7. What hours of the day, and days of week, do you heat your unit to that temperature?

   _____

8. Do you set your thermostat back at night, or when you leave the unit? (yes/no)

   If yes, what is the setback temperature? _____F or low/high

If no, do you turn your heat all the way off at night or when you leave your unit? (yes/no)

9. Do you heat your entire unit? (yes/no)

   If no, what part of your floor area is not heated? ____% or rooms not heated _____

10. Do you use a portable air conditioner in the summer? (yes/no)

11. We need to ask one question about how many people live in your unit. That is because people of different ages sometimes need a different heat level. How many people live in your unit on a full time basis, by age group?

Child (0-18)	Adult	Senior (65+)

12. As we said at the beginning, your building owner has given City Light permission to install some small meters in this building. Would you be willing to do this in your unit for about 2 months? You must agree not to tamper with the equipment. It will be removed after the project is over. We may want to ask you a few more questions at the end of the project. (Yes/no)

    Thank you for your time.

    We will pass the information that you gave us on to the project manager at Seattle City Light. They will decide if we need to follow up on any of the housing units in your building.

    There is one more step we have to go through before the project meters could be installed. We need to visit you in the near future to test the thermostats in your unit. If your unit qualifies based on the measurements taken in that test, then your unit can take part in the metering project. In return for your permission and your help, City Light will provide you with $40 in gift-cards that you can use to shop at any Safeway store.

    The way the project works, we install some small meters in your electric panel (the circuit box). We also install temperature sensors near your thermostats. After about four weeks of measurements, we come back to install a new thermostat and continue our metering for an additional four weeks. At the end of the project we will remove the metering equipment. The new thermostat will be left in place unless you or the owner do not like its performance

    If your unit is selected for the metering project, after our test measurements, the City Light manager will send you a letter confirming these facts about the project.

    In the meantime, if you have any questions about this project, let me give you the telephone number for the project manager at Seattle City Light. Her name is Debra Tachibana, and her phone number is 206.684.3874.

Appendix D. Sampling Attrition

Table 28: Attrition of Dwelling Units, Phase 1 and Phase 2

Buildings	Units	
		Phase 1 Metering
12	436	Initial sampling pool
12	84	Full year tenancy and significant space heat
10	69	Owner/manager willing and able to join study
10	27	Tenant preliminary permission
10	26	Old thermostats tested
10	22	Suitably large hysteresis
7	18	Sites metered
7	14	Energy savings analyzed
5	10	Space temperature and energy usage correlated for Combined Phase report
		Phase 2 Metering
10	334	Initial sampling pool (excluding poor windows)
10	142	Full year tenancy and significant space heat
8	74	Owner/manager willing and able to join study
6	20	Tenant preliminary permission, old thermostats tested, suitably large hysteresis
6	20	Sites metered
4	8	Energy savings analyzed, space temperature and energy usage correlated
		Combined Phases Summary
13	38	Sites metered
9	18	Final energy savings analyzed for Combined report

Appendix E. Characteristics of Sampled Apartments

Table 29: Characteristics of Sampled Dwelling Units, Phase 1

		Survey							Bins					
Building	Unit	Thermostat Count	Top Floor?	Bottom Floor?	Exterior Walls	Bedrooms	Floor Area, sqft	Percent Heated	Weatheriz-ation	Floor Area	External Exposure	Heating Hours	Setback	Bin
1	A107	3	No	Bot.	2	2	1000	100	Wz	Lg	Ext	Hi	No	1
1	A302	2	Top	No	2+	1	500	67	Wz	Sm	Ext	Lo	Yes	6
1	A309	3	Top	No	1	2	1000	30	Wz	Lg	Ext	Lo	Yes	2
1	B102	2	No	Bot.	2	1	500	100	Wz	Sm	Ext	Lo	Yes	6
1	B303	2	Top	No	2	1	500	100	Not	Sm	Ext	Lo	Yes	14
1	A205	3	No	No	2	2	1000	100	Wz	Lg	Min	Hi	No	3
2	48	3	Top	No	2	2	908	65	Wz	Lg	Ext	Hi	No	1
2	61	2	Top	No	2	1	680	100	Wz	Sm	Ext	Hi	No	5
3	15	1	No	Bot.	1	0	505	100	Not	Sm	Min	Hi	No	15
3	10	1	No	Bot.	2	1	850	70	Not	Lg	Ext	Hi	No	9
3	32	1	Top	No	1	0	505	100	Not	Sm	Min	Hi	No	15
3	30	1	Top	No	2	1	710	100	Not	Sm	Ext	Lo	Yes	14
6	207	3	No	No	2	2	830	85	Not	Lg	Min	Lo	Yes	10
10	205	2	No	Bot.	2	1	640	100	Not	Sm	Min	Hi	No	6
10	404	3	Top	No	2	2	845	70	Wz	Lg	Ext	Lo	Yes	2
10	406	2	Top	No	2	1	845	65	Wz	Lg	Ext	Hi	No	5
11	503	3	Top	No	3	2	775	100	Not	Sm	Ext	Lo	Yes	14
12	407	3	Top	No	1	2	895	70	Wz	Lg	Ext	Lo	Yes	2

Table 30: Characteristics of Sampled Dwelling Units, Phase 2

		Survey							Bins					
Building	Unit	Thermostat Count	Top Floor?	Bottom Floor?	Exterior Walls	Bedrooms	Floor Area, sqft	Percent Heated	Weatheriz-ation	Floor Area	External Exposure	Heating Hours	Setback	Bin
13	103	3	No	Bot.	2	2	816	75	Wz	Sm	Min			C
14	11	3	No	Bot.	3	2	1165	100	Wz	Lg	Min			A
14	12	3	No	Bot.	3	2	1109	100	Wz	Lg	Min			A
14	13	3	No	Bot.	3	2	1253	100	Wz	Lg	Min			A
14	16	3	No	Bot.	3	2	1128	75	Wz	Lg	Min			A
14	17	3	No	Bot.	3	2	1350	100	Wz	Lg	Min			A
14	22	3	No	No	3	2	1109	67	Wz	Lg	Min			A
14	23	3	No	No	3	2	1269	75	Wz	Lg	Min			A
14	36	3	No	No	3	2	1128	67	Wz	Lg	Min			A
14	42	3	Top	No	3	2	1109	100	Wz	Lg	Min			A
14	44	3	Top	No	3	2	1082	100	Wz	Lg	Min			A
15	16	3	Top	No	3	2	700	100	Wz	Sm	Min			C
16	106													
16	107	5	No	No	3	2	1600	75	Wz	Lg	Min			A
16	210	4	No	No	3	2	1050	50	Wz	Lg	Min			A
16	214	4	No	No	3	2	910	50	Wz	Lg	Min			A
17	304	3	Top	No	3	2	1186	100	Wz	Lg	Min			A
18	4	2	No	Bot.	3	1	790	100	Wz	Sm	Min			C
18	301	1	Top	No	3	0	625	100	Wz	Sm	Min			C
18	304	1	Top	No	2	0	600	100	Wz	Sm	Min			C

Appendix F. Phase 1 Post-Measurement Survey Questions and *Responses*

..... Building 1, Unit A107:

General inquiry: Try to determine the extent of bedroom heaters making up for living room heater that did not function due to faulty thermostat.

Question 1: When the living room heater was not working, do you feel that you were able get a fair amount of heat from the bedrooms to make up for the living room heater not working?

> ***Response:*** *We left the bedroom doors open, but it did not heat the living room enough. We spent a lot more time in the bedrooms during that period.*

..... Building 1, Unit B102

General inquiry: Try to determine why the bedroom was kept 3.4°F warmer in the post-period than in the pre-period.

Question 1: Did you use the new thermostats any differently than the old thermostats?

Question 2: We noticed from the data loggers that the bedroom was heated about 3-1/2 degrees warmer with the new thermostat. Were you aware of any difference in room?

> ***Unable to reach respondent.***

..... Building 2, Unit 61

General inquiry: Try to determine the extent that the bedroom heater, which was stuck on at a high temperature, also contributed heat to the living room.

Question 1: Did it seem like a lot of heat from the bedroom would spill over into the living room to help keep it warm?

Question 2: Did you compensate the overheating of the bedroom be either opening the window or turning off the circuit breaker?

> ***Unable to reach respondent.***

.....Building 10, Unit 406:

General inquiry: Try to determine why the living room was kept 4.1°F warmer in the post-period than in the pre-period.

Question 1: Did you use the new thermostats any differently than the old thermostats?

Response: *No, I used them the same.*

Question 2: We noticed from the data loggers that the living room was heated about four degrees warmer with the new thermostat. Were you aware of any difference in room temperature?

Response: *No, it seemed the same to me.*

Question 1: When the electrician was changing the thermostat, he noticed that half of the living room heat was not working. Has the bad heater been changed?

Response: *No, and I don't want that one on. It is not needed.*

.....Building 11, Unit 503:

General inquiry: Try to determine why the living room was kept 2.5°F cooler in the post-period than in the pre-period.

Question 1: Did you use the new thermostats any differently than the old thermostats?

Response: *No, I used them the same.*

Question 2: We noticed from the data loggers that the living room was about two and a half degrees cooler with the new thermostat. Were you aware of any difference in room temperature?

Response: *No, it seemed the same to me. The weather was warmer, so the heat wasn't needed as much.*

.....Building 12, Unit 407:

General inquiry: Try to determine why the living room and one bedroom was kept about 1.7°F warmer in the post-period than in the pre-period.

Question 1: Did you use the new thermostats any differently than the old thermostats?

Response: *No, we used them the same.*

Question 2: We noticed from the data loggers that the living room and one bedroom were about two degrees warmer with the new thermostat. Were you aware of any difference in room temperature?

> ***Response:*** *No, it seemed the same to us. The bedroom heat was not used at all. The living room heater does the whole apartment. The weather was warmer so sometimes we would forget to turn the thermostat down when we left.*

Appendix G. Phase 2 Post-Measurement Survey Questions and *Responses*

..... Building 13, Unit 103:

General inquiry: Try to determine why the bedroom was kept 2.0°F warmer in the post-period than in the pre-period. Try to determine why the living room was kept 3.7°F warmer in the post-period than in the pre-period.

Question 1: Did you use the new thermostats any differently than the old thermostats?

> ***Response:*** *No, I used them the same.*

Question 2: We noticed from the data loggers that the bedroom was heated about 2 degrees warmer with the new thermostat. Were you aware of any difference in room temperature?

> ***Response:*** *No, it seemed about the same to me.*

Question 3: We noticed from the data loggers that the living room was heated about 3.7 degrees warmer with the new thermostat. Were you aware of any difference in room temperature?

> ***Response:*** *I didn't notice any difference.*

..... Building 14, Unit 11:

General inquiry: Try to determine why the south bedroom was kept 4.0°F warmer in the post-period than in the pre-period. South bedroom is the one with three exterior walls. Both bedrooms showed much less temperature variation during the post-period between on and off heater times.

Question 1: Did you use the new thermostats any differently than the old thermostats?

> ***Response:*** *No. Although in the living room, I set the old thermostat at about 63 degrees and the new one I had to set at about 68 to 70 to get the same comfort level.*

Question 2: We noticed from the data loggers that the south bedroom was heated about four degrees warmer with the new thermostat. Were you aware of any *difference in room temperature?*

> ***Response:*** *No, other than the grandsons were over for two days.*

Question 3: Did you turn the bedroom thermostat down at night or when you left with the old thermostat? With the new thermostat?

> ***Response:*** *Left them the same temperature all the time.*

.....Building 14, Unit 12:

General inquiry: Try to determine why the south bedroom was kept 4.0°F warmer in the post-period than in the pre-period. South bedroom is not the master bedroom.

Question 1: Did you use the new thermostats any differently than the old thermostats?

> ***Response:*** *No, I just set them so I stayed comfortable. The old ones I used to turn way up and them way down. With the new ones, I only turn them down a little when I leave and back up when I am home.*

Question 2: We noticed from the data loggers that the south bedroom (not the master bedroom) was heated about four degrees warmer with the new thermostat. Were you aware of any difference in room temperature?

> ***Response:*** *I don't use this room. I left it at the temperature that you set it at, but after a couple of week I went in and noticed it warm and turned it down.*

.....Building 14, Unit 22:

General inquiry: Try to determine why the living room was kept not setback in the post-period. There was no heat consumption in the bedrooms in either the pre-or post-periods.

Question 1: Did you use the new thermostats any differently than the old thermostats?

> ***Response:*** *No, the new one is set one or two degrees higher than the old one. It is hard to read the numbers on the new one.*

Question 2: Did you turn the thermostat down at night or when you left with the old thermostat? With the new thermostat?

> ***Response:*** *No. The living room is at about 65 degrees all the time and the bedrooms are at about 55 degrees all the time.*

.....Building 14, Unit 23:

General inquiry: Try to determine why the living room was kept not setback in the post-period. Also both bedrooms were about 3F warmer in the post-period.

Question 1: Did you use the new thermostats any differently than the old thermostats?

> ***Response:*** *No.*

Question 2: Did you turn the living room thermostat down at night or when you left with the old thermostat? With the new thermostat?

> ***Response:*** *No. Both the old and new living room thermostat I would turn down at night and up during the day.*

Question 3: We noticed from the data loggers that both bedrooms were heated about 3 degrees warmer with the new thermostat. Were you aware of any difference in room temperature?

> ***Response:*** *I kept the old master bedroom thermostat at the same temperature all the time. The new one I turn up at night and down during the day. The back bedroom I just leave low all the time.*

..... Building 14, Unit 42:

General inquiry: Try to determine why the unused bedroom had heat use in post-period but not in pre-period.

Question 1: We noticed that the unused bedroom had heater use with the new thermostat, but not with the old thermostat. Did you use the heat more with the new thermostat?

> ***Response:*** *That is mostly an unused room. I left it where you set it and have only been in the room a couple of times.*

..... Building 14, Unit 44:

General inquiry: Try to determine why the west bedroom was kept 4.0°F cooler in the post-period than in the pre-period. This bedroom is used as a den.

Question 1: Did you use the new thermostats any differently than the old thermostats?

> ***Response:*** *No, we always turn the thermostat down a few degrees when we leave or when we go to bed.*

Question 2: We noticed from the data loggers that the west bedroom, that you use as a den, was about four degrees cooler with the new thermostat. Were you aware of any difference in room temperature?

> ***Response:*** *No, we kept is set the same as always.*

.....Building 17, Unit 304

General inquiry: Try to determine why both bedrooms were kept 2.0°F cooler in the post-period than in the pre-period. Try to determine why the living room was kept 3.7°F cooler in the post-period than in the pre-period.

Question 1: Did you use the new thermostats any differently than the old thermostats?

Response: *No.*

Question 2: We noticed from the data loggers that both bedrooms were about 2 degrees cooler with the new thermostat. Were you aware of any difference in room temperature?

Response: *It took a couple of weeks, but I finally noticed that it was cooler and I then set the thermostat up a bit from the old thermostat setting.*

Question 3: We noticed from the data loggers that the living room was about 3.7 degrees cooler with the new thermostat. Were you aware of any difference in room temperature?

Response: *Same Response as to* **Question 2**.

Appendix H. Correlated Variables and R-squared Values

Table 31: Correlated Variables and Regression R-squared Values, Phase 1

			Pre-Period		Post-Period	
Building	**Unit**	**Space**	**Correlated Variables ***	**R^2**	**Correlated Variables**	**R^2**
1	A205	LR	OAT	0.092	OAT, Day of Week	0.116
		BR1 BR2	OAT, Hour of Day	0.070	OAT, Hour of Day	0.043
1	A302	LR	Day of Week, Hour of Day	0.093	OAT, Hour of Day	0.110
		BR1*				
1	A309	LR*				
		BR1 BR2	OAT, Hour of Day	0.088	OAT, Day of Week, Hour of Day	0.127
1	B102	LR	OAT, Hour of Day	0.029	OAT, Hour of Day	0.047
		BR1	OAT, Hour of Day	0.018	OAT, Hour of Day	0.139
2	48	LR	OAT, Hour of Day	0.114	OAT, Hour of Day	0.058
		BR1* BR2*				
3	15	LR	OAT, Hour of Day	0.508	OAT, Hour of Day	0.016
3	30	LR	OAT, Day of Week	0.066	OAT, Hour of Day	0.065
3	32	LR	OAT, Day of Week, Hour of Day	0.427	OAT, Day of Week, Hour of Day	0.066
6	207	LR BR1 BR2	OAT	0.016	OAT, Hour of Day	0.062
10	205	LR	OAT, Day of Week, Hour of Day	0.214	OAT, Day of Week, Hour of Day	0.329
		BR1	OAT, Day of Week, Hour of Day	0.099	OAT, Hour of Day	0.150
10	404	LR	OAT, Day of Week, Hour of Day	0.086	OAT, Hour of Day	0.035
		BR1* BR2*				
10	406	LR	OAT	0.088	OAT	0.067
		BR1*				
11	503	LR	OAT **	0.001	OAT	0.053
		BR1 BR2	OAT	0.012	OAT, Day of Week	0.038
12	407	LR BR1	OAT, Day of Week, Hour of Day	0.386	OAT, Hour of Day	0.074
		BR2	OAT, Hour of Day	0.070	OAT, Day of Week	0.013

OAT: Outside air temperature.

* Insignificant or no heater use in both pre- and post-periods.
** No variables were statistically related to kW for Building 11, Unit 503, Living room space.

Table 32: Correlated Variables and Regression R-squared Values, Phase 2

			Pre-Period		Post-Period	
Building	**Unit**	**Space**	**Correlated Variables ***	**R^2**	**Correlated Variables**	**R^2**
13	103	LR	OAT, Hour of Day	0.013	OAT, Day of Week	0.014
		BR1* BR2*				
4	11	LR	OAT, Hour of Day	0.150	OAT, Hour of Day, Day of Week	0.180
		BR1 BR2	OAT, Hour of Day	0.070	OAT, Hour of Day	0.186
14	12	LR	OAT, Hour of Day	0.017	OAT, Day of Week	0.201
		BR1 BR2	OAT, Hour of Day	0.077	OAT, Hour of Day, Day of Week	0.034
14	13	LR	OAT, Hour of Day	0.048	OAT, Hour of Day	0.233
		BR1 BR2	OAT	0.044	OAT, Hour of Day	0.272
14	16	LR	OAT, Hour of Day	0.069	OAT, Hour of Day	0.056
		BR1 BR2	OAT, Hour of Day, Day of Week	0.080	OAT, Hour of Day	0.099
14	17	LR	Hour of Day, Day of Week	0.034	OAT, Hour of Day, Day of Week	0.018
		BR1 BR2	OAT, Hour of Day	0.201	OAT, Hour of Day, Day of Weekl	0.225
14	22	LR	OAT	0.060	OAT	0.045
		BR1* BR2*				
14	23	LR	OAT	0.027	Hour of Day, Day of Week	0.056
		BR1 BR2	Hour of Day, Day of Week	0.032	OAT, Hour of Day, Day of Week	0.122
14	36	LR	OAT, Hour of Day	0.046	OAT, Hour of Day	0.062
		BR1 BR2	OAT, Hour of Day	0.046	OAT, Hour of Day	0.018
14	42	LR	OAT	0.061	OAT, Hour of Day	0.086
		BR1	OAT, Day of Week	0.003	OAT, Hour of Day, Day of Week	0.082
		BR2*				
14	44	LR	OAT, Hour of Day, Day of Week	0.132	OAT	0.184
		BR1	OAT, Day of Week	0.038	OAT	0.084
		BR2*				

OAT: Outside air temperature.

* Insignificant or no heater use in both pre- and post-periods.

Table 32: Correlated Variables and Regression R-squared Values, Phase 2, Continued

			Pre-Period		Post-Period	
Building	**Unit**	**Space**	**Correlated Variables ***	**R^2**	**Correlated Variables**	**R^2**
15	16	LR	OAT	0.022	OAT	0.038
		BR1 Bath	OAT, Hour of Day	0.028	OAT	0.086
16	107	LR	OAT, Hour of Day	0.067	OAT	0.004
		Dine BR1	OAT, Hour of Day, Day of Week	0.065	OAT, Hour of Day, Day of Week	0.033
		BR2 BR3	OAT, Hour of Day	0.178	OAT, Hour of Day, Day of Week	0.168
16	210	LR	OAT, Hour of Day	0.083	OAT	0.031
		BR1 BR2 Bath	OAT, Hour of Day	0.047	OAT	0.049
16	214	LR	OAT	0.110	OAT, Day of Week	0.067
		BR1 BR2 Bath	OAT, Hour of Day	0.075	OAT	0.005
17	304	LR	OAT, Hour of Day	0.039	OAT, Day of Week	0.035
		BR1 BR2	OAT	0.014	OAT, Hour of Day, Day of Week	0.063
18	4	LR	OAT, Day of Week	0.233	OAT, Day of Week	0.181
		BR1	OAT	0.044	Hour of Day	0.013
18	301	LR	Hour of Day	0.039	OAT, Hour of Day	0.027
18	304	LR	OAT, Day of Week	0.174	OAT, Day of Week	0.136

OAT: Outside air temperature.

* Insignificant or no heater use in both pre- and post-periods.

Appendix I. Estimated and Billing Space Heat Consumption

Table 33: Pre-Period Estimated and Billed Space Heat Consumption, Phase 1

Building	Unit	Estimated Annual kWh Heat	Space	Estimated Annual kWh Heat	Billed Annual kWh Heat	Billed – Estimated kWh Heat
1	A205	3,028	LR	5,245	3,781	–1,464
		2,217	BR1 BR2			
1	A302	2,726	LR	2,726	2,361	–365
		0	BR1			
1	A309	**0**	LR	1,221	1,942	721
		1,221	BR1 BR2			
1	B102	1,441	LR	2,132	2,503	371
		691	BR1			
2	48	**0**	LR	1,829	1,854	25
		1,829	BR1 BR2			
3	15	3,129	LR	3,129	2,597	–532
3	30	1,655	LR	1,655	3,039	1,384
3	32	2,790	LR	2,790	2,789	–1
6	207	1,749	LR BR1 BR2	1,749	2,578	829
10	205	3,066	LR	3,614	3,506	–108
		548	BR1			
10	404	3,672	LR	3,672	2,492	–1,180
		0	BR1 BR2			
10	406	333	LR	333	3,557	3,224
		0	BR1			
11	503	1,455	LR	1,952	2,961	1,009
		497	BR1 BR2			
12	407	3,630	LR BR1	3,630	3,890	260
		0	BR2			
Average				**2,548**	**2,846**	**298**
Std. Dev.				1,253	643	1,159
Average		**Adjusted ***		**2,719**	**2,792**	**73**
Std. Dev.				1,123	634	829

* Adjusted by excluding Building 10, Unit 405 (Bin 5)

Table 34: Pre-Period Estimated and Billed Space Heat Consumption, Phase 2

Building	Unit	Estimated Annual kWh Heat	Space	Estimated Annual kWh Heat	Billed Annual kWh Heat	Billed – Estimated kWh Heat
13	103	5,497	LR	5,497	3,131	–2,366
		0	BR1			
			BR2			
14	11	4,510	LR	6,099	4,714	–1,385
		1,589	BR1			
			BR2			
14	12	2,545	LR	4,208	2,795	–1,413
		1,663	BR1			
			BR2			
14	13	3,952	LR	6,726	8,392	1,666
		2,774	BR1			
			BR2			
14	16	2,261	LR	4,388	3,048	–1,340
		2,127	BR1			
			BR2			
14	17	6,125	LR	12,566	8,976	–3,590
		6,441	BR1			
			BR2			
14	22	4,847	LR	4,847	2,911	–1,936
		0	BR1			
			BR2			
14	23	6,102	LR	6,441	4,958	–1,483
		339	BR1			
			BR2			
14	36	1,799	LR	2,847	2,936	89
		1,048	BR1			
			BR2			
14	42	6,698	LR	7,709	4,768	–2,941
		1,011	BR1			
		0	BR2			
14	44	5,060	LR	6,490	3,411	–3,079
		1,430	BR1			
		0	BR2			

Table 34: Pre-Period Estimated and Billed Space Heat Consumption, Phase 2, Continued

Building	Unit	Estimated Annual kWh Heat	Space	Estimated Annual kWh Heat	Billed Annual kWh Heat	Billed – Estimated kWh Heat
15	16	3,049	LR	4,957	2,936	–2,021
		1,908	BR1 Bath			
16	107	1,181	LR	12,706	8,181	–4,525
		1,716	Dine BR1			
		9,809	BR2 BR3			
16	210	4,468	LR	4,804	2,919	–1,885.0
		336	BR1 BR2 Bath			
16	214	3,156	LR	3,448	2,926	–522.0
		292	BR1 BR2 Bath			
17	304	5,632	LR	6,107	3,861	–2,246
		475	BR1 BR2			
18	4	5,079	LR	5,367	4,914	–453
		288	BR1			
18	301	4,869	LR	4,869	3,404	–1,465
18	304	3,556	LR	3,556	3,102	–454
Average				**5,981**	**4,331**	**–1,650**
Std. Dev.				2,646	2,010	1,401

Appendix J. Weighted Average per Unit of Change in Space Temperature

This weighting technique is used to smooth the data and reduce bias related to variations in unit size (floor area) and other characteristics that impact energy savings such as occupant space temperature preference.

The Delta T "on" values in Table 26 were area weighted based on the area that they served in the unit. Bedrooms were assumed to have an average area of 144 square feet. Dining rooms were also assumed to have a floor area of 144 square feet. Bathrooms were assumed to be about 1/3 of a bedroom area, or 48 square feet.

The average room space temperature was also considered to determine if a room was unheated when more than one room was assigned to a single heat channel. If one of two rooms had a significantly lower space temperature than the other, it was assumed unheated. This was also used to assign energy savings to a room. There were always only one, two, or three spaces defined in the unit for area weighting. When two or three rooms were assigned to a single space, the average delta temperature of all heated rooms were used as the representative delta T for that space. An average delta T for the unit was then calculated using the representative area weighting.

Next, for each of the up to three spaces were assigned energy savings from Table 26. For conditions where a single savings value represent two rooms, the savings value was prorated to each of the single rooms by the delta T of each room. As an example if one room had a delta T of 1.0 degrees and the second room had a delta T of 2.0. The first room would be assigned a savings of 1/3 of the total for the two rooms, while the second room would get the remaining 2/3 of the savings. After the savings were assigned to each space, the average unit delta T was calculated as the savings weighted average.

Table 35: Unit Average Temperature Differences, Pre Minus Post (Delta T), Weighted by Floor Area and Temperature-adjusted Annual Energy Savings, Combined Phases

		Average ON Delta T			KWh Savings				Space Temperature Pre – Post			
Bldg	Unit	LR	BR1	BR2	LR	BR1	BR2	Unit Total Annual	Simple Average Δ T	Area Weighted Δ T	Savings Weighted Δ T	Average Weighted Δ T
1	A302	1.2	0.0	0.0	653	0	0	653	1.2	1.2	1.2	1.2
1	A309	0.0	2.1	-2.2	0	732	0	732	2.1	2.1	2.1	2.1
1	B102	0.9	-3.4	0.0	225	-890	0	-665	-1.3	0.1	-2.9	-1.4
2	48	0.0	0.7	2.7	0	193	745	938	1.7	1.7	2.3	2.0
3	15	0.8	0.0	0.0	1591	0	0	1591	0.8	0.8	0.8	0.8
3	30	-0.1	0.0	0.0	-792	0	0	-792	-0.1	-0.1	-0.1	-0.1
3	32	3.0	0.0	0.0	1073	0	0	1073	3.0	3.0	3.0	3.0
10	205	2.4	2.7	0.0	806	207	0	1013	2.6	2.4	2.5	2.5
10	406	-4.1	0.0	0.0	-2112	0	0	-2112	-4.1	-4.1	-4.1	-4.1
12	407	-1.8	-1.7	0.0	-248	-234	0	-483	-1.8	-1.8	-1.8	-1.8
13	103	-2.0	0.0	0.0	-947	0	0	-947	-2.0	-2.0	-2.0	-2.0
14	12	-1.6	-0.9	-4.2	-737	-250	-1361	-2348	-2.2	-1.8	-3.0	-2.4
14	13	0.2	-0.5	-0.6	-13	-514	-515	-1042	-0.3	0.0	-0.5	-0.3
14	16	-0.1	-0.2	1.7	-985	0	496	-489	0.5	0.1	0.6	0.4
14	44	1.0	4.3	0.0	471	601	0	1072	2.7	1.4	2.9	2.1
16	214	-0.5	-2.0	0.0	-751	-59	0	-810	-1.3	-0.6	-0.6	-0.6
18	301	2.5	0.0	0.0	1314	0	0	1314	2.5	2.5	2.5	2.5
18	304	-1.0	0.0	0.0	-304	0	0	-304	-1.0	-1.0	-1.0	-1.0

The two weighted average values were then averaged to determine the final area and savings weighted average delta T for the unit, which is what is shown in Figure 6. The table below shows the unweighted and weighted delta T values for the 18 units.

Table 36: Annual Space Heat Energy Consumption Estimated from Electric Bills, Combined Phases

Building	Unit	Billed Annual Heat, kWh
1	A302	2,361
1	A309	1,942
1	B102	2,503
2	48	1,854
3	15	2,597
3	30	3,039
3	32	2,789
10	205	3,506
10	406	3,557
12	407	3,890
13	103	3,131
14	12	2,795
14	13	8,392
14	16	3,048
14	44	3,411
16	214	2,926
17	304	3,861
18	301	3,404
18	304	3,102
Average		**3,786**

Appendix K. ACEEE 2008 Conference Paper

The Challenge of Vapor-diaphragm Thermostat Retrofits in Existing Multifamily Buildings

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..... ABSTRACT

Various space-heat thermostats have been proposed over the years by utilities and manufacturers as a potential source of space heat energy savings – including electronic line voltage, vapor diaphragm, and programmable models. The question remains, do thermostat retrofits generate actual energy savings – and if so, under what conditions?

This paper describes two phases of metering research conducted during the 2004-2005 and 2005-2006 heating seasons. The study was designed to confirm or dispel the following hypotheses: (1) reducing the thermostat temperature setting results in savings of about 7% of space heat for a 1ºF reduction in temperature; (2) equivalent comfort can be achieved at lower temperatures where hysteresis is reduced; and, (3) changing bimetal thermostats to vapor diaphragm thermostats, without thermostat pre-sets, labeling, or tenant education, automatically results in energy savings. The study focused on multifamily units having extensive external surface exposures and larger than average floor areas.

The first key finding was that, among selected units, annual energy consumption decreased by 513 kWh for each 1ºF decrease in the space temperature: nearly 14% of the annual space heat. The second finding was that equivalent comfort was in fact delivered by the reduced hysteresis and lower space temperatures. Findings on the third hypothesis were inconclusive, because tenants were not able to discern space temperature differences of 1-2ºF, and were not, without further education or product labeling, able reliably to set thermostats to the lower levels required for energy savings. The paper concludes with a discussion and recommendations for product research and program design.

Introduction

This study arose out of uncertainty about the energy impacts of residential space heat thermostat retrofits in multifamily housing units. Seattle City Light proposed residential thermostat replacements as an eligible measure in negotiations with the Bonneville Power Administration for a Conservation Augmentation contract in 2001. At that time Bonneville was not willing to allow this as an eligible measure for multifamily buildings. Since then, the Northwest Power and Conservation Council's Regional Technical Forum reviewed available data on energy savings from thermostat replacements and established deemed energy savings for a similar measure (electronic line voltage thermostats) under Bonneville's Conservation and Renewables Discount program, but only for single family homes. Existing research did not convincingly demonstrate energy savings for

thermostat replacements in multifamily buildings. There was no current research on vapor diaphragm thermostat replacements in multifamily buildings.

Based on the Regional Technical Forum endorsement of the measure in single-family homes, City Light approached Bonneville to ask if multifamily thermostat replacements would be accepted as an eligible measure under the existing Conservation Augmentation contract. Bonneville agreed to accept multifamily thermostat replacements if City Light could convincingly quantify the energy savings from this measure. This metering study is intended to help answer the question of what energy savings result from multifamily thermostat replacements.

This paper describes two phases of metering research conducted during the 2004-2005 and 2005-2006 heating seasons. The analysis focuses on a combined analysis of both phases and identifies differences between the two as appropriate. The paper concludes with a discussion and recommendations for product research and program design.

.....Objectives and Hypotheses

The purpose of this study was to investigate the performance of vapor-diaphragm thermostat retrofits in multifamily residential units. The study focused on multifamily units having extensive external surface exposures and larger than average floor areas, with the expectation that these had the greatest likelihood of demonstrating any possible impacts. The first phase of this study (winter 2004-2005) had three objectives. In the second phase (winter 2005-2006), objectives were added to confirm or dispel three hypotheses.

1. Energy Savings Objective. Evaluate energy savings from vapor diaphragm thermostats installed in multifamily residential units with electric baseboard space heat, located in the Seattle City Light service area.

2. Associated Characteristics Objective. Determine significant building and tenant characteristics that are major determinants of energy savings associated with installing vapor diaphragm thermostats to replace bimetal thermostats.

3. Proof of Concept Objective. Critique the “proof of concept” from the metering methodology, and offer recommendations regarding a Phase 2 round of additional metering study.

4. Thermostat Setback Hypothesis. Reducing the thermostat temperature setting results in savings of the expected magnitude, which is approximately seven percent (7%) of annual space heat for a one-degree (1ºF) reduction in temperature, based on reported savings for single-family housing.

5. Comfort Hypothesis. Equivalent comfort can be achieved at lower temperature settings when hysteresis is reduced.

6. Thermostat Retrofit Hypothesis. Changing bimetal thermostats to vapor diaphragm thermostats, without thermostat pre-sets, labeling, or tenant education, automatically results in energy savings.

..... Theory: How Vapor Diaphragm Thermostats Save Energy

Vapor diaphragm thermostats maintain the temperature in the space closer to the set temperature on the dial (smaller hysteresis) than do bimetal thermostats. The hysteresis, also known as dead-band, refers to the temperature difference range between a thermostat coming on and shutting off (or conversely the range between shutting off and coming on). Typically the hysteresis of a vapor diaphragm thermostat is about 2°F as opposed to a bimetal thermostat at 5°F or above. Occupants can achieve the same or better comfort levels than before while setting the thermostat to a lower average temperature. This action saves space-heating energy. By lowering the thermostat set-point, the same level of comfort can be achieved.

Most of Seattle's multifamily housing units have electric resistance space heat, which was the lowest-first-cost choice for builders. Baseboard and radiant heaters allow for zonal heating with independent thermostats, which can save energy when unoccupied rooms have lower temperature settings or are operated fewer hours. It is believed that occupants often set thermostats higher than the desired average temperature in order to avoid extended cool periods during times between heater on-cycles, causing the room at times to overheat. It is difficult for traditional bimetallic thermostats to maintain near-constant temperatures in these systems.

Newer design vapor diaphragm and line voltage thermostats offer more precise temperature control than conventional bimetal thermostats. The more accurate calibration and more frequent duty cycles yield increased comfort for occupants. The basis for replacing space-heat thermostats is achieving a tighter 'dead-band' and avoiding excessive temperature 'droop'.

Dead-band (also known as hysteresis) is the difference between the temperatures at which the heater switches off or on. Bimetallic thermostats typically cycle on and off every 90 minutes, have a dead-band of about 5°F, and a droop of about 5°F. Droop occurs when heat builds up from the current passing through wires inside the thermostat. A sensor not insulated from this build-up turns off the heater too soon. Occupants can become uncomfortable from excessive droop, because ambient temperatures do not rise to the expected level. They can also become uncomfortable from a wide dead-band, which leaves the heater off too long between duty cycles and allows the space to cool excessively before re-warming.

Vapor diaphragm and electronic line voltage thermostats have a narrower dead-band, around 2°F, and a commensurately smaller droop of about 2°F. These thermostats come on and off more frequently, responding to smaller changes in room temperature, often operating in 10-15-minute cycles. Thermodynamically, these thermostats by themselves do not save more energy over the bimetallic type. However, occupants can achieve the same or better comfort levels than before while setting the thermostat to a lower average temperature. By lowering the thermostat set-point, space heating is saved and the same level of comfort is achieved. Room temperatures do not need to swing as high as before, while the low point of the cycle remains the same. If the thermostat were set down by

only 1ºF on average, energy savings could be about 7% of space heating; and if by 2ºF , savings could be about 14% (EPRI 1994; E Source 1997; Johnson et al. 2000).

Methodology

The study team investigated energy impacts of replacement thermostats by conducting metering research over two winter seasons, supplemented by tenant interviews. Basic characteristics were collected for 22 candidate multifamily buildings: 12 in Phase 1 and 10 in Phase2. Characteristics included year built, floor area, number of living units, energy efficiency upgrade history and bimonthly electric billing histories for each unit. The billing histories were screened to identify units with significant heating energy consumption, resulting in the identification for the study of 418 candidate apartments: 84 in Phase 1 and 334 in Phase 2. A characteristics binning strategy for Phase 1 was defined and included two divisions for each of the four categories of weatherization, floor area, exterior surface exposure and occupant behavior of heater operating hours. The binning strategy included 16 characteristics bin combinations. The binning strategy was modified for Phase 2 to include two divisions for each of two categories on floor area and exterior surface exposure for only one weatherization category. The Phase 2 strategy included four characteristic bin combinations.

.....Baseline Data Collection and Final Sample Selection

Interviews were performed with each of the twenty-two resident managers to verify previously identified characteristics and supplement additional characteristics to further categorize the candidate units into the characteristics bins. Residents were also interviewed for recruitment into the study and to obtain further characteristics. The units recruited were also screened by testing the thermostat to verify significant hysteresis in operation of the existing bimetal thermostat. Eighteen units were ultimately recruited for the Phase 1 study. Table 1 summarizes the distribution across the characteristics bins. The investigators decided to delete heating hours from the binning strategy for Phase 2. This factor is tenant behavior dependent and not available for population extrapolation. Twenty units were recruited for the Phase 2 study and are summarized in Table 2 across the characteristic bins.

Table 1. Final Sample Selection, Phase 1

Bin	Weatherization	Floor Area	External Exposure	Heating Hours	
1			Extensive	High	2
2		Large	5	Low	3
3			Minimal	High	1
4	Weatherized	6	1	Low	0
5			Extensive	High	2
6		Small	5	Low	3
7			Minimal	High	0
8	11	5	0	Low	0
9			Extensive	High	1
10		Large	2	Low	1
11			Minimal	High	0
12	Not Weatherized	2	0	Low	0
13			Extensive	High	0
14		Small	3	Low	3
15			Minimal	High	2
16	7	5	2	Low	0
Cases	18	18	18		18

Table 2. Final Sample Selection, Phase 2

Bin	Weatherization	Floor Area	External Exposure	
A		Large	Extensive	14
B	Weatherized	15	Minimal	1
C		Small	Extensive	5
D	20	5	Minimal	0
Cases	20	20		20

..... Test Equipment and Procedure

A device was developed for hysteresis testing of wall-mounted thermostats. It consisted of a transparent plastic container with dimensions of about 12 inches by 6 inches by 4-1/2 inches. Two sealable ventilation holes were cut in it. A small fan was installed to circulate air around the thermostat. An air temperature sensor was included to measure the air temperature around the thermostat during testing. And, a switched light bulb was mounted inside as a heat source. The following steps were used in testing the hysteresis of the thermostats:

1. The thermostat was turned up, if off, until it clicked on.
2. The test equipment was held in place against the wall covering the thermostat and remained there until the test was completed.
3. The fan was turned on and remained on until the test was completed.

4. The air vents in the device were closed and the light was switched on. This heated the air circulating around the thermostat in the small enclosed space.

5. When the thermostat clicked off from the heated air in the device, the air temperature was noted.

6. The light bulb was switched off and the air vents opened. This allowed the air in the device to cool down to room temperature.

7. When the thermostat clicked on, again the air temperature in the device was noted.

8. The cycle was repeated several times until the readings provided consistent on and off temperatures.

9. The difference between the off and on temperatures was considered a strong indicator of the thermostat hysteresis.

.....Interpreting Hysteresis Test Results

The hysteresis testing device did not provide an exact measurement of the actual thermostat hysteresis; however, it did provide a relative indication of thermostat performance. The test repeatedly showed an off-on temperature difference of about 6°F for the new vapor diaphragm thermostats that were rated at a hysteresis of 2°F. Therefore, only test results on bimetal thermostats with temperature difference values greater than 15°F in the study were accepted. Most bimetal thermostats tested with this device resulted in temperature differences in excess of 20°F. In all, thermostats were tested in 26 units (57 total thermostats), of which 22 were determined to have large hysteresis for all thermostats. Of the 57 total thermostats tested, four were determined to have small hysteresis. This resulted in 93% of bimetal thermostats tested to have significantly large hysteresis.

.....Detailed On-Site Measurement Using Data Loggers

Ampere loggers were installed on up to two heat circuits in each the sampled units (up to three circuits in Phase 2). Temperature loggers were installed at each bimetal thermostat that was to be replaced with a vapor diaphragm thermostat. One temperature logger was installed to obtain outdoor air temperature at each building. The metering equipment remained in place for four weeks, then the thermostats were replaced and an additional four weeks of data were collected. All data channels were downloaded and analyzed. Anomalous data were identified and specific questions were generated to ask the tenants for possible explanation of anomalies. Some tenants were unreachable. The tenants interviewed indicated consistent use of both thermostats and were unaware of pre-post temperature differences observed in the data.

Phase 1 Data Collection. Two units were dropped from the sample: one due to significant logger data loss and one due to vacating the unit shortly after the thermostat was retrofitted. Two other units experienced thermostat mechanical failures, which resulted in half the electric heat logger data (one of two channels) being invalid for the failed

thermostats. These units were eventually dropped because the failed thermostats affected the operation of the remaining thermostats in the units. General observations of the data included: two living rooms and five bedrooms had insignificant heater use in both the pre- and post-periods; post-period outdoor temperature was about 5ºF warmer than pre-period outdoor temperature; 17 thermostats had a lower post-period average temperature when the heat was on; and, 11 thermostats had a higher post-period average temperature when the heat was on. During intervals when the thermostat was "on", the space was 0.4ºF cooler in the post- than in the pre-period. When it was "off", the space was 0.3ºF warmer in the post- than in the pre-period. The average observed space temperature was 70 ºF.

Phase 2 Data Collection. One unit was dropped from the sample because it had very low heat consumption. It was erroneously identified as a high space heat consumption unit due to anomalies in the billing data. General observations included: six bedrooms had insignificant heater use in both the pre- and post-periods; post-period outdoor temperature was about 2 ºF degrees cooler than the pre-period outdoor temperature; 26 thermostats had a lower post-period average temperature when the heat was on: and, 20 thermostats had a *higher* post-period average temperature when the heat was on. During intervals when the thermostat was "on", the space was 0.2ºF warmer in the post- than in the pre-period. When it was "off", the space was 0.8ºF warmer in the post- than in the pre-period. The average observed space temperature was 69 ºF.

Findings

The energy savings analysis included the three primary tasks of performing a regression analysis, adjusting the data for pre-post outdoor temperature differences and extrapolating the energy savings to an annual basis. The metered data were used to correlate hourly kW heat to outside air temperature for both the pre- and post-periods. The correlations were then applied to Typical Meteorological Data (TMY) hour temperature data to extrapolate pre- and post-consumption to the entire heating season. Anomalous data, which included units where space heat increased at the same time space temperatures decreased (and the reverse condition), were eliminated from the sample.

The data were further analyzed for inconsistencies between adjusted annual savings and space temperature differences between the pre-and post-periods. Four Phase 1 units were found to have either increased heat consumption with decreased space temperatures or decreased heat consumption with increased space temperatures. These four units were removed from the sample. This left 18 units from the combined research phases for analysis of energy savings.

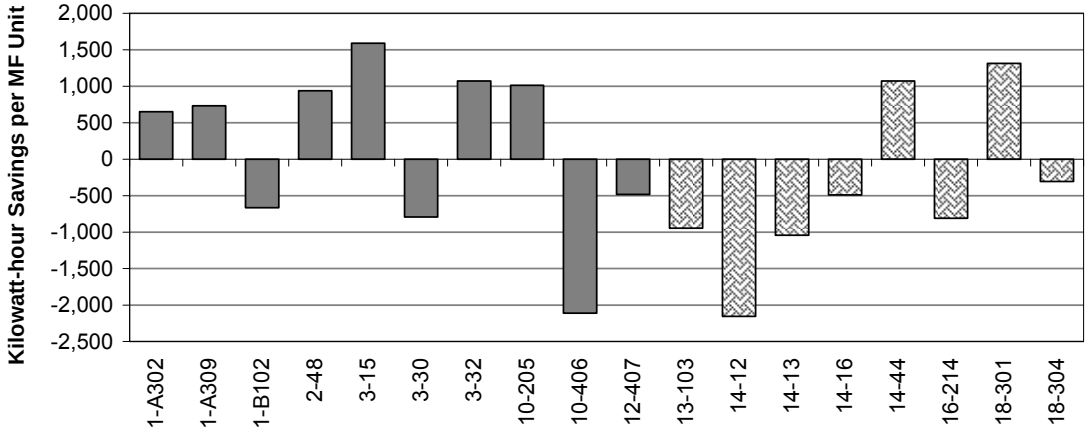
The average energy savings were 195 kWh with a standard deviation of 1,152. Values that were more than + or – two standard deviations from the mean were considered outliers. All savings values fell within two standard deviations; therefore no outliers were eliminated.

Annual energy savings for the whole apartments ranged from -2,154 to 1,591 kWh per year with an average value annual energy increase of 78 kWh per year (see Figure 1). The average annual energy increase relates to an average space temperature increase of 0.1°F during periods that the heat was on and an average increase of 0.5°F when the heat

was off. The standard deviation of savings was 1,155 kWh per year. All savings values fell within two standard deviations; therefore no outliers were eliminated.

The average space temperature difference, Delta T "off", is somewhat ambiguous because it is a measure of only the difference in space temperature while the heaters are off. This can be an indication of difference in the amount of temperature setback between pre-and post-periods based on how far the tenant turned the thermostat back when they left or went to bed. It can also be a function of how far the temperature drifted down when they turned it back based on how cold or warm the outside air temperature was. Therefore, it has limited value in determining actual differences in the amount of tenant setback

Figure 1. Adjusted Annual Energy Savings, Combined Phases



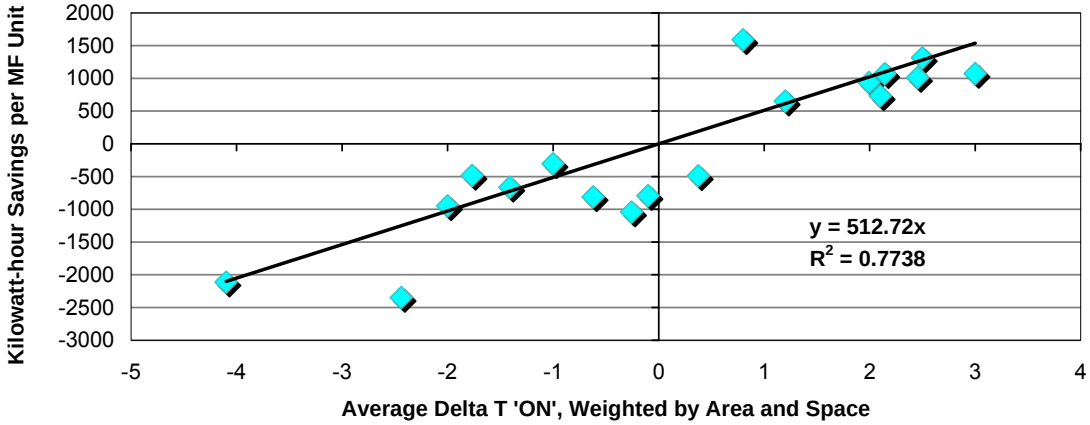
.....Space Heat Savings and Space Temperature Analysis

An important aspect of the data collected in the study is that the relationship between energy consumption and space temperature can be determined. This section provides that analysis and adjustments to best represent the data on a multifamily dwelling unit level.

As the space temperature was increased or decreased, the space heat consumption correspondingly increased or decreased. Using the Delta T "on" and the annual kWh savings, this relationship was plotted in a figure (not shown) similar to Figure 2. The Delta T values were simple averages of all temperatures within the unit associated with space heat savings. The original correlation line through the data had a good statistical fit with an R-squared of 0.748. The slope of the line showed that for every 1°F change in average room temperature, the annual space heat changed by 514 kWh.

Using the average space temperature change to represent the total unit savings introduces bias in the relationship because each space temperature represents a different sized unit and other factors such as different room temperatures based on occupant temperature preferences. To reduce the bias, the average temperature change values were weighted by approximate floor area of each space to normalize the unit size. The values were also weighted to the magnitude of the energy savings of each space to further normalize to other factors that effect energy savings such as the variations in preferred space temperature.

Figure 2. Space Heat Energy Changes as a Function of Space Temperature Change, Weighted by Area and Space



Even though the values are somewhat different due to the weighted averages, the results shown in Figure 2 are almost the same as (less than 1% different from) the correlation previously described. The figure summarizes the data to illustrate the relationship between change in space temperature and impact on energy consumption. The slope of the correlation line indicates the sensitivity of the relationship. The correlation line through the data has a good statistical fit with an R-squared of 0.774. The slope of the line shows that for every 1°F change in average room temperature, the annual space heat changes by 513 kWh.

Conclusions

It is difficult to draw firm conclusions concerning energy savings resulting from installing vapor diaphragm thermostats in weatherized multifamily units, based on the Phase 1 and Phase 2 results. However, the following conclusions are offered.

> ***Energy Savings Objective.*** *Phase 1 of the study proved the concept of energy savings from replacing bimetal thermostats with vapor diaphragm thermostats.*

Overall energy savings per multifamily housing unit fell within the range of 166 to 342 kWh per year as a result of replacing bimetal thermostats with vapor diaphragm thermostats. This represents 6-12% of the November-April space heat. Given the expectation of 7% savings from every 1°F drop in average thermostat temperature settings, this would imply a 1-2°F drop in those settings. The average temperature reading taken near those thermostats only changed by 0.5 degrees. However, this does not necessary equate to the same change in thermostat settings because the average observed values include significant heat-off hours for those cases where more than one thermostat was associated with the heating circuit.

It should be noted that, in Phase 2, overall post-period annual energy consumption increased by 420 kWh over the pre-period. This value is based on an average overall increase in space temperature of 0.5°F during the post-period compared to the pre-period.

This may be due to the colder post-period average outdoor temperature, which may have prompted tenants to keep their units slightly warmer.

The following observations were also made from combined Phase 1 and Phase 2 analysis. Across both phases of the study, annual energy consumption increased by 78 kWh after installation of the vapor diaphragm thermostat. This was accompanied by a 0.1°F increase of the average space temperature during the post-period compared to the pre-period. The Phase 2 units tended to have significantly greater space heat consumption based on the billing analysis. This may have also been a factor relating to the demographics of the sample. Although we did not collect demographic data from tenants, investigators observed that the Phase 2 participants tended to be a higher income group. This is also reflected by the significant number of Phase 2 units that were condominiums, presumably owner-occupied.

> ***Associated Characteristics Objective.*** *Phase 1 energy savings were greater in units that had not been weatherized, in units with larger floor areas, in units with more extensive exterior exposure, in units where the occupants do not set back the thermostats at night or when they leave the unit, and in living room spaces within units.*

Energy savings were significantly greater in units that had not been weatherized. Savings in these units are on the order of about 650 kWh per year. Energy savings in weatherized units were more uncertain and fell in the range of about -100 (increased energy use) to +150 kWh per year. However, it appears likely that the savings value is closer to the 150 kWh per year value.

Units with larger floor areas use more space heat so the vapor diaphragm thermostat provided greater energy savings. They also require more thermostats because the units are larger, due to more bedrooms.

Units with more exterior surface area resulted in greater energy savings from the thermostat retrofit. Units with small exterior surfaces do not have significant heat consumption. No sample units in the small-surface categories were found in the recruiting process.

Vapor diaphragm thermostats installed in living room spaces saved more energy than thermostats installed in bedroom spaces.

Units where the occupants do not set back the thermostats at night or when they leave the unit resulted in greater energy savings from thermostat retrofit. This follows from the higher baseline energy use, due to not setting back temperatures.

This last point is useful information in support of tenant education. It should be emphasized that occupants reduced the thermostat setting as much as was comfortable, and that setting back the thermostat when they are away or at night would save even more energy.

> ***Proof of Concept Objective.*** *Phase 1 of the study proved the methodology for determining savings. The hysteresis testing methodology developed for the study was successfully implemented. The tests resulted in determining that 93% (54 of 57) bimetal thermostats tested had significantly larger hysteresis than the vapor diaphragm thermostats.*

Minor changes in the methodology from Phase 1 were implemented in Phase 2 to reduce data loss and contain study costs. These steps significantly reduced data collection problems; no thermostat failures occurred in Phase 2. However, investigators found that it is more difficult to correlate and extrapolate annual heat consumption based on data collected during very cold periods.

In the course of Phase 1, investigators noted that some replacement thermostats malfunctioned, and that there is a possibility of thermostat failure from manufacturing defects. Complete more rigorous thermostat testing was done at time of installation to ensure equipment was functioning properly. There was a 5% failure rate of the new vapor diaphragm thermostats, at the time of installation.

In Phase 2, investigators deferred hysteresis testing until the metering equipment installation site visit. This eliminated one site visit that only resulted in a seven percent rejection of units. Initial recruitment in similar studies should include 10% extra units to compensate for attrition due to hysteresis testing. Downloading of data loggers at thermostat replacement helped identify failed loggers in the pre-period, and provided an opportunity to correct and extend the pre-period for a few additional weeks so that the site would not be lost. It was helpful to call each tenant within one week of thermostat replacement to verify the equipment was functioning properly.

Investigators considered vacancy and tenant turnover in units adjacent to the sampled units, in the attempt to explain variations in heat consumption of the sampled units; no relationship was in fact found.

In another study of this type, investigators would make use of longer periods covering "shoulder months", with greater variability of exterior temperatures. It is more difficult to correlate and extrapolate annual heat consumption based on data collected during very cold periods.

> ***Thermostat Savings Hypothesis: Confirmed****. Reducing the thermostat temperature setting did result in savings. However, the savings observed were of greater magnitude than expected. The expected magnitude was approximately 7% of annual space heat for a 1ºF reduction in temperature. Actual savings were 14% per degree reduction, in affected units.*

Multifamily units across the study showed a heat to space-temperature relationship of 513 kWh per 1ºF change in temperature. A 1ºF drop accomplished by thermostat retrofits across all units in a building would result in average savings would be some fraction of 513 kWh. (Keep in mind that units selected for this study had higher than average pre-period consumption.) The sample size of the non-weatherized category was too small to accurately determine the variation between weatherized and non-weatherized categories. The energy savings for the study sample are greater than the literature suggests, but was also expected to be greater due to the stratification of the sample selecting high space heat consumers.

> ***Comfort Hypothesis: Confirmed.*** *Equivalent comfort was achieved at lower temperature settings when hysteresis was reduced.*

Based on post-period interviews, the study found that most tenants cannot distinguish a one- or two-degree difference in space temperature. There were many tenants who maintained a slightly higher space temperature in the post-period, and were unaware that there was a difference, just as there were many who were unaware of a lower post-period temperature. Tenants were satisfied with the new thermostat and elected to keep it at study end.

> ***Thermostat Retrofit Hypothesis: Not confirmed (results inconclusive).*** *Changing bimetal thermostats to vapor diaphragm thermostats, without re-sets, labeling, or tenant education, did not automatically result in energy savings in all sampled units.*

There was a large variation in results across the sampled units. This was due to confirmation of hypothesis 5. Since the tenants could not tell if the temperature were higher or lower during the post-period, some slightly increased the temperature and some slightly decreased the temperature. Findings on the final hypothesis were inconclusive, because tenants were not able to discern space temperature differences of 1-2ºF, and were not, without further education or product labeling, able reliably to set thermostats to the lower levels required for energy savings.

This was also compounded since many tenants did not have thermometers or degree markings on their old thermostats, and the thermostats that did have degree markings may have been out of calibration. This emphasizes the need for an educational component to accompany new thermostats.

Program implementers should be aware that there is the possibility of thermostat failure from manufacturing defects. Tenant education about thermostat operation would likely provide savings beyond values observed in this study, where setbacks did occur. The study did not provide any instruction to the tenant about thermostat operation. Any instruction may be only effective for the duration of tenancy; however the knowledge would carry over to wherever the tenant moved to next.

Discussion

It is difficult to draw firm conclusions regarding the magnitude of energy savings that can be achieved in multifamily units that are retrofitted from bimetal to vapor diaphragm thermostats. The study purposely instructed the tenants to use the new thermostats as they would the old ones. There was no mention about energy savings to the tenants, so that they would not be consciously or unconsciously biasing energy consumption (they were simply asked to try out a new type of thermostat in which the utility was interested). As a result, there was a large variation in unit energy savings. In general, when the occupants reduced the thermostat set-point temperature, energy consumption decreased and when they set the new thermostat higher, energy consumption increased.

This is a similar result to that found in a study that was conducted on Pacific Northwest single-family homes using electronic thermostats to replace bimetal thermostats (Lambert 1996). Lambert similarly instructed tenants that the study was to assess operation and acceptance of the new thermostats. As a result, some apartments experienced an increase

in average temperature and some experienced a decrease. This finding was also similar to that found among single-family and multifamily units served by Northeast Utilities, receiving electronic thermostat retrofits (Johnson et al. 2000). In that study, dead-band was also significantly reduced, and yet some residents increased the set point and others decrease the set point, leading to savings at some sites and increased energy use at others.

Our study did show, as in the two preceding field studies, that if the new thermostats were set at a lower average temperature, energy savings would be the result. Among the 18 units in the combined Phase 1 and Phase 2 analysis, the average annual electric consumption for space heat was about 3,780 kWh, as estimated from the utility bills. The estimated energy savings of 513 kWh per degree temperature drop, then, represents nearly 14% of annual space heat of the multifamily units. This is twice as much as concluded in the EPRI study (1994). However, the EPRI results were based on single-family homes that were not screened to be significantly high space heat users. Across the entire population of multifamily units in Seattle, the savings would be much closer to the EPRI result because many multifamily units with few external exposures have significantly small space heat consumption.

Lambert concluded that, for the average observed decrease in space temperature of 0.88°F, annual energy savings would be about 222 kWh per year. Lambert, also, did not screen the sampled units for high heat consumption as we did, so a lower savings value would be expected in his study. Johnson (2000) concluded that annual savings were about 642 kWh per site: 1,228 kWh in single-family homes and 333 kWh for multifamily units, all unscreened for prior high heat consumption.

Johnson (2000), for Northeast Utilities, notes that "the ability to identify sites with potential savings would maximize program impacts." It appears from current study observations that the best candidates for vapor-diaphragm thermostats in existing multifamily buildings would be dwelling units with three or more external exposures (walls, ceiling, floor), a factor which happens to be highly correlated with those units meeting the significant-space heat criteria, having 2,400 kWh or more of space heat per year. In this study, about 25% of building units were screened into this category. Energy savings were also greater for studied units in buildings that had not been weatherized. Other factors correlated with higher savings were larger floor area (hence heated space), living-room installation, and use by occupants who do not manually set-back the thermostat at night or when leaving the unit. Observed savings in units having these factors occurred in spite of the lack of product labeling or tenant education. Thermostat retrofits should be avoided in smaller units with few external exposures and insignificant space heating, and in weatherized buildings, as cost-effective energy savings are unlikely to result.

Closing Remarks

Various space-heat thermostats have been proposed over the years by utilities and manufacturers as a potential source of space heat energy savings – including electronic line voltage, vapor diaphragm, and programmable models. The question remains, do thermostat retrofits generate actual energy savings – and if so, under what conditions?

This study focused on multifamily units having extensive external surface exposures and larger than average floor areas. The study found annualized savings of 513 kWh per unit for each 1ºF decrease in the space temperature: nearly 14% of the annual space heat. Across all units in a building, the average savings would be some fraction of this level. The study found that equivalent comfort was in fact delivered by the reduced hysteresis and lower space temperatures. However tenants were not able to discern space temperature differences of 1-2ºF, and were not, without further education or product labeling, able reliably to set thermostats to the lower levels required for energy savings. Hence the following recommendations are offered.

Focus Impact Analysis on Set-point.

Instead of focusing on absolute savings for the sampled units in this study, the area of focus should be on determining the impact of thermostat set-point on space heat. This change in focus is judged appropriate primarily due to the comments from the post-period data collection tenant interviews, which indicated respondents were not able to determine that they were maintaining the spaces at different average temperatures. This inability follows logically from the increased comfort provided by a thermostat with decreased hysteresis.

Focus Process Analysis on Product Labeling and Tenant Education.

Those interested in thermostats as a program measure should work with thermostat manufacturers to test alternative methods for permanent product labeling. It would be beneficial to have the new thermostats labeled such that the "ideal" energy-savings temperature set-point, say 68°F, were at the top center of the thermostat dial with an arrow or mark indicating the ideal setting during unit occupancy. Market research should be conducted to determine the product design most effective at influencing short-term and long-term behavior. Market research should also focus on methods of tenant education that are effective at conveying information about how vapor diaphragm thermostats produce increased comfort, about how that increased comfort can lead to uncertainty about the best thermostat setting, about ideal daytime and nighttime set-points, and about the environmental and bill savings benefits.

Require Product Labeling and Tenant Education in Thermostat Program.

Energy savings will not be achieved from a thermostat replacement program unless the thermostat installation is accompanied by a significant emphasis on product labeling and tenant education.

Product labeling with an arrow or mark indicating the ideal or recommended temperatures set-point (say 68°F) would indicate to people that this is the normal or best setting. It also provides the installer with an initial set-point. However, if an installer finds an old thermostat in the low or off position, the new thermostat should be set to the minimum position. Occupants may not know what temperature their old thermostat has been set at because it may only have "low" to "high" or "comfort zone" labels, or may be significantly out of calibration.

Tenants must understand that most people will not notice a small decrease in space temperature, and that the resulting energy savings can be significant from a lowered set-point. Without ongoing education, program savings will likely decline or not occur as

tenancies turn over. It may be advisable to place an educational sticker on or near the thermostat, or mail an annual educational flyer to program participants.

As for program design, thermostat replacement is more appropriate in retrofit applications rather than in new construction. Where building codes have tightened, many multifamily units may now use minimal space heating, and thermostats may become less effective as a conservation measure. Retrofits in older buildings with zonal heat should receive the program emphasis, and then only key units within those buildings, as identified in this study.

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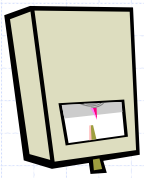
Appendix L. Presentation Slides

Vapor-diaphragm Thermostats

The Challenge of Retrofits in Existing Multifamily Buildings



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2008 Summer Study on Energy Efficiency in Buildings, Panel 2
American Council for an Energy Efficient Economy

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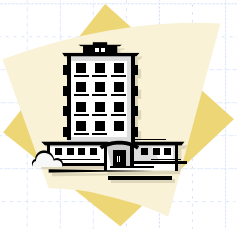
Question...

Do thermostat retrofits generate energy savings?

Study created to answer this question for multifamily housing units in the Seattle City Light service area



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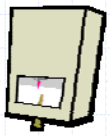
Theory of Thermostat Savings

How Vapor-Diaphragm Thermostats Save:

- Smaller Hysteresis: ~2°F
  (versus ~5°F in bi-metal thermostats)
- Difficult for bi-metal thermostats to maintain constant temperatures
- Thermostat "droop" less of a problem
- Greater comfort at lower temperatures



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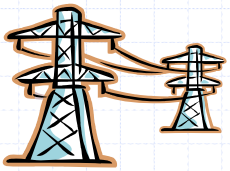
Objectives



1. Are there Energy Savings?
   ANSWER:
   - Differences between Phase 1 and 2 results
   - Phase 1: energy use fell up to 342 kWh/yr
   - Phase 2: energy use *increased* up to 420 kWh/yr
2. With What Associated Characteristics?
   ANSWER: Phase 1 energy savings greater in certain units
3. Methodology Proof of Concept?
   ANSWER: 93% (54 of 57) bimetal thermostats tested had significantly higher hysteresis

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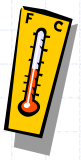
Hypotheses



Study designed to confirm or deny if:

1. Savings: Reducing the thermostat temperature setting results in savings of about 7% of space heat for a 1ºF drop.
   ***ANSWER:* CONFIRMED**
2. Comfort: Equivalent comfort can be achieved at lower temperatures where hysteresis is reduced.
   ***ANSWER:* CONFIRMED**
3. Retrofit: Changing bimetal thermostats to vapor diaphragm thermostats, without thermostat pre-sets, labeling, or tenant education, automatically results in energy savings.
   ***ANSWER:* NOT CONFIRMED (inconclusive)**

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Study Design

- Phase 1 (Winter 2004-2005)
  - 18 apartments chosen
  - Phase 1 answers the 3 objectives
- Phase 2 (Winter 2005-2006)
  - 20 apartments chosen
  - Phase 2 answers the 3 hypotheses

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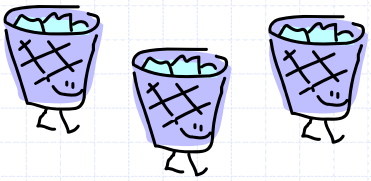
Study Design



Study apartments chosen by process of "binning"

- 22 candidate multifamily buildings
- 418 apartments of candidate buildings screened

Apartment Characteristics Strategy

- Two divisions for each of four categories: weatherization, floor area, exterior surface exposure, and heater operating hours

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Methodology

Sample Selection, Phase 1

Bin	Weatherization	Floor Area	External Exposure	Heating Hours	N
1			Extensive	High	2
2		Large	5	Low	3
3			Minimal	High	1
4	Weatherized	6	1	Low	0
5			Extensive	High	2
6		Small	5	Low	3
7			Minimal	High	0
8	11	5	0	Low	0
9			Extensive	High	1
10		Large	2	Low	1
11			Minimal	High	0
12	Not Weatherized	2	0	Low	0
13			Extensive	High	0
14		Small	3	Low	3
15			Minimal	High	2
16	7	5	2	Low	0
Cases	**18**	**18**	**18**		**18**

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Methodology

Sample Selection, Phase 2

Bin	Weatherization	Floor Area	External Exposure	N
A		Large	Extensive	14
B	Weatherized	15	Minimal	1
C		Small	Extensive	5
D	20	5	Minimal	0
Cases	**20**	**20**		**20**

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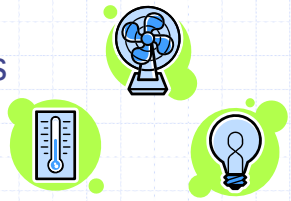
Hysteresis Testing

Device developed to test wall-mounted thermostats included:

- Transparent plastic container
- Two sealable ventilation holes
- Small fan to circulate air
- Air temperature sensor
- Switchable light bulb inside as heat source



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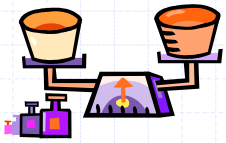
Hysteresis Testing



Hysteresis testing not precise:

- Provided a *relative* indication of hysteresis
- Vapor-diaphragm on-off temperature difference of 6°F (3 x **2°F** rated hysteresis)
- Accepted only bi-metal thermostats with test result ≥15°F (3 x **5°F** rated hysteresis)
- 93% of bi-metals tested had significantly large hysteresis

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On-Site Data Logging

- Meter for 4 weeks with bimetal thermostat
  - Ampere loggers installed
  - Indoor temperature loggers installed
  - One temperature logger outside building
- Retrofit vapor-diaphragm thermostat
- Monitor for another 4 weeks
  - Then remove sensors, loggers
  - Buildings keep new thermostats

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Findings

Analysis required:

- Regression analysis
- Adjusting data for outside air temp change
- Extrapolate findings to annual basis

Average energy savings:	195 kWh
Standard deviation:	1,152 kWh
Range:	-2,154 to 1,591 kWh

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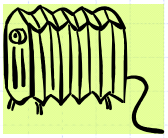
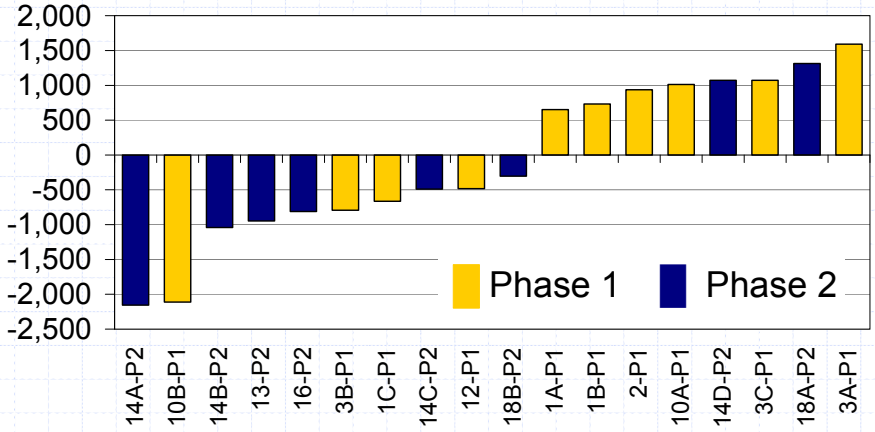
Findings



Adjusted Annual Energy Savings, Combined Phases



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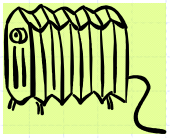
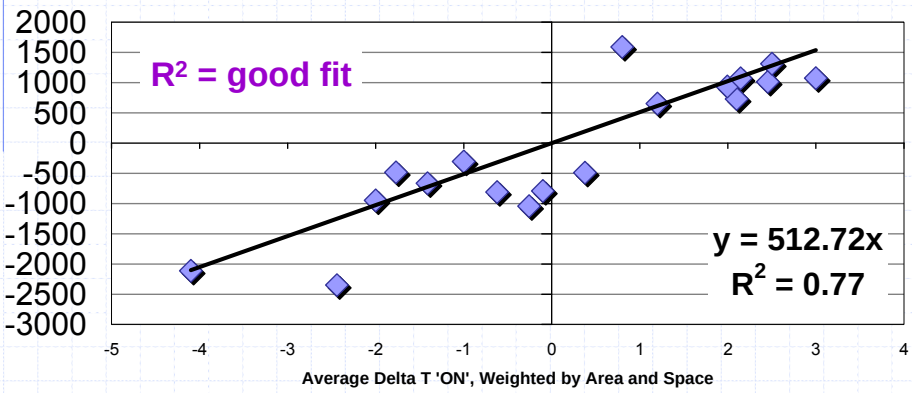
Findings



Space Heat Energy Changes as a Function of Space Temperature Change (weighted by Area and Space)



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Conclusions

Difficult to draw conclusions – wide variety in energy savings:

- Tenants not instructed to change settings
- In general, occupants who reduced thermostat setting saved energy
- Only half of occupants reduced settings
- Other half raised settings (unknowingly)

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Conclusions

Sites with potential savings include:

- Dwelling units with three or more exterior exposures (walls, ceiling, and floor)
- Non-weatherized buildings
- Larger floor area
- Living room installation
- Occupants do not manually set thermostat back at night

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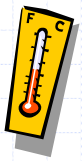
Conclusions



For every 1°F decrease in temperature setting, saved 14% on space heat

However, tenants unable independently to set thermostat lower

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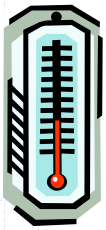
Recommendations



1. Analyze impacts on set-point

- Instead of absolute savings, focus on the impact of thermostat set-point on space heat
- … Because respondents were not able to determine that they were maintaining the spaces at different average temperatures
- Their inability follows logically from the increased comfort provided by a thermostat with decreased hysteresis

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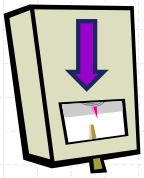
Recommendations



2. Focus market research on product labels & tenant education

- With manufacturers, test permanent product labels
  - "Ideal" 68°F energy-saving arrow at the top center of dial
- Test product designs to influence short-term and long-term behavior
- Focus on methods of tenant education about …
  - How thermostats produce increased comfort
  - How increased comfort can lead to uncertainty about the best thermostat setting
  - What are ideal daytime and nighttime set-points
  - The significant bill savings and environmental benefits

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Recommendations

3. Require product labels and tenant education in programs

- Thermostat installation must include significant emphasis on product labeling and tenant education
- Place educational sticker on or near the thermostat, or mail an annual educational flyer to participants
- Retrofits best rather than new construction
  - ***Focus on Key Units within Older Buildings with Zonal Heat***

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Questions?

Vapor-diaphragm Thermostats:
The Challenge of Retrofits in Existing Multifamily Buildings

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Seattle City Light

Printed on recycled paper

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(12-06)