Improving Occupant Comfort Without an Energy Penalty in Homes Heated by Electric Heat Pumps

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ABSTRACT

The purpose of this project was to evaluate the effectiveness of an add-on control device designed to improve occupant thermal comfort when installed on standard residential air-source electric heat pumps. The device was not expected to incur an energy penalty compared to normal heat pump operation. This experiment evaluated both occupant comfort and energy consumption.

An add-on control device designed to proportionally control supplemental electric heating coils was installed on seven heat pumps in central Pennsylvania. During a five-month period between October 1994 and March 1995, the device was switched on and off for alternating week-long intervals. Energy consumption was measured continuously using portable data loggers, and occupant comfort was assessed with a questionnaire filled out by the occupants at the end of each monitoring period.

Results of the study indicate that the device may save energy. For the houses tested, an average savings of 10% was recorded. The device also improved the homeowner's perception of comfort in some of the test houses.

INTRODUCTION

This study was undertaken to determine whether the use of an add-on control device for standard residential air-source heat pumps could improve occupant thermal comfort without an energy penalty during the heating season. This device was developed in response to customer dissatisfaction with residential heat pumps during cold weather. Dissatisfaction can occur when the supply air temperature drops below skin temperature during normal operation of a heat pump, which has been observed when the supply air falls below 90°F (Yuill and Werling 1994). This pilot study was initiated by an electric utility to investigate whether use of the device could improve comfort in homes with electric heat pumps without consuming additional energy.

Residential heat pumps are normally controlled by a two-stage thermostat. The first stage of the thermostat is engaged when the house temperature drops below the setpoint, and the thermostat then activates the heat pump. If the heat pump is not able to meet the load while working continuously on its own, the temperature of the house drops to some set amount, usually about 2°F, below the setpoint and the second stage of the thermostat is engaged. When this occurs, the compressor continues to run, and the thermostat also activates the supplemental heating coils. This method of operation can cause discomfort for some occupants. In most cases, this occurs because as the outdoor air temperature drops, the temperature of air delivered by the heat pump drops. A heat pump that cycles between the first and second stages will, therefore, alternately supply cooler air (from the heat pump) and hotter air (from the resistance heat).

DESCRIPTION OF THE ADD-ON DEVICE

Although the add-on device control strategy is different from the strategy normally used to operate heat pumps, it is important to understand that the thermostat sends the same signals to the heat pump in both cases. When the house temperature is above the thermostat setpoint, the heat pump does not operate and the thermostat is said to be satisfied. When the house temperature is below the setpoint, but within a set temperature difference, usually 2°F, the thermostat sends what is called a first-stage signal. If the house temperature falls below the setpoint temperature minus two degrees, the thermostat sends a second-stage signal. The response of the heat pump to first- and second-stage signals is determined by the control strategy used.

As shown in Figures 1 and 2, the two control strategies initially respond to the signals from the thermostat in the same way. On the left side of the diagram, the house temperature

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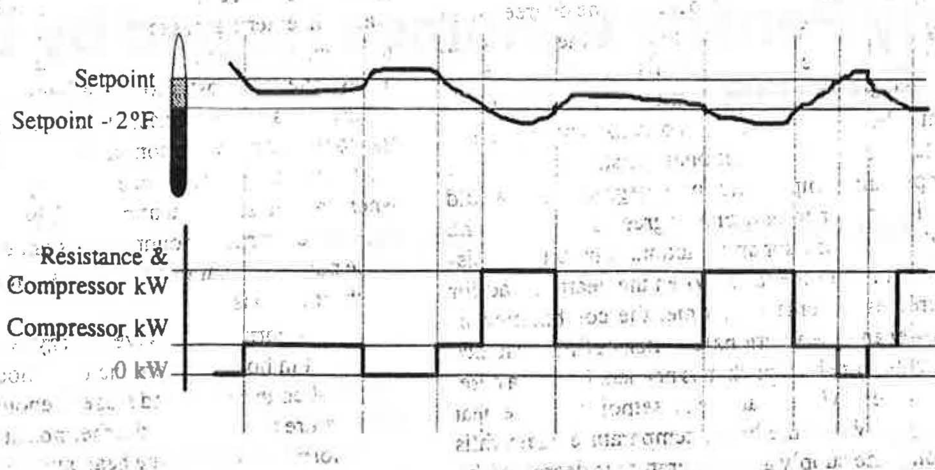


Figure 1 Thermostat temperature and heat pump power consumption for normal operation.

drops below the thermostat setpoint, resulting in a first-stage signal. Both strategies respond by activating the heat pump's compressor. The compressor is able to provide enough heating to raise the house temperature above the thermostat setpoint and the heat pump is shut off. Later, the house temperature again falls below its setpoint temperature and again both strategies call for the compressor to operate. This time, however, the compressor is not able to raise the house temperature above the setpoint on its own and the house temperature falls two degrees below the thermostat setpoint, causing a second-stage signal. Both control strategies respond to this initial second-stage signal by allowing the compressor to continue to run and activating the resistance heating at its full capacity. This additional heating causes the house temperature to rise to within two degrees of the thermostat setpoint, so that the system is now back in its first stage. At this point, the two control strategies begin to respond differently.

The standard operation of the heat pump shuts off the resistance heat entirely when the system moves back from the second to first stage. The compressor continues to provide heating until the house temperature once again falls two degrees below the thermostat setpoint temperature, when the full resistance heating will once again be activated. In some cases, we have observed that the combination of compressor and resistance heating under this control strategy is enough to cause the house temperature to overshoot the thermostat setpoint. The result, as shown on the far right of Figure 1, is that the system shuts off entirely for a brief period. The house temperature then falls below its setpoint, and, since the compressor itself cannot meet the load, the house temperature eventually falls two degrees below the setpoint, resulting in another second-stage signal, and resistance heating must again be used.

The add-on device control strategy handles the transition from second to first stage differently. When the combination of compressor and resistance heating is able to raise the house temperature to within 2°F of the thermostat setpoint, the control strategy continues to operate the compressor but also uses a small amount of power to provide enough resistance heating to raise the supply temperature one degree. This small addition of resistance heating may be enough to keep the house temperature within two degrees of the thermostat

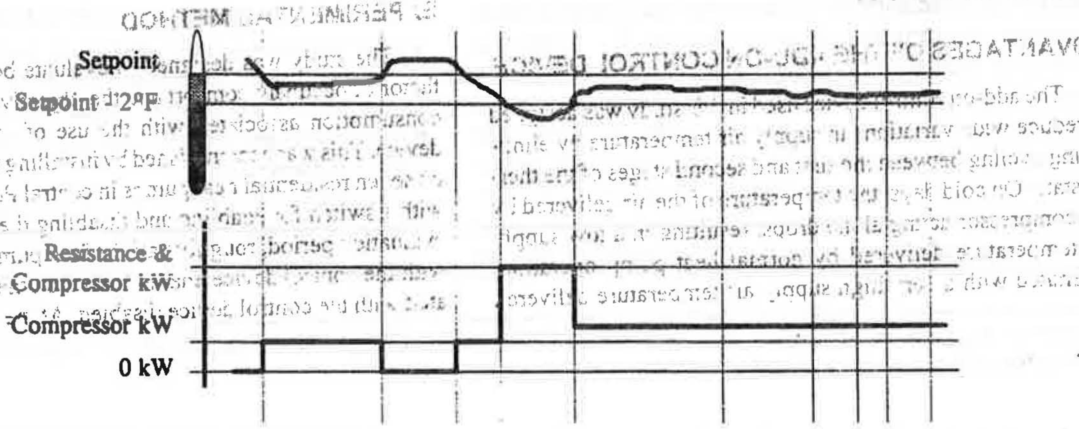


Figure 2 Thermostat temperature and heat pump power consumption for the add-on device control strategy.

setpoint, and the system remains in the first stage. As shown on the right side of the diagram, the resistance heating does not need to be activated at full power again, and the compressor runs continuously with smaller fluctuations in supply air and house temperature. If the heating load had been higher than the situation shown in the diagram, the additional resistance heating added to raise the supply air temperature one degree might not be enough to meet the heating load, and the thermostat would again drop to its second stage. If this were to happen, the control strategy would again activate the resistance heating at full power until the thermostat returned to its first stage. The strategy would then operate additional resistance heating to raise the supply air temperature two degrees and would continue in this manner to add one degree for each second stage call until the compressor and fractional amount of resistance heating could meet the load. When the heating load for the house decreases at some later time, the combination of compressor power and the additional fraction of full resistance power will provide more heating than is needed. In such a case, the house temperature will rise above its setpoint and the heat pump will shut off. When the house temperature again falls below its setpoint, the supply air temperature is decreased by three degrees, and the compressor and a fraction of the available resistance heating (if still needed to achieve the lower supply air temperature) activate. Each subsequent time the thermostat is satisfied, the supply air temperature is decreased by three degrees, so that eventually the compressor is again able to operate alone.

The add-on device control strategy described above and shown in Figure 2 was used in all of the houses monitored for this study. When the weather is mild and very little heating is needed, this control strategy does allow the supply air temperature to drop below 90°F. Some people may find this supply air temperature to be objectionable, even in mild weather. To address this problem, the control device does have an optional setting that establishes a minimum supply air temperature. This minimum temperature can be set by the occupant, and the heat pump will activate additional resistance heating as necessary to provide this minimum supply temperature at all times. This method of operation is not standard and was not used in any of the houses in this study. It is expected that this type of operation would consume more energy than both normal heat pump operation and typical operation of the add-on device. The additional expense might be worthwhile, however, for occupants who continue to experience discomfort even with use of the add-on device.

ADVANTAGES OF THE ADD-ON CONTROL DEVICE

The add-on control device used in this study was designed to reduce wide variations in supply air temperature by eliminating cycling between the first and second stages of the thermostat. On cold days, the temperature of the air delivered by the compressor acting alone drops, resulting in a low supply air temperature delivered by normal heat pump operation, alternated with a very high supply air temperature delivered when the full amount of resistance heating is activated. With the add-on device, warmer supply air is supplied more continuously, and this should improve thermal comfort for some occupants.

It has been hypothesized that since the add-on control device uses just enough resistance heating to keep the thermostat from entering its second stage, this control strategy should not consume more energy than an operating strategy that allows the thermostat to cycle between the first and second stages. This makes sense, since both strategies should allow the compressor to run continuously and use roughly the same total amount of resistance heating. The difference occurs when the resistance heating is activated: the add-on device would use a small amount of resistance heating continuously, while normal operation would consume the maximum amount for short periods.

An opportunity to save energy with the add-on device does exist in houses where the full amount of resistance heating supplied in the second stage is enough to cause the house temperature to overshoot the thermostat setpoint. In this case, under normal operation the heat pump would actually shut off completely for a short time. Soon, the house temperature would fall and the compressor would again be activated, and eventually resistance heating might also be needed again. Thus, the compressor would not be running continuously, and more resistance heating than necessary would actually be used. On the other hand, during periods when some resistance heating is needed, the add-on device would tend to use the minimum amount of resistance heating, allowing the compressor to run continuously to meet the load. Of course, when the demand for heating in the house drops and resistance heating is no longer required, the house must rise to the thermostat setpoint before the device shuts off the proportional resistance heating. However, this typically occurs far less often than the cyclic problem described above. Also, since only a fraction of the total resistance heating is activated, little excess heating would take place and the thermostat would move back to first-stage operation much more quickly. The original intention of the device was not to remedy this type of the problem; however, it is anticipated that this would be an additional benefit associated with use of the device.

This study evaluates the two variables of energy use and occupant thermal comfort under actual operating conditions to determine whether any actual energy savings can be achieved.

EXPERIMENTAL METHOD

The study was designed to evaluate both the subjective factor of occupant comfort and the objective factor of energy consumption associated with the use of the add-on control device. This was accomplished by installing the control device on seven residential heat pumps in central Pennsylvania, each with a switch for enabling and disabling the device. For each evaluation period, roughly half the heat pumps were operated with the control device enabled and the other half were operated with the control device disabled. At the end of each eval-

Weekly Questionnaire

This questionnaire is designed to help us evaluate the effectiveness of an add on control device that we have installed on your heat pump. Each week we will adjust the control device so that you will not know whether it is affecting your heat pump. This way, your answers to the questions should not be biased by your knowledge of the purpose of the control device. If you don't know the answer to a question, make your best guess. Please remember to operate your heating system just as you would without the add on control device. If you would normally raise your thermostat when you feel cool, please do so.

Since my last visit, ...

1. about how many times did you adjust your thermostat?

2. did you notice any uncomfortably cool air blowing from your heating system?

   if yes, how often?

3. did you notice any uncomfortably hot air blowing from your heating system?

   if yes, how often?

4. did you notice any difference in indoor comfort compared with last week?

5. did you notice any other differences in the operation of your heating system compared with last week?

6. did you have any other observations about your heating system?

Figure 3. Weekly questionnaire.

uation period, some of the switches were reversed so that the control device in each house was enabled and disabled on a random basis. The switches were unmarked and located inside the heat pump access door so that occupants were not aware of the setting for each period.

Because of the small number of houses investigated and the preliminary nature of this study, a simple questionnaire was used to assess occupant thermal comfort. Questionnaires were filled out by the occupants and collected at the end of each week-long monitoring period (see Figure 3). Occupants were not told whether the control device was enabled or disabled during each period. They were told to operate their heat pumps as they would normally (i.e., change thermostat as usual.) At the end of the study, all the questionnaires for each house were compared to see if occupants noticed a difference in thermal comfort associated with use of the control device.

The effects of the add-on control device on energy consumption were evaluated by monitoring the energy consumption of the entire HVAC system (outdoor unit and indoor unit separately) for each period and correcting for weather. The results with the control device enabled were then compared with the results obtained when the device was disabled for each of the houses. The seven houses were equipped with portable data loggers to measure current drawn by the compressors and by the supplementary electric coils separately, as well as supply air temperature and room air temperature. Voltage was measured in a one-time test at each house. Standard kilowatt-hour meters were used in five of the houses as a backup to the data loggers.

THERMAL COMFORT EVALUATION

At the conclusion of the study, the questionnaires filled out by the homeowners were compiled for each house and compared. The most common type of dissatisfaction with thermal comfort reported was uncomfortably cool air being supplied by the heating system. Table 1 records the number of "yes" and "no" responses to this question for each house. The following observations were made from the subjective questionnaires:

1. Three of the seven respondents consistently reported an improvement in thermal comfort during colder weather when the control device was enabled.

2. One of these three (shown in Table 1 as House 6) noticed an improvement in thermal comfort when the device was enabled in both cold and mild weather. This was the only homeowner in the study who was dissatis-

TABLE 1
Responses to Thermal Comfort Questionnaire

House Number	Did You Notice Uncomfortably Cool Air Blowing From Your Heating System?			
	Device Enabled		Device Disabled	
	Yes	No	Yes	No
1*	0	6	0	9
2*	0	7	0	15
3⁺	0	5	3	10
4*	0	7	0	16
5⁺	0	10	7	11
6⁺⁺	1	8	7	1
7*	0	8	0	12
Total Votes	1	51	17	74
% Yes	1.9%		18.7%	

*No effect determined, house always comfortable.
⁺Improved thermal comfort during colder weather.
⁺⁺Improved thermal comfort under all weather conditions.

fied with the thermal comfort performance of his heat pump when the study began. The HVAC supply vents in this house are located such that air blows directly on the occupants.

3. Four of the seven respondents noticed no change in indoor comfort throughout the study as a result of operating the control device. One of these four ran the heat pump with the fan operating continuously for health reasons. This would result in supply air temperature swings even when the control device is enabled. Also, the occupants of this house frequently used a wood stove (although they had previously agreed not to do so during the study), making it impossible to obtain a correlation between outdoor temperature and energy consumption.

Responses were obtained from questionnaires gathered between October 1994 and March 1995. These results are in agreement with those obtained in a preliminary study of the same houses conducted between February and April of 1994 (Yuill and Werling 1994).

ENERGY CONSUMPTION EVALUATION

Figures 4 through 9 show plots of the total energy consumption of the heat pump for five-day periods plotted as a function of the heating degree-days in each period. Energy consumption data are reported for six houses. Data are omitted for the house where the wood stove was used.

Traditionally, a heating degree-day is defined as the difference between 65°F and the average daily temperature. However, this definition is not valid for modern houses. Because they have more appliances (and thus higher internal heat generation) and more insulation, the balance temperatures (the ambient temperatures above which they do not require heating) for newer houses are lower than for older houses. Therefore, in this analysis, the true balance temperature of each house was used instead of 65°F. The balance temperature does not change when the device is enabled. The balance temperature was estimated for each house using all of the energy consumption information collected. For each house, the plot of energy consumption vs. heating degree-days is, therefore, a line that passes through the origin.

Linear regression was used to calculate the slope of the "best fit" line for the two cases when the control device is

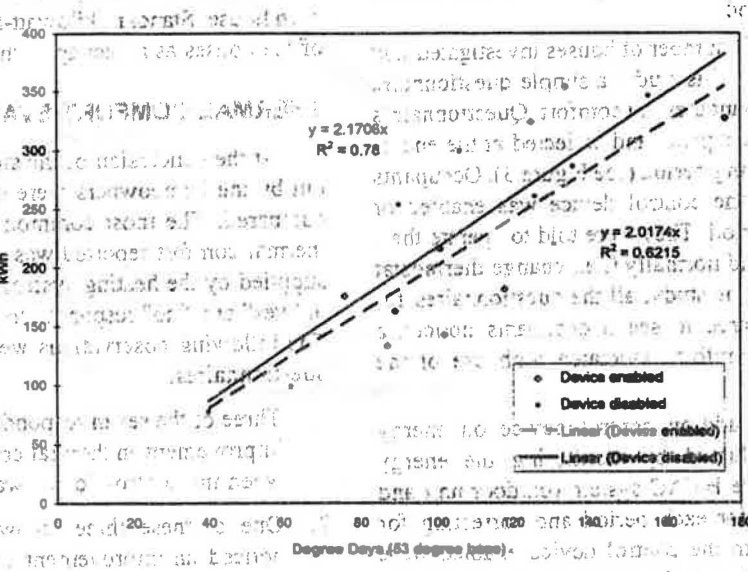


Figure 4 Energy consumption, House 1.

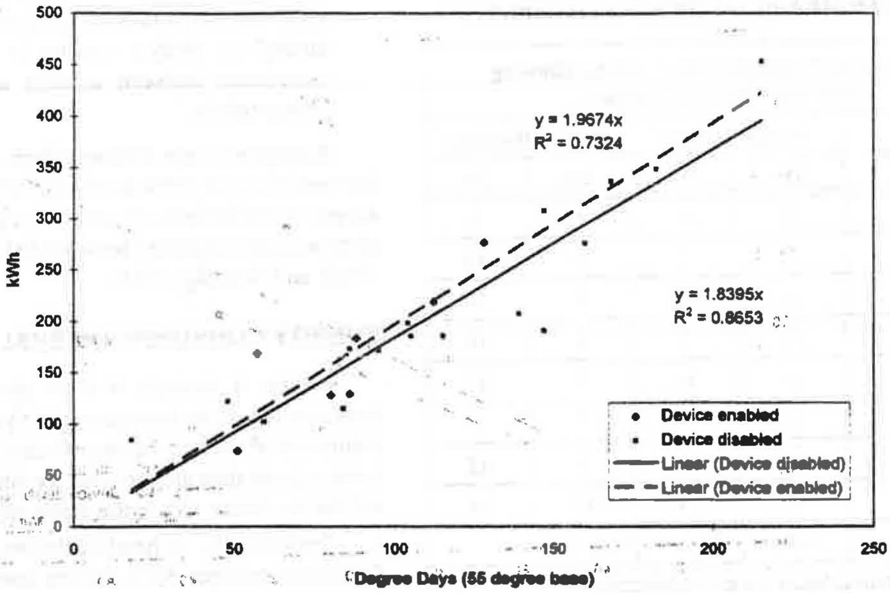


Figure 5 Energy consumption, House 2.

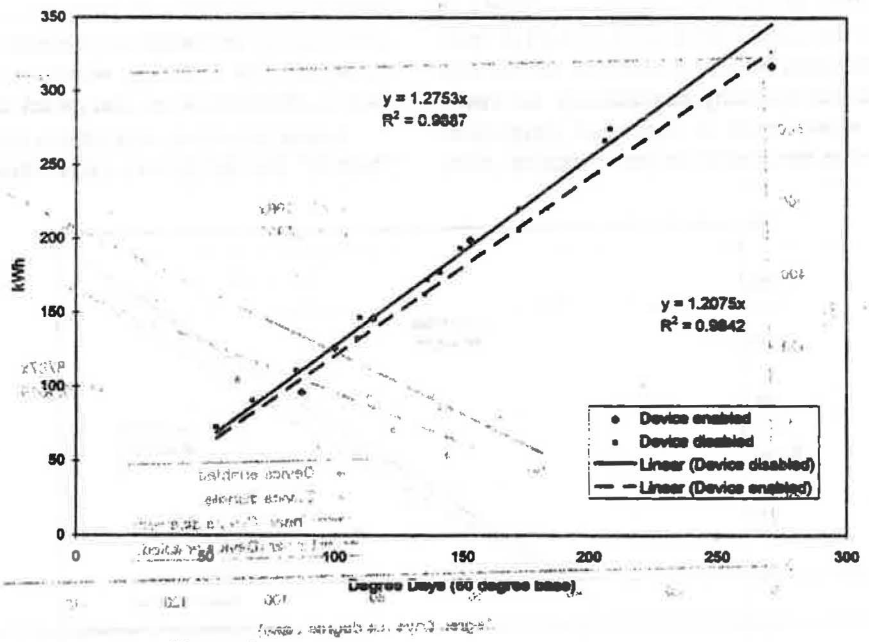


Figure 6 Energy consumption, House 3.

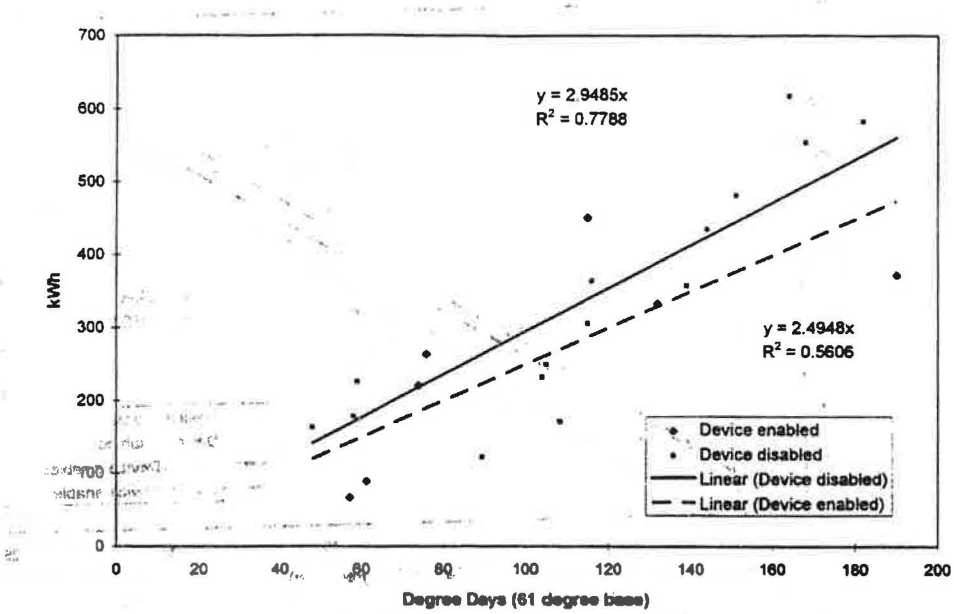


Figure 7 *Energy consumption, House 4.*

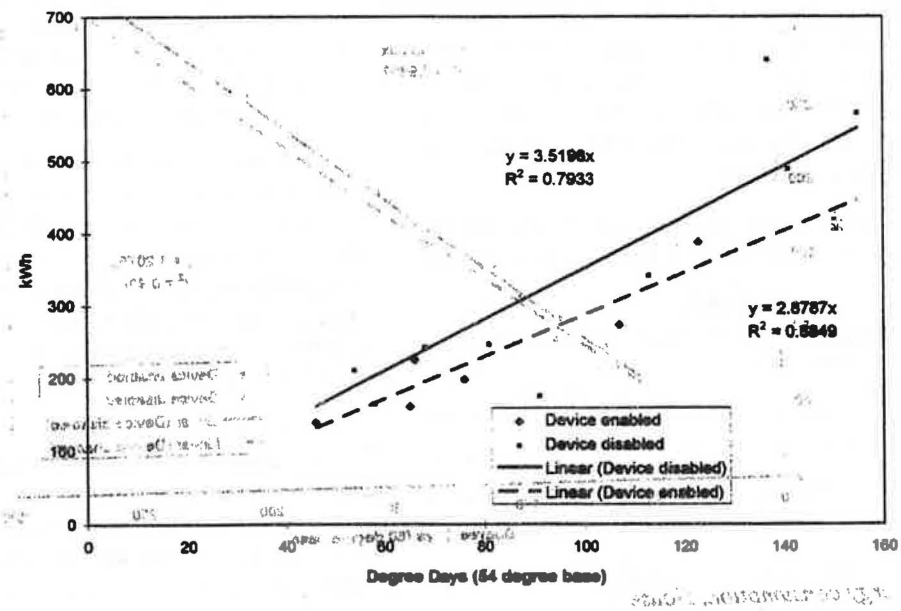


Figure 8 *Energy consumption, House 5.*

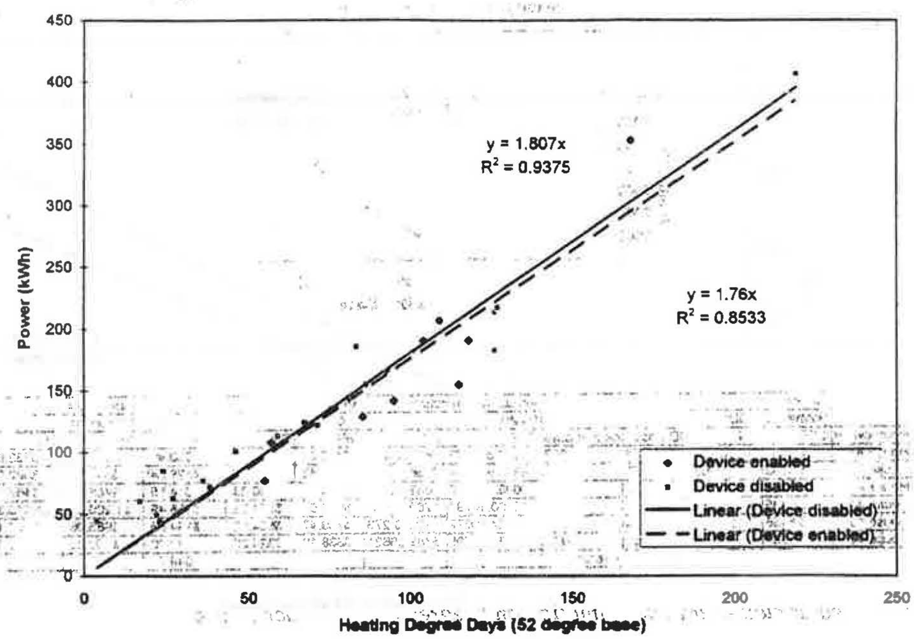


Figure 9 Energy consumption, House 6.

enabled and disabled. These "best fit" lines are plotted on Figures 4 through 9 along with the data points used to calculate them. It should be noted that the energy consumption of a heat pump is not a linear function of ambient temperature, since the COP of the compressor varies with ambient temperature. The actual energy consumption of a heat pump is the sum of compressor energy and resistance heating energy consumed. Other relationships, such as higher order curve fits, were investigated but were not found to provide a significantly more accurate correlation. Therefore, linear curve fits were used to correlate the data.

Statistical analysis was used to predict whether the differences in energy consumption were actually significant or whether they could have occurred by coincidence if no changes had been made using the add-on control device. To determine whether the predicted "best fit" lines were significantly different from one another, a two-sample t-test was used. The slope of each point was calculated, and the data with the device enabled and disabled were compared for each house. Changes in energy consumption were considered to be statistically significant if the t-test found the two data sets to be different with a confidence level of 80% or higher.

Analysis of the energy consumption of the houses showed an energy savings associated with use of the device in five of the six homes. Table 2 shows the percentage savings associated with operating the control device, compared to the energy consumed when the device was not used. In three of the six homes, the savings associated with use of the control device were found to be statistically significant. These homes are marked on Table 2 using a +.

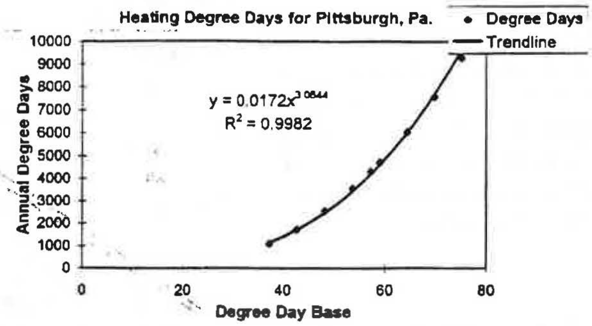
Note that in Table 2, negative savings indicate a loss. The one home in which more energy was consumed, House 2, uses two independent heat pumps for heating different parts of the house. This would not affect the results obtained if the two heat pumps kept the two parts of the house at exactly the same temperature. However, if the homeowner adjusted the two thermostats differently during different periods of the test, heat could flow from the part of the house served by one heat pump to that served by the other heat pump. This introduces an uncertainty into the final results. House 1 also had two heat pumps, only one of which was monitored. If these two houses are excluded from the analysis, the average percentage savings caused by enabling the

TABLE 2
Savings Associated with Use of the Add-On Device

Location	HCC (% savings)
Home 1*+	7.06%
Home 2*	-6.93%
Home 3+	4.01%
Home 4	15.38%
Home 5+	18.21%
Home 6	2.60%
Corrected Average Savings	10.05%

* These houses are heated using two heat pumps, only one of which was monitored. These houses are not considered in the computation of the corrected average savings.

+ This savings was found to be statistically significant.



	Slopes (kWh=slope*DD)				Annual Consumption (kWh)		Annual cost ($.06/kWh)			Annual cost ($.08/kWh)		
Homeowner	OFF	ON	DD Base	degree days	OFF	ON	OFF	ON	Savings	OFF	ON	Savings
House #1	2.1706	2.0174	53	3307	7177.599479	6671.00764	$430.66	$400.26	$30.40	$574.21	$533.68	$40.53
House #2	1.8395	1.967	55	3704	6813.898574	7286.18565	$408.83	$437.17	-($28.34)	$545.11	$582.89	-($37.78)
House #3	1.258	1.2075	60	4836	6083.811923	5839.58895	$365.03	$350.38	$14.65	$486.70	$467.17	$19.54
House #4	2.9485	2.4948	61	5087	15000.10591	12691.9668	$900.01	$761.52	$138.49	$1,200.01	$1,015.36	$184.65
House #5	3.5196	2.8787	54	3502	12324.49672	10080.273	$739.47	$604.82	$134.65	$985.96	$806.42	$179.54
House #6	1.807	1.76	52	3119	5636.470595	5489.86621	$338.19	$329.39	$8.80	$450.92	$439.19	$11.73
				Average					$49.77			$66.37

Figure 10 Expected annual energy consumption and degree-days for each house.

device jumps from 6.72% to over 10%. This result is indicated in Table 2 as the corrected average savings.

To further validate the energy savings observed in the houses, graphs of compressor and resistance heating power similar to those shown in Figure 2 were generated using actual energy consumption data from the houses. In the houses where savings were recorded, energy consumption data for the periods when the device was disabled showed that in colder weather there was a tendency for house temperature to rise above its setpoint and the heat pump to shut off completely for a few minutes following an activation of the resistance heat. Inspection of the energy consumption profiles for the monitoring periods when the device was enabled showed more continuous operation of the compressor. This behavior confirms the theoretical explanation for possible energy savings with the add-on device.

TABLE 3
Expected Annual Savings Associated with Use of the Add-On Device

House	Savings ($.06/kWh)	Savings ($.08/kWh)
House 1	$30.40	$40.53
House 2*	$-28.34	$-37.78
House 3	$14.65	$19.54
House 4	$138.49	$184.65
House 5*	$134.65	$179.54
House 6	$8.80	$11.73
Corrected Average	$74.14	$98.87

*These houses are heated using two heat pumps, only one of which was monitored. These houses are not considered in computation of the corrected average savings.

ENERGY COST EVALUATION

Based on the energy savings predicted by this study, an estimated yearly savings was calculated. Since the degree-day base varies from house to house, the number of degree-days in a typical year will be different for each house even though they are located in the same city. ASHRAE degree-day data calculated for Pittsburgh, Pa (chosen as the closest city with tabulated data available), at several different degree-day bases was fit to a power-law relationship so that the number of annual degree-days for any degree-day base could be obtained (ASHRAE 1986). The annual degree-days for each house were calculated and used to predict energy consumption with the device enabled and disabled. The total cost of energy used for heating and the expected annual savings associated with use of the device were calculated for electric utility rates of \$.06/kWh and \$.08/kWh. Figure 10 shows the expected energy consumption and degree-days for each house. Table 3 shows the expected annual savings in each house with utility rates of \$.06/kWh and \$.08/kWh. Again, the corrected average savings is the average savings experienced in the houses with only one heat pump.

CONCLUSIONS

The results of this study indicate that the control device improves the homeowner's perception of comfort in some houses. One homeowner participating in this study was dissatisfied with the thermal comfort provided by his heat pump before the study began, and he noticed a distinct improvement when the control device was enabled. Two other homeowners noticed improvements in thermal comfort, although they had not originally been dissatisfied with the thermal comfort provided by their heat pumps. The study also suggests that the add-on control device may save energy. For the houses tested in Pennsylvania with one heat pump, the energy savings averaged 10%. This indicates that the control device offers a possible remedy for discomfort experienced by occupants of residences heated using electric heat pumps without imposing an energy penalty.

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