Measured Impact of Mechanical Thermostat Replacement

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ABSTRACT

This study determined the energy impact and user satisfaction with the **replacement of mechanical line voltage thermostats** on baseboard electric heaters **with electronic thermostats** having better control. Heating energy use and indoor temperature data were collected from 60 sites between December 1998 and April 1999. From a useable sample of 56 sites the **heating energy use was reduced 642±405 kWh or 7.1%** weighted by energy use. This reduction corresponded to an average thermal balance temperature reduction of 1.2±1.0°F at a 90% significance level.

Results varied widely among the sites, ranging from a reduction of 39% (2,087 kWh) to an increase of 79% (955 kWh) in heating energy use. The greatest absolute savings was 6,700 kWh/yr (20%). The greatest increase was 4,730 kWh/yr (37%). While we found examples of sites where savings were produced (by a reduction in thermostat setting to the lower range of the original control dead-band), we also found sites that increased their usage (because set point was raised to the upper range of the dead-band). Frequent user set point changes and the initial temperature levels had the largest effect on the energy impact and caused wide variability in the results.

The thermostats were overwhelmingly well received. 49 of 57 occupants stated that the new thermostats' performance was better than the original thermostats'. Users liked the improved control, ease of setting and the digital display of actual temperature and set point.

Introduction

This paper describes a field test that measured the performance of replacement thermostats. The test was done for the SPECTRUM Residential Electric Heat conservation program at Northeast Utilities. All test sites had electric baseboard heat controlled by mechanical line voltage thermostats. Replacement thermostats were electronic (with one exception). We measured heating power, outdoor and indoor temperatures to look for savings due the more accurate temperature control. User satisfaction with the new thermostats was evaluated.

Background

Advanced thermostats for the control of electric resistance baseboard heating are currently being promoted on the basis of energy savings. Justification for the amount of energy savings comes from an EPRI study (Bender 1992) that found 12% average energy savings in seven homes, where bimetallic thermostats were replaced with electronic thermostats. Another study by Hydro-Quebec (Handfield et al. 1994) found similar savings in a larger, combination field and laboratory study.

The new thermostats provide better temperature control, primarily through reduced temperature deviation about the set point. We believe the main mechanism producing savings is that the occupants reduce the set point when they have tighter control of the temperature. This assertion is based on the idea that occupants set their thermostats based on the minimum temperature reached in the control band. This fluctuation is due to the thermostat differential (dead-band) and droop. A thermostat with less temperature deviation, set to match the minimum temperature of a thermostat with more temperature deviation, will maintain a lower average space temperature as illustrated in Figure 1.

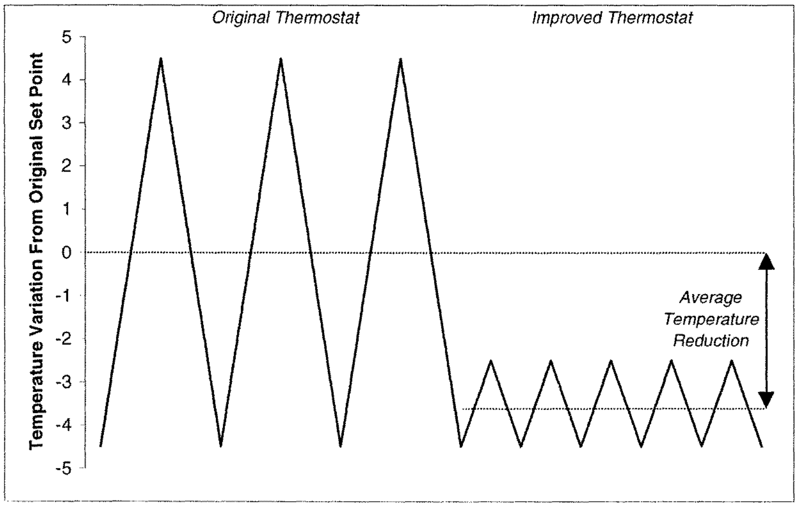

Figure 1. Potential Space Temperature Reduction with Improved Control

To obtain an 8% energy savings with the new thermostats, a simplified heat transfer model of a house [$Q = UA (T_{in} - T_{out})$] implies that the seasonal average temperature difference between the interior space and outdoor temperature must decrease by 8%. Based on bin weather data for Hartford, CT, a 1.9°F change in indoor temperature will produce an 8% change in heating energy use.

Objectives

The intent of this project was to verify the energy savings of replacement thermostats, and to provide feedback about customer satisfaction with the thermostats. The specific objectives were:

1. Determine the gross energy savings of thermostat replacements.
2. Investigate the savings mechanism from both the balance temperature estimation in the heating load line and direct space temperature measurements.
3. Identify other possible changes that contribute to, or reduce, the expected thermostat savings.
4. Document thermostat performance characteristics from the space temperature data.
5. Develop correlations of savings to site and thermostat-usage characteristics.
6. Assess occupant satisfaction with the advanced thermostats.

Approach

The project was completed in a single season. Thermostats were replaced at mid-season. The use of sub-metered heating energy use before and after the new thermostat installation allowed us to develop *heating load lines* for each site as depicted in Figure 2. These heating load lines facilitated calculation of annualized and normalized heating energy use, which were used to produce gross savings estimates. They also provided a means to detect a change in the thermostat set point. In addition to the heating end-use data, we collected space temperature data, site characteristics and occupant feedback about their existing and new thermostats.

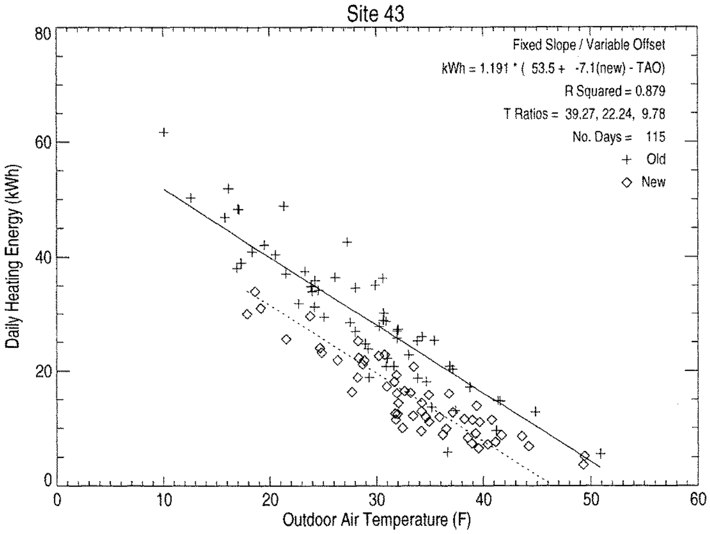

Figure 2. Heating Load Line Regression Analysis, Site 43

Sixty sites (24 single family and 36 multifamily units) were selected by program administration personnel. The sample was a mix of previous program participants (who had installed other measures through the program) and non-participants who qualified for participation in the SPECTRUM Electric Heat Program. We visited each site at least three times: to install the metering, retrieve the pre-retrofit data, and to retrieve the post-retrofit data as depicted in Table 1.

Table 1. Project Site Visit Schedule and Goals

Visit	Time Frame	Purpose	Scope
1	12/1-12/18	Initial installation of metering equipment Administer site characteristics survey	all sites
2	12/18-12/20	Follow up to verify data collection	14 sites
3	2/1-2/5	Pre-Retrofit data retrieval & Thermostat replacement	all sites
4	4/5-4/8	Post-Retrofit data retrieval Administer thermostat satisfaction survey Verify site characteristics	all sites

Heating power was submetered with self-contained four-channel power loggers. Loggers were normally mounted within the electrical panel. We attempted to isolate the main living area on a single channel, but usually found multiple heating zones on each circuit. Other heating circuits were combined based on type of space (bedrooms, living areas) and proximity. Each heating zone was documented to include the description, floor area, power draw and circuit number. The logger recorded power data on 30-minute intervals.

At each site we installed several temperature loggers near thermostats and one to measure outdoor air. The loggers were mounted directly below or to the side of the thermostat to avoid the heat plume produced by the thermostat anticipator. Temperature data were logged every 5 minutes in order to capture the dynamics of the temperature control. A total of 262 temperature loggers were installed.

We visually and statistically reviewed the data, producing a brief data summary report of the pre-retrofit data for verification. These site summaries contained a sample of site characteristics, a heating load line, a shade plot showing the heating power use pattern, interior temperature distributions, and the interior temperature profile from the coldest day in the period.

The impact of the thermostat change on energy use was determined with a heating load line regression model. The most general form of the model is shown below. The slope of the heating load line relates to the shell thermal performance – mimicking a thermal conductance (UA value). The horizontal intercept of the heating load line corresponds to the balance temperature.

$$W = b_0 + b_1 T + b_2 D + b_3 DT + b_4 Q_{solar}$$

Where,

W = Daily heating energy use
T = Daily average outdoor temperature
D = Dummy variable (0=before thermostat change, 1 = after thermostat change)
Q_{solar} = daily total solar horizontal radiation
$b_{0\text{-}4}$ = Model parameters

With the replacement of the thermostats we expected the balance temperature to be reduced as the occupants settled on a lower average interior temperature. There should be no other changes associated with the thermostat replacement, so the slope or thermal conductivity of the shell should remain the same ($b_3 = b_1$). Neglecting the solar term the model parameters can be reformulated to correspond to the physical characteristics of shell conductivity and balance temperature as follows:

$$UA = -b_1, \qquad T_{bal} = \frac{b_0 + b_2 D}{-b_1}$$

Normalized and annualized heating energy values were determined by driving the model with Typical Meteorological Year (TMY) weather data for Hartford, with and without the retrofit dummy variable D. Heating energy was forced to be greater than or equal to zero by eliminating weather data above the balance temperature.

$$Q_{impact} = \sum_{hours} \left(b_0 + b_2 + b_1 T_{o,n}\right)^+ - \sum_{hours} \left(b_0 + b_1 T_{o,n}\right)^+$$

Findings

Of the 60 sites, 56 produced useful data. Data availability averaged 57 days of data for the original thermostats and 60 days of data for the new electronic thermostats. The only data filtering was the elimination of unoccupied periods at four sites.

We evaluated the more general forms of the heating load line models to check if the model form changed the results significantly; we found little difference. The solar variable was significant at 32 sites, but since the solar term was strongly cross-correlated with the thermostat change (the insolation was greater after the thermostat replacement), it was not included.

The average balance temperature reduction (b_2) was 1.2±1.0°F at a 90% significance level. This balance temperature change corresponds to a 5% annual change in energy use. **The annual energy reduction with the thermostat replacement was 642±405 kWh or 7.1%** weighted on energy use. The results vary widely among the sites from a reduction of 39% to an increase of 79% in heating energy use as shown in Figure 3. Since the driving factor for the energy impact is the user behavior of setting the thermostats, this large variability was expected.

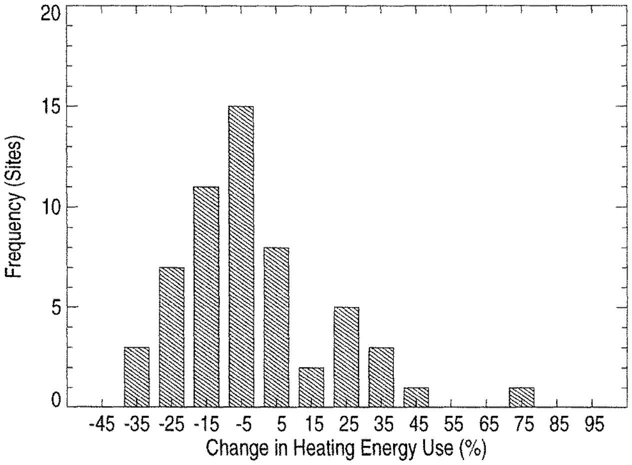

Figure 3. Relative Change in Heating Energy with New Thermostats

Of the 56 sites, 23 showed a reduction in energy use with the new thermostats that were statistically significant (t-ratios greater than two). 10 sites showed a statistically significant increase in energy use with the new thermostats. Changes in energy use at the remaining 23 sites could not be correlated to the thermostat replacement. The high level of "noise" in the data was due to the variability of the occupants' behavior in setting the thermostats.

The energy reductions at the single-family sites averaged 1,228±866 kWh or 8.5%. Of the 22 single-family sites, 11 had significant savings and only two had significant increases with the new thermostats. The results from the multi-family sites showed savings of 264±333 kWh. This 4.7% reduction is not statistically significant due to the large variability of the sample. Twelve sites had statistically significant savings, while eight sites had statistically significant increases out of a total sample of 34.

The study included a wide range of residences in the sample. The thermal conductance of the shell, normalized by floor area, spanned a nearly five-fold range (0.6 to 2.8 Wh/day °F ft^2). **Heating energy use varied from 0.20 to 5.8 kWh/HHD.** Annualized and weather normalized heating energy use varied from 1,000 to 34,000 kWh among the sites. **When normalized by heated floor area, the heating energy varied from 1.4 to 20 kWh/yr ft^2.** The thermal balance temperatures ranged from 44°F to 77°F. With the new thermostats, balance temperatures changed significantly in both directions, from -12°F to +10°F. Assuming there were no changes in interior heat gains, the balance temperature change corresponds to the thermostat set point change.

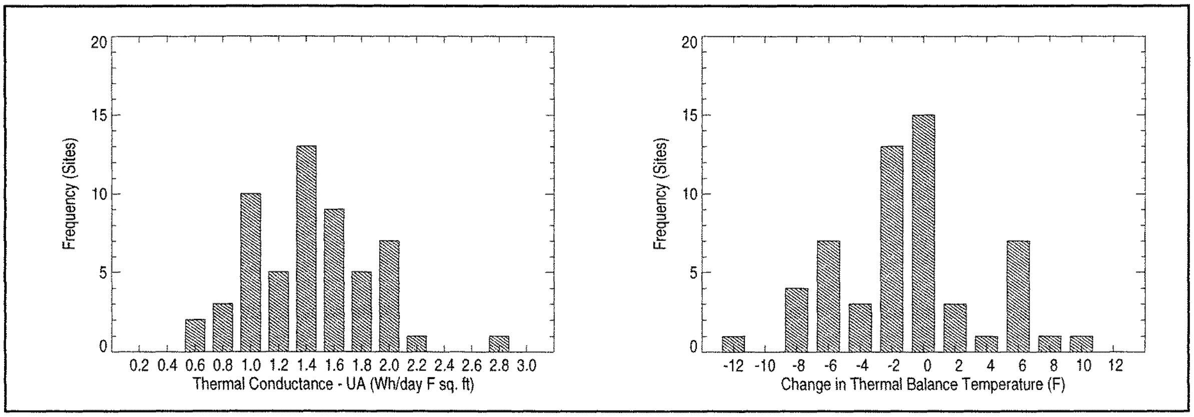

Figure 4. Sample Distributions of Model Parameters

There is a slight relationship in the thermal balance temperature and the relative size of the heating energy savings, at least at the extremes as shown in Figure 5. The thermal balance temperature represents the highest outdoor temperature where heating begins to be needed to maintain space conditions. Lower thermostat settings or larger internal heat gains (e.g. refrigerator, occupants, etc.) can cause a lower balance temperature. **The sites with the lowest balance temperature (below 50°F) all increased heating energy use with the new thermostats, while the sites with the highest balance temperatures (above 70°F) all decreased heating energy use.** This trend is logical, since houses kept cooler would be less likely to reduce the temperature further, and houses kept warmer would be less likely to increase the interior temperature.

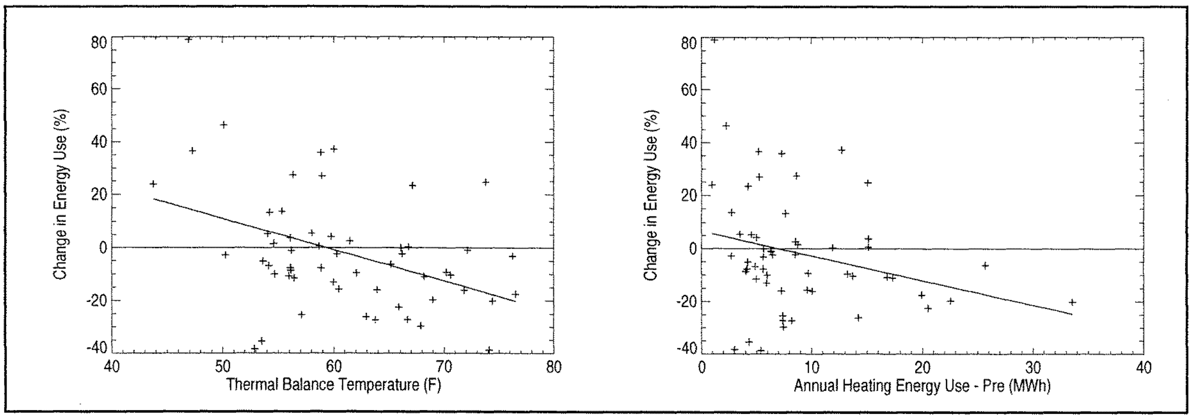

Figure 5. Change in Energy Use Related to Balance Temperature and Initial Energy Use

With electric baseboard heat most sites changed their thermostat settings frequently to minimize heating cost. The interior temperature measurements showed standard deviations from the mean ranging from between 1.2°F to 6.7°F. Assuming a normal distribution, the temperatures would be within two standard deviations 95% of the time. In other words the indoor temperature of the main living areas varied from ±2.4°F to ±13.4°F, 95% of the time. This variance in the temperature data is mostly caused by set point changes. The sites that left the thermostat settings unchanged had standard deviations in the 1°F to 2°F range.

Savings Mechanism

The three sites discussed below illustrate the range in occupant behavior seen at the test sites. They demonstrate that occupant behavior determines the savings with new thermostats. The sample shows a wide range of differences in occupant habits leading to a large variance in the savings.

The desired savings mechanism is illustrated in data from Site 43. At Site 43 the occupants changed the thermostat settings infrequently. The time series temperature trends in Figure 7 show the reduction in interior temperature variation with the installation of the new thermostats. They also show the indoor temperature being maintained at a relatively constant temperature.

Superimposing one day of pre and one day of post retrofit data on the same plot in Figure 6 illustrates the performance change. The temperature varied between 72°F and 76°F with the original thermostats. The new thermostats kept the temperature within 71°F to 72°F. With the temperature maintained at the lower edge of the original dead-band, the new thermostats reduced the average indoor temperature about 3°F.

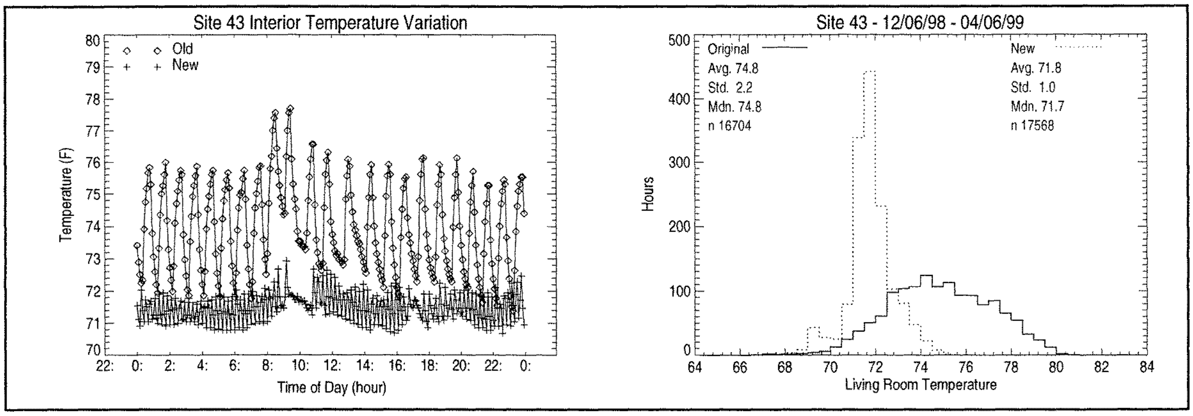

Figure 6. Interior Temperature Comparisons with Thermostat Replacement, Site 43

The regression model, Figure 2, found that a 7.1°F reduction in thermal balance temperature best fit the heating data for the entire residence. This temperature reduction resulted in an annual heating energy reduction of 35%, one of the largest savings amounts observed.

The premise that people set the thermostat for comfort at the low end of the dead-band is not true for all cases. At site 45, as shown in Figure 8, the occupants set the new thermostat at the high end of the original thermostat dead-band range. The temperature varied between 61°F and 68°F with the original thermostats. The new thermostats maintained the temperature in the 67°F to 69°F, an average temperature increase of 4°F.

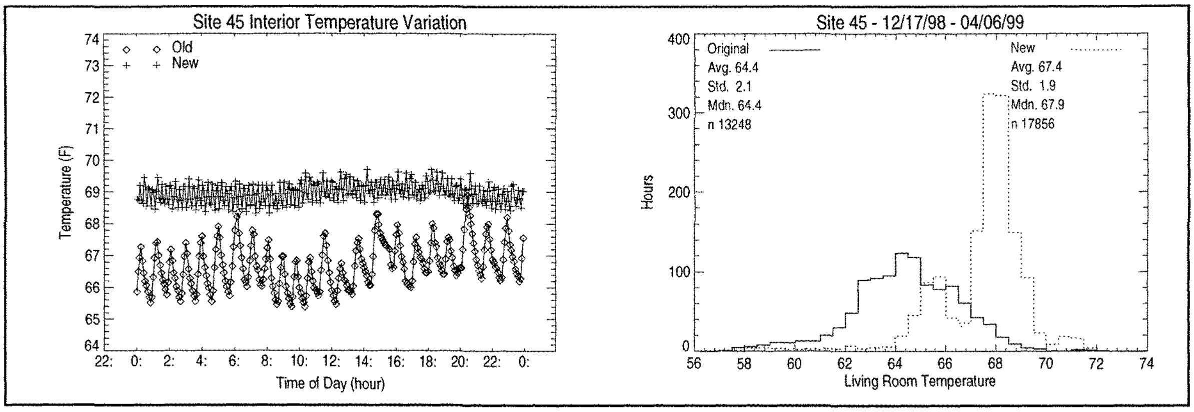

Figure 8. Interior Temperature Comparisons with Thermostat Replacement, Site 45

The regression model in Figure 9 found a 5.1°F increase in thermal balance temperature best fit the heating data for the entire residence, resulting in an annual heating energy use increase of 27%.

While the new thermostat settings were closer to the typical comfort range at both sites 43 and 45, the temperatures with the original thermostats were greatly different. One was above and one was below the typical comfort range. This disparity led to widely divergent energy impacts with the thermostat replacement.

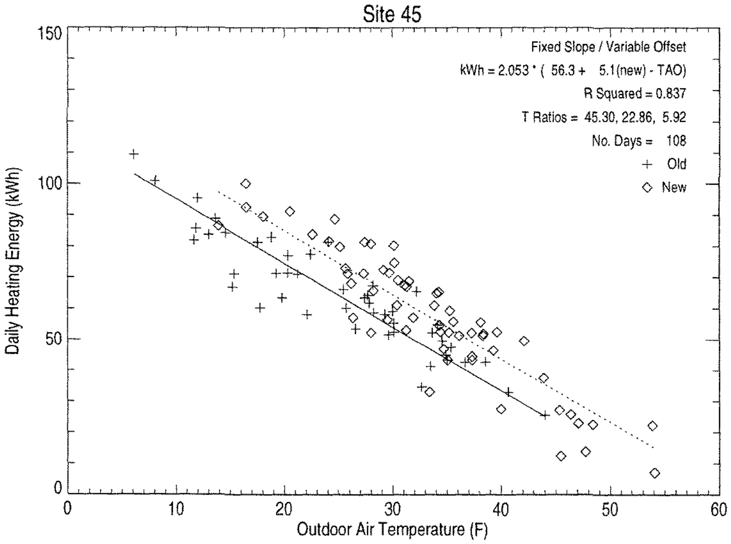

Figure 9. Heating Load Line Regression Analysis, Site 45

These two examples show cases where the thermostat settings were infrequently changed. The daily heating energy use plots in Figure 2 and Figure 9 show distinct differences between the pre and post retrofit periods. The heating energy use shows a strong correlation to outdoor temperature. Most of the variation in indoor temperature was due to the thermostat dead-band, so reducing the dead-band with the new thermostats had a quantifiable impact on the temperature and energy use.

A common scenario with electric heat is for the occupants to shut off heat in rooms they are not currently occupying, or turning down the heat whenever they leave the room or

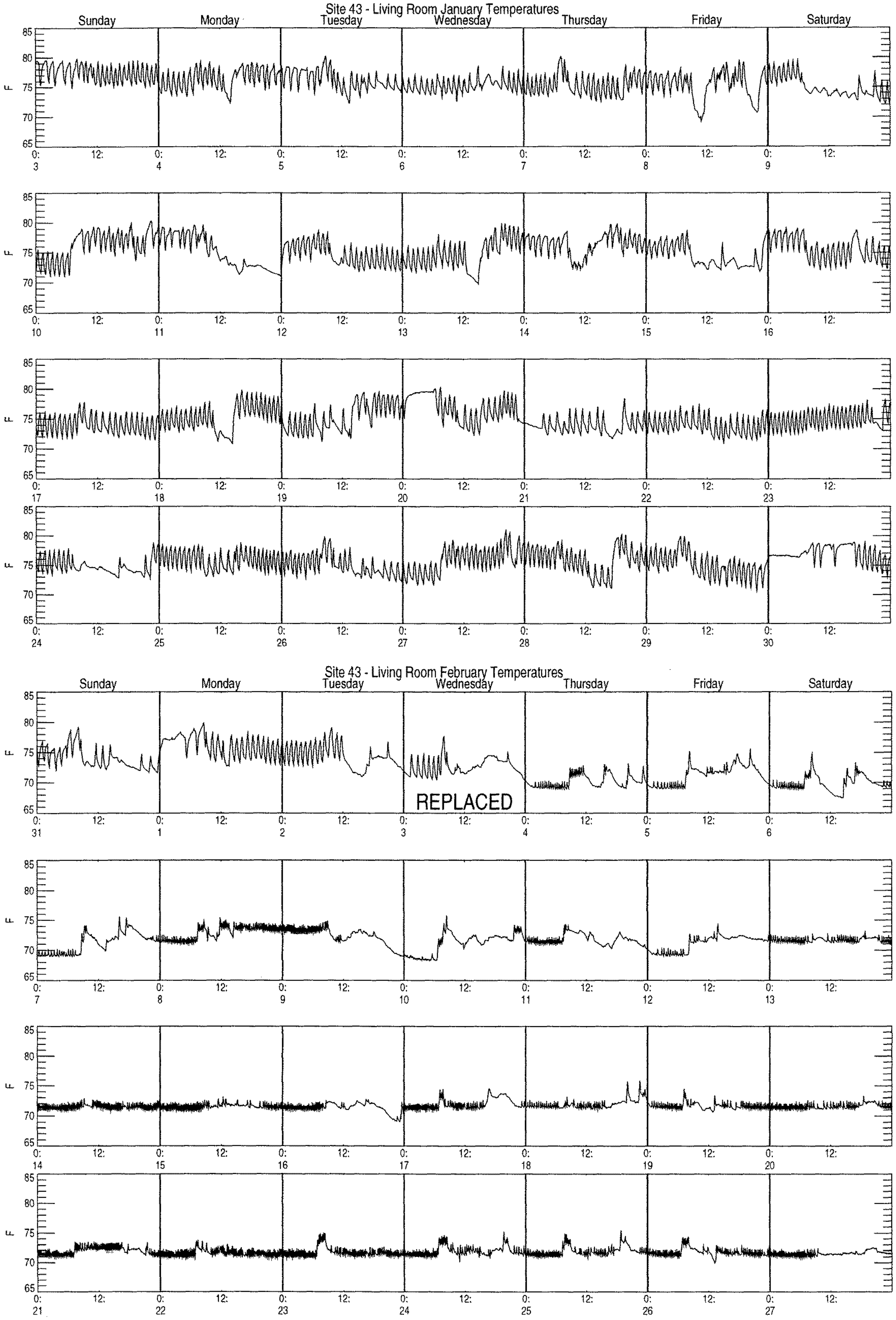

Figure 7. Indoor Space Temperatures Before and After Thermostat Replacements, Site 43

residence. **Under conditions of frequent user set point adjustment, the amount of time the thermostats are actually controlling the temperature is diminished.** Therefore it is less credible to attribute energy changes to the thermostat replacements, rather than to variations in the occupant habits. The interior temperature time series data from site 1 illustrate this point in Figure 10.

This site exhibited extreme user intervention in setting the space temperatures. During the month of January there were only a few days when the thermostat controlled the room temperature long enough to cycle the heat on and off. The most cycling occurred on the 14th through the 16th. On these days the individual on/off heat cycles are readily apparent. On other days the heat was turned on only for a few hours each evening. At other times the temperature was drifting downward or being maintained by heat gains from adjacent apartments, resulting in no temperature change with the thermostat replacement as shown in Figure 11. **The thermostats were simply not controlling the space temperature very often.**

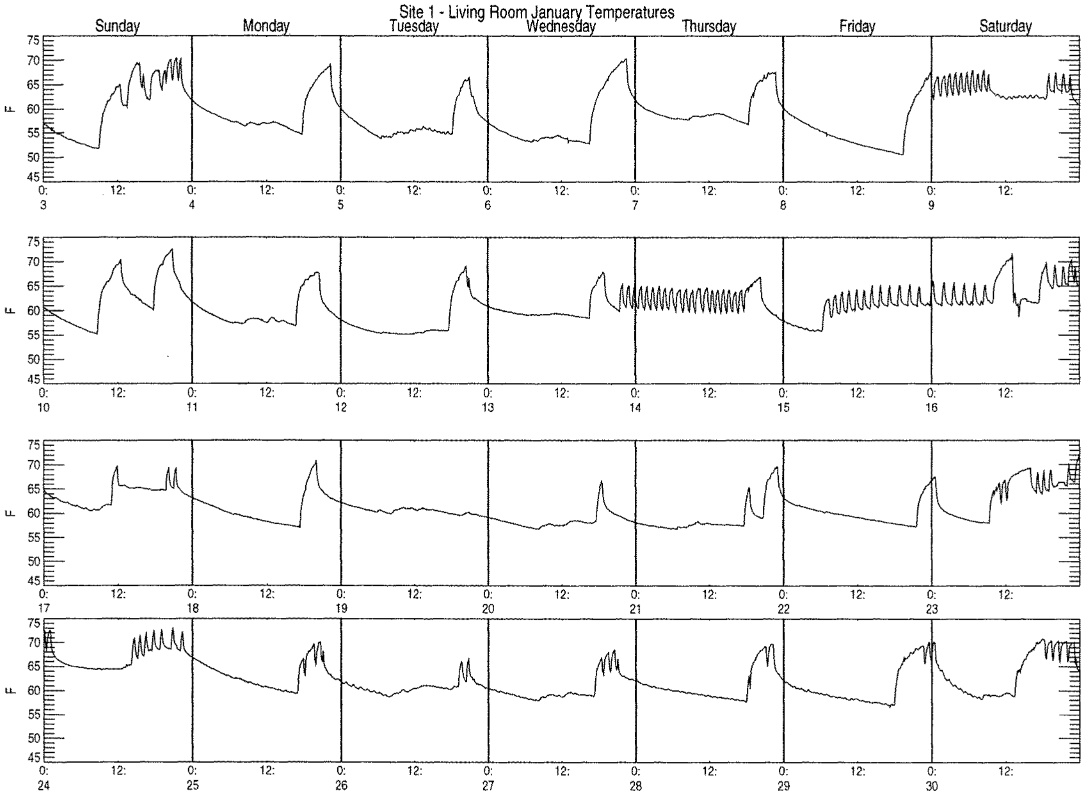

Figure 10. Indoor Space Temperature Time Series Before Thermostat Replacements, Site 1

Under these conditions it is not justifiable to attribute the 38% heating energy reduction found from the model to the thermostat. The heating energy use was less a function of outdoor temperature and more a function of occupant behavior. On days when the average temperature was near 30°F, the heating energy use varied by as much as a factor of seven, from 4 kWh/day to 34 kWh/day. It happened that more of the lower heat days occurred after the thermostats were replaced, but the thermostats did not control the heat on those days.

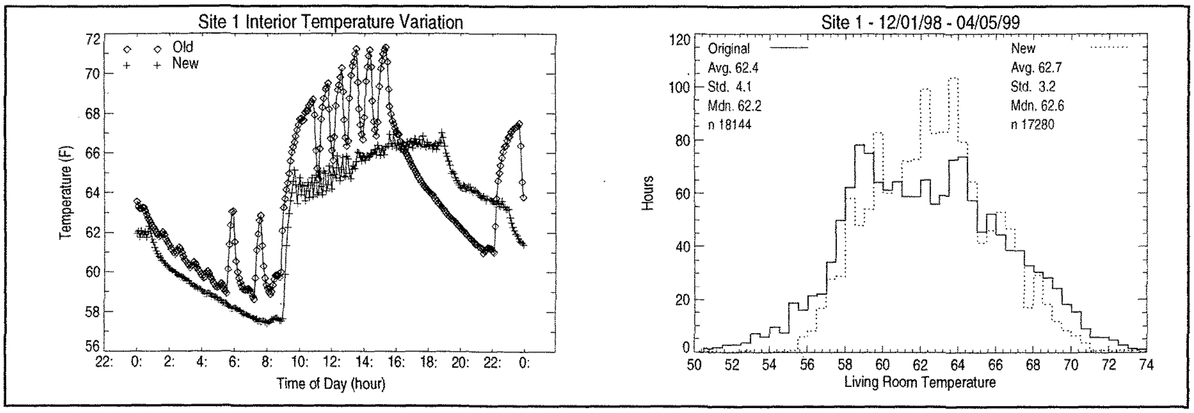

Figure 11. Interior Temperature Comparisons with Thermostat Replacement, Site 1

Savings Relationship to Program Participant Characteristics

The ability to identify sites with potential savings would maximize program impacts. Unfortunately there was no correlation of the change in energy use to characteristics of the participants. None of the surveyed characteristics tended to predict who would increase or decrease their thermostat settings.

The best forecasting parameters of savings appear to be the interior temperatures and heating energy use. **Those sites with cooler interior temperatures tended to increase heating energy use with the new thermostats, while those with warmer interior temperatures tended to decrease heating energy use. The ten sites with the highest heating energy use all reduced heating energy use with the new thermostats.**

User Satisfaction

Response to the thermostats was overwhelmingly positive: 49 of 57 occupants stated that the thermostat performance was better than the original thermostats. This improvement presumably exceeded expectations, since 40 out of 54 had stated that their rooms were already comfortable with the original thermostats.

During the site visit to install the metering equipment we asked the occupants about their current comfort levels and use of the thermostats. Their responses to five questions indicate that 60% believe they actively change their thermostat settings, 74% stated they were comfortable and 79% said the room temperatures were stable. This questioning occurred at the beginning of the heating season, so they had little recent experience with their heating system. Of 27 general comments, seven were positive about their heating system, seven related to poor comfort, and nine mentioned the high cost of electric heat.

During the last site visit to remove the monitoring equipment, we asked the occupants about their experiences and satisfaction with the new thermostats. The responses were overwhelmingly positive about the thermostats and program. People liked being able to read the temperature they had set and see the actual temperature. Comments associated with the comparison to the previous thermostats mentioned improved displays, ability to set the temperature where they wanted it and improved comfort and accuracy of the space temperature. Eight respondents noted that the contactors on the new thermostats were loud. Four complained that having to reset the temperature settings (with one thermostat brand) after a power failure was annoying and that the unit should be able to remember the last setting.

Overall, the new thermostats were well received. They improved comfort with less temperature variation. They were easier to set and gave more feedback about the current space temperature and setting.

Summary

The space temperature data showed reduced dead-band with the new thermostats, as expected. At sites where set points were rarely adjusted, the interior space temperatures fluctuated within a 1°F to 2°F range. With the original thermostats the dead-band range was as much as 9°F.

This study found savings of 642±405 kWh (7.1%) for a sample of 56 sites. This result represents a reduction of 7.1% of the heating energy with the new thermostats. Segregating the sites into single and multi-family groups found annual savings of 1,228±866 kWh (8.5%) for the single family and 264±333 kWh (4.7%) for the multi-family sites. Due to the large variance the multi-family site savings were not statistically significant. The single-family sites generally had larger heating loads and less variability among the sites.

Site characteristics were of little value in predicting the energy impact of the thermostat replacements. Sites with the largest heating bills and those keeping the space temperature the warmest tended to have savings.

Interior temperature measurements showed that some sites reduced average space temperatures to the lower range of the original thermostat dead-band producing savings. However, others increased the space temperature to the high end of the dead-band resulting in increased heating energy use. Still others frequently adjusted their set points, limiting the amount of time the thermostat actually controlled the space temperature. This frequent user control led us to believe that the occupants' variations in temperature settings produced most of the energy impact (both increases and decreases) at these sites.

Occupants were extremely satisfied with the new thermostats. They mentioned improved control, ease of setting and satisfaction in being able to see the actual temperature and set point on the thermostat display. They noted that the contactor was loud and that the thermostats should remember the set point during power failures instead of resetting to 55°F.

Care must be taken in including a thermostat measure in a program justified solely by energy savings. While on average there are savings (around 7%), at individual sites results can vary, to a reduction or increase of 40%. The impact of the measure is highly behavior driven. Participants must be educated about how changing the average set point will change heating energy use.

References

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Handfield, L., Le Bel, C., Minea, M., Lam, C., Pare, M., Electronic Wall Mounted Line-Voltage Thermostats for Electric Space Heating Systems. Canadian Electrical Association, March 1994