Temperature Changes in Residential Dwellings from Direct Control Actions

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Direct load control has been in widespread use for many years but there have been very few published studies which have actually described the temperature impacts of load control actions in residences. This paper presents data showing the effects of controlling air conditioners on indoor temperature based on a monitoring study of 200 residential dwellings by Consumers Power Company (CPCo) during the summer of 1995. Data were collected at five minute intervals for whole house loads, air conditioner use, indoor temperature, and operation of the relay in the direct control receiver. The paper also describes average indoor temperatures across a range of outdoor temperatures.

Air conditioners were controlled approximately 30 times during the summer of 1995. The intensity of control ranged from 25% to 75%. On a 97°F day, a 50% control strategy caused a maximum rise in temperature of approximately 2.8°F in any half hour interval during the four-hour control period. The average temperature rise for the four hour control period on any control day was never greater than 1.8°F.

Although customers reported that they were generally aware of control activities, they were unaware, for the most part, of specific control actions. A few customers reported that they became warm during control periods on some occasions.

INTRODUCTION

Direct load control has been in widespread use for many years (Weller et. al.). While there have been many studies that have assessed the load impacts of direct control (Reed et. al. 1990; Reed et. al. 1989), there have been very few published studies which have actually addressed the temperature impacts of load control in residences. A recent survey of the literature failed to identify even one such study that has been published in the last 15 years that has treated the issue in more than a cursory manner. There have been subject reports for utilities that are not in the public domain that have presented more comprehensive data.

Indoor temperature has been an issue in a variety of other contexts. There is a fairly extensive literature on temperature take backs after efficiency equipment has been installed (Levins & Ternes, 1994; Ternes & Stovall, 1988; Stovall & Fuller, 1988; Stovall & Kuliasha, 1985; Dinan, 1987). In Europe, there has also been a fairly extensive discussion of indoor temperature in relation to indoor environment (Fanger, 1993).

Load control limits the run times of air conditioners during some portion of the day. This reduces air conditioner load by storing energy in the form of heat in customer residences. Theoretically, this stored heat is removed after control actions are completed.

There has been widespread concern among utility program managers that customers will respond negatively to load control because of the discomfort associated with rising indoor temperatures during periods of control. However, there is little empirical evidence to support this view. Most well run direct load control programs have received few complaints. When there have been complaints it has often been because load control devices have been installed on dwellings with significantly undersized air conditioners. Further, the experience in most well run programs is that very few customers drop out.

It is possible that direct control programs are not controlling severely enough to cause sufficient discomfort to engender complaints. Or, it is possible that in many dwellings the effects of control go unnoticed or are regarded as a minor annoyance. Even in programs where air conditioner duty cycles have been severely limited, for example, a program run by a southern utility in which customer air conditioners were completely shut off for periods up to four hours, very few customers complained or dropped out (Stoval, 1995). The purpose of this paper is to describe the effects of control on residences and to provide some indication of the degree to which customers are aware of control.

This study is based on a direct load control pilot program, ''The Lighten the Load Program'', conducted by Consumers Power Company (CPCo) between 1993 and 1995. The Lighten the Load pilot program directly controlled residential central air conditioners during periods of peak system load. Radio-activated load controllers connected to customer air conditioners were operated from a central control console located at the Grand Rapids regional facility. The pilot program involved approximately 1,050 customers served by three substations in three areas. End-use monitoring equipment was installed in 200 households.

THE END-USE MONITORING SYSTEM

The end-use monitoring system collected data at five minute intervals for whole household load, air conditioner load, status of the relay switch in the load management receiver, and indoor temperature. The system was in operation throughout the summer of 1995.

The end-use monitoring system was wired as shown in Figure 1. One leg of the power feed to the air conditioner was placed through a 50:1 current transformer. These leads were attached to a current transducer which was connected to one of the analog channels of the Universal Network Monitor (UNM) to record air conditioner energy usage.

At most households a thermocouple to measure indoor temperature was installed inside the duct and as closely as possible to the return air vent. The thermocouple was placed in the return air duct because it provided a consistent location that was reasonably comparable among homes. Previous efforts to monitor indoor temperature had shown that indoor air temperature varies widely throughout a home. For instance, temperatures near the ceiling are quite different than temperatures near the floor, and temperatures at the interior of the home are different than the temperatures near the outside wall. The thermocouple device was connected to one of the analog channels on the UNM. Whole household load and the status of the control relay were also monitored.

Data were uploaded using the customer's telephone line. The 200 UNMs were assigned to one night of a three night call cycle. Units called their console at assigned times between 11:00 pm and 6:00 am. Data were transferred from the three data consoles to a fourth machine where data were cleaned and analyzed. The console software was used to write intermediate files which were then processed into master SAS files. The analysis was completed using SAS and EXCEL.

INDOOR TEMPERATURES ON NONCONTROL DAYS

Before discussing the effects of air conditioner control on indoor temperature, it is useful to understand how indoor temperatures varied on noncontrol days. Figure 2 shows the average half-hourly indoor temperature for the 200 households in the sample for a selected set of days with different daily high temperatures. The days in Figure 2 were chosen because they represent the range of indoor summer temperatures.

Compared with one's own experience with air conditioning and thermostat settings, the temperatures represented in and the graphs that follow may seem lower than what one might expect. Temperature was measured in the cold air return. The cold air return is a location in the house where one will find some of the coolest air. The average temperature at this location in these homes is probably 4–6°F lower than the temperatures at the thermostats even though the thermostats may be only a few feet above the return air vent. Ambient temperatures at the middle of rooms, near the ceiling, and near exterior walls may be even warmer (during the summer). Also, these curves represent average temperatures. The temperatures in individual homes will vary from these average temperatures. The temperature in any individual home is dependent on the thermostat setting and the capacity of the air conditioner relative to the cooling load.

The temperatures for May 31 are typical for late spring / early summer when outdoor nighttime temperatures may be in the 50°F to 60°F range and the outdoor daytime high is around 80°F. There was very little air conditioning usage on May 31. The 4° average temperature swing between about 5:00 AM to 7:00 PM on May 31 is almost entirely driven by changes in outdoor temperature. Throughout the late spring and summer, average indoor temperatures seldom dipped below 70° except for the early morning hours at the beginning and end of the summer. For the remaining three days in Figure 2, the average indoor temperatures fall within a range of 72°F to 76°F. Depending upon the onset of hot weather in the early summer and the arrival of cooler outdoor temperatures in the fall, indoor temperatures remain in this range for most of the period from around the middle of June to late August or early September.

Intuitively, one might expect average indoor temperatures to increase with outdoor temperatures. However, the profile for September 5, when the maximum outdoor temperature for the day was 86°F, averaged about 2°F higher than did the profile for July 14 when the high temperature outdoors for the day was 97°F. The fact that indoor temperatures were higher on September 5 than on July 14 is due to the many fewer households which used air conditioning on September 5 than on July 14. It should also be pointed out that the

Figure 1. *Diagram showing load control system and the load control monitoring system.*

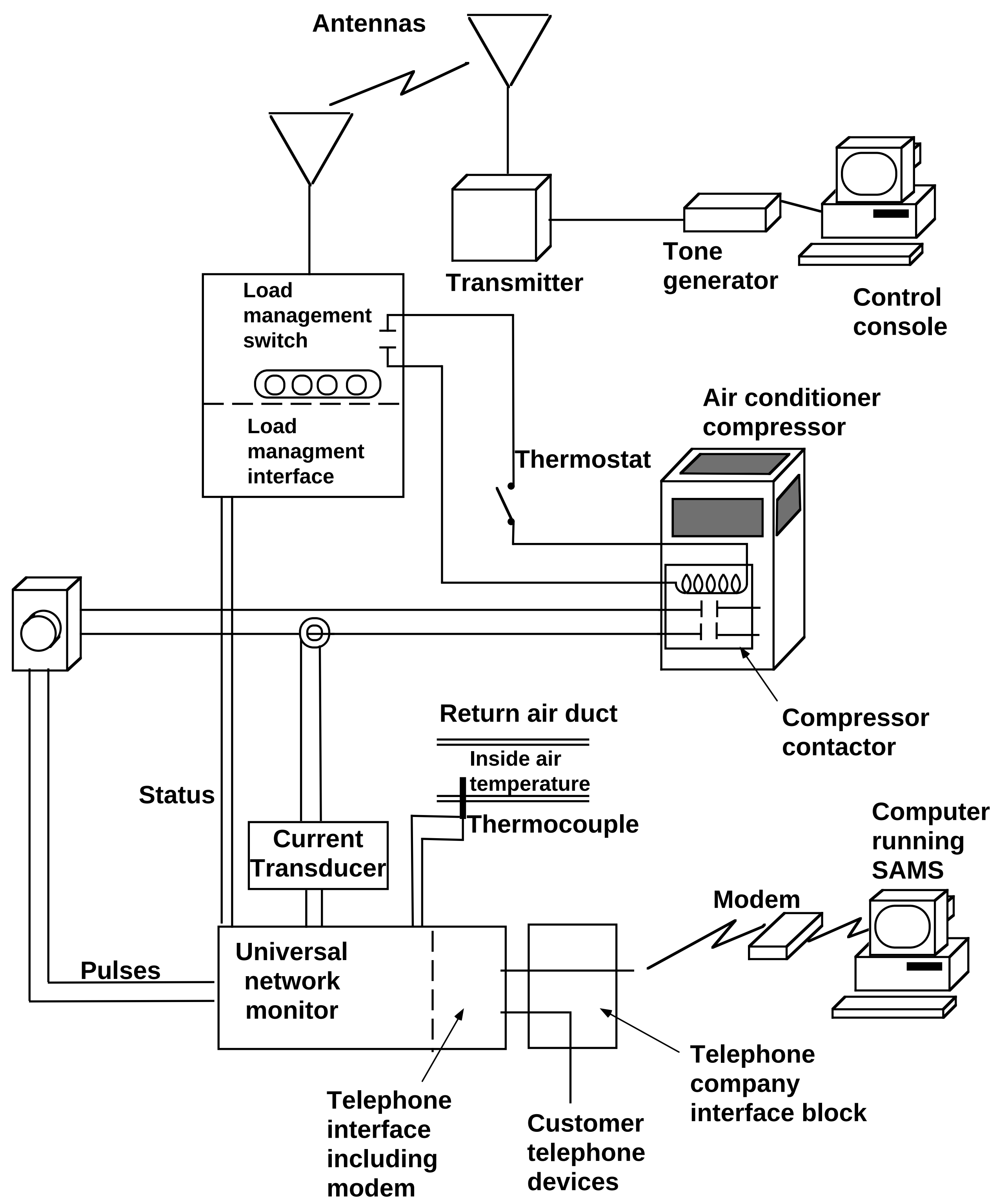
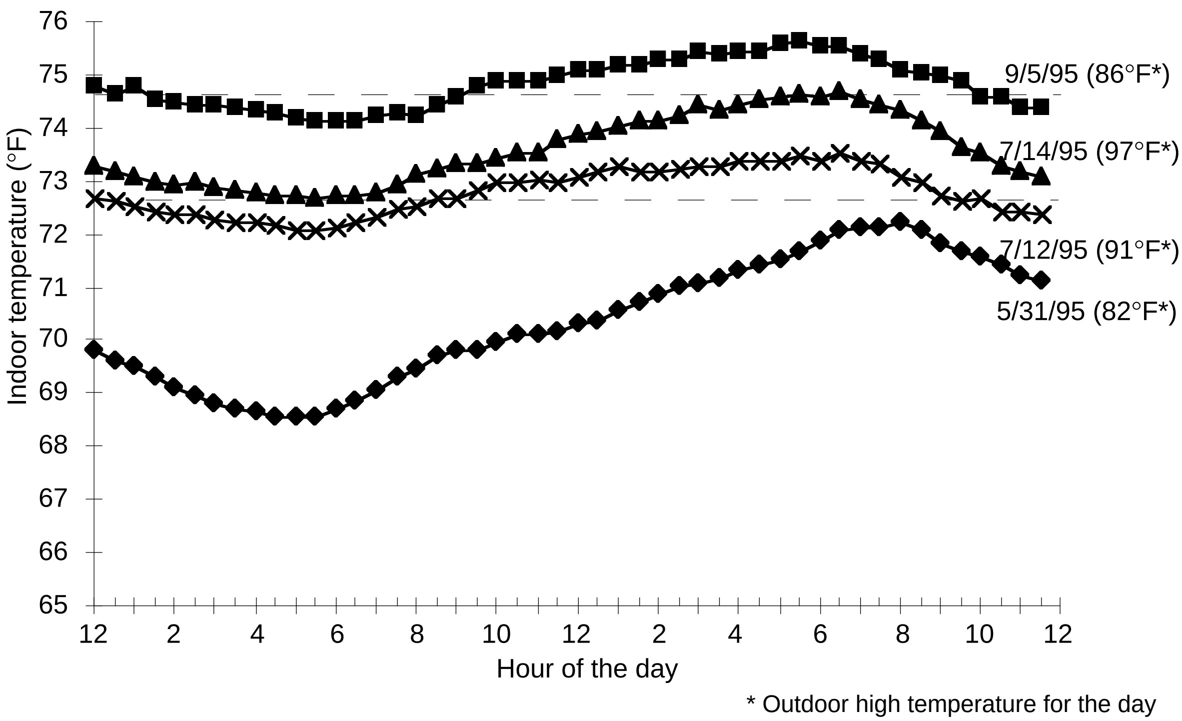


Figure 2. *Indoor temperature for selected noncontrol days during the summer of 1995.*



average indoor temperatures for September 5 were among the highest for the summer, almost 76°F. The low air conditioner use on this day suggests that people will choose indoor temperatures of 76°F without air conditioning. This is useful to know when we consider the impact of changes in temperature caused by direct load control.

July 14 was one of the two hottest days during the summer. The indoor temperature curve for July 14 has been framed with two dotted lines representing the low and high average indoor temperatures. As one might expect, temperatures were lowest at about six in the morning and highest in late afternoon. The lines help to illustrate that the average indoor temperatures fell within a range of 2° for the 24-hour period this hot day when air conditioning usage was highest.

The indoor temperature on July 14 was about 2°F higher during each interval than for a similar 97° day in June (not shown). July 14 was the third day of a heat storm and there was heat buildup in building components. The overnight temperature for the June day also was somewhat cooler. Both of these factors contributed to the higher indoor temperature on July 14.

On very warm days in mid-summer, the heavier use of air conditioning can reduce the variation in indoor air temperature compared to other days. The temperature profiles for July 12 and June 21 presented in Figure 3 help to illustrate this. The indoor temperature profile for July 12 is much flatter than the profile for June 21. The outdoor temperature on these two days is an almost identical 65° (Figure 4) in the early morning although the temperature profiles diverge at the end of the day. July 12 was the first day of a heat storm but was proceeded by several days with high temperatures in the low 80°s while June 21 was one of the very first hot days of the summer preceded by days with high temperatures in the mid to high 80°s. The flatness of the curve on July 12 is due to the much heavier use of air conditioning which removes variation in the average temperature. This was determined by comparing the distribution of duty cycles (not shown) for the two days. An important point is that by mid-summer householders are more likely to use air conditioning than they were on similarly warm days in the early summer.

Increased understanding of indoor temperature can be gained by considering the distributions of indoor temperature across dwelling at different times of the day. Averages may mask what happens in the tails of the distributions of the temperature distributions for the 200 households. For example, there may be a significant proportion of dwellings where air conditioners are undersized and where indoor temperatures are somewhat higher than the average, especially on hot days. The occupants of these dwellings are likely to be most affected by control.

Figure 3. *Indoor temperature for noncontrol days with maximum outdoor temperatures between 90°F and 93°F.*

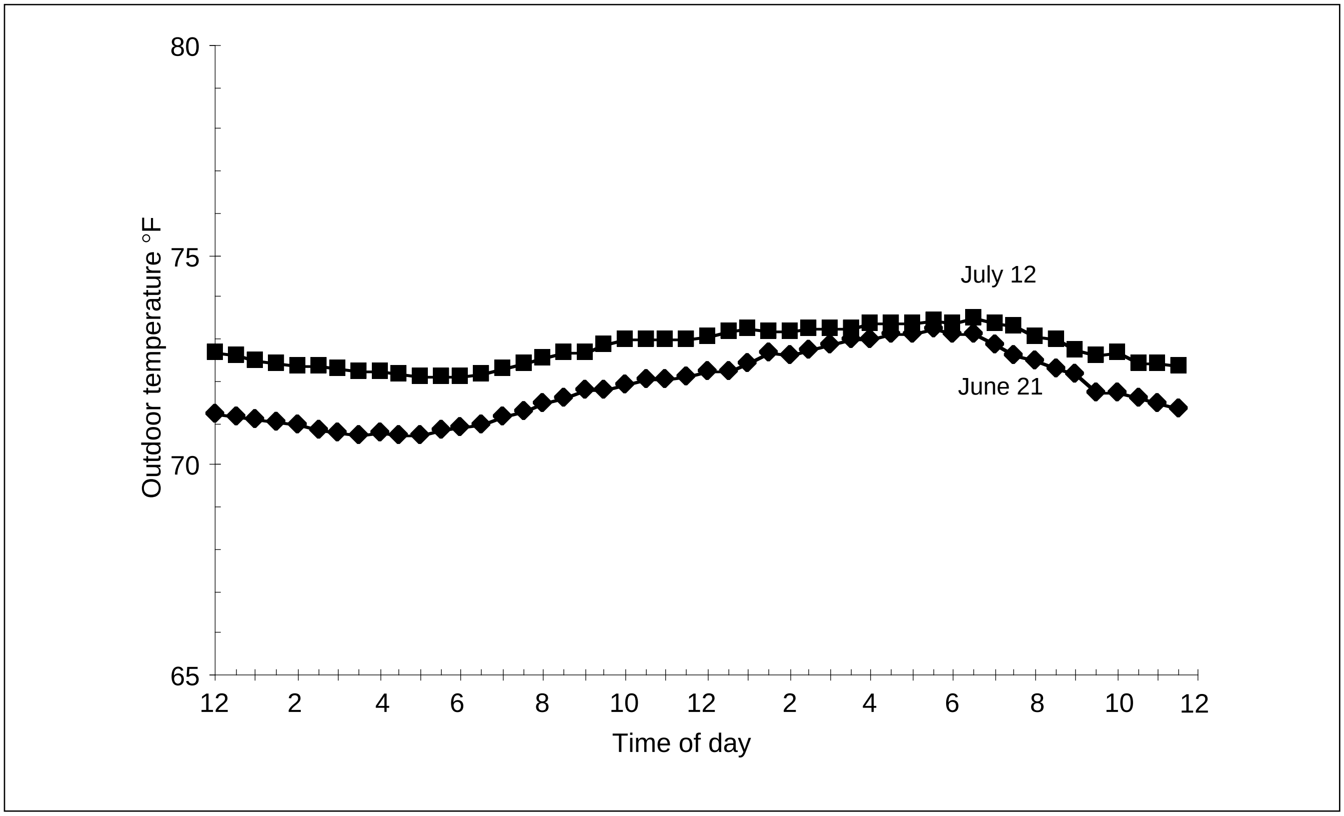


Figure 5 shows the percentages of dwellings at different temperatures at different hours of the day for a 97° day (July 14). This figure is read like a contour map with the variations in gray representing elevations. The hours of the day are represented on the horizontal axis and the indoor temperature on the vertical. The shadings of gray represent the percentage of customers in the temperature range.

This contour map shows that most dwellings had indoor temperatures below 80° throughout a 97° day. Only one customer had an indoor temperature that exceeded 85° (determined from inspecting the distribution of temperatures). There were a few dwellings where the temperatures exceeded 80°, usually one or two in each half-hour category. Looking across the graph at 79°, between 4 and 8% of households had temperatures ranging from 79° to 80° from 12:00 to 4:00 pm and from 8:00 to 10:00 pm.

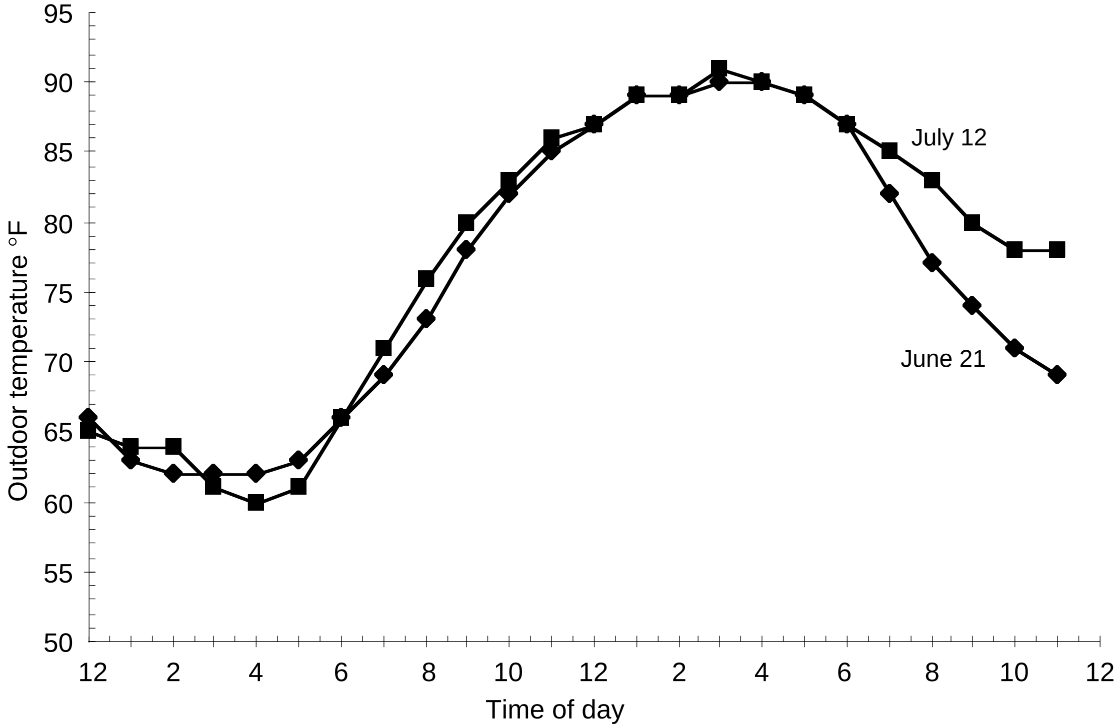
However, between 4:00 and 8:00 pm, the percentage of households with temperatures above 78.5°F drops. During these hours there is a cluster of between 8 and 12% of households with indoor temperatures around 77°. This pattern demonstrates what happens in the homes of customers who let the temperatures in their homes drift higher during the day when they are away from home and then lower their thermostat setting and therefore the temperature in their homes when they reoccupy the residence during the late afternoon hours. Later in the evening, temperatures are set higher again so that the temperatures in some homes increase. This distinctive pattern can be seen in the air conditioner duty cycle distributions (not shown).

These data indicate that most customers are managing their air conditioners so that they do not experience indoor temperatures above 80°F at any time on a high temperature a noncontrol day. However, the reader is reminded that the ambient temperatures experienced by the occupants of the residence may be a few degrees higher than the temperatures displayed in these graphs.

THE EFFECTS OF CONTROL ON TEMPERATURE

Figure 6 displays an indoor temperature difference curve. This is the difference in indoor temperature between a control day and a matched noncontrol day. The match days were selected by comparing the outdoor temperature for a control day with the outdoor temperature of all noncontrol days throughout out the summer. For each comparison, the hourly temperature difference between the control day and a comparison day was squared and summed to form a sum-

Figure 4. *Outdoor temperature profile for selected noncontrol days with maximum temperatures between 90°F and 93°F.*



of-squares of the temperature differences for the days being compared. Noncontrol days with low sums-of-squares were selected for further investigation. Additional criteria such as similar temperature profiles in the hours just before and during control were applied to assure good matches. Once a match day was selected, the indoor temperature for the match day was subtracted from the temperature for the control day to obtain the difference. As might be expected given this technique, the temperature differences prior to control period in figure 6 are very close to zero.

On July 13, which was a 97° day, the average temperature in dwellings rose by 1° within half an hour of the onset of control, by 1.5° within an hour and a half, and peaked at approximately 3° near the end of the control period. It should also be noted that the temperature dropped by about 1.5° within an hour and a half of the end of the control period although on this day the temperature did not return to zero as might be expected. There were many dwellings where the air conditioning systems were operating near capacity and could only reduce overall temperatures slowly. For instance 56% of the units had a duty cycle between .9 and 1.0 (running full time for all practical purposes) immediately following the release of control. This compares to about 25% of units on a similar hot day. At two hours after the release of control, 45% of the units were still running nearly full time compared to 20% on the noncontrol day. On the noncontrol day, all units had dropped below a duty cycle of .9 by 9:00 pm but on the control day at least 10% of the units were still running full time at this hour.

Figure 7 serves to amplify these points. Temperature rises rapidly after control is instituted at 1:00 pm. The maximum increase in temperature from these control actions is approximately 1.7 degrees which occurs about 4:30 just before control is released. Indoor temperature begins to drop fairly quickly after the end of the control actions at 5:00 pm but it does not decrease to its pre-cycling level immediately. Rather, the temperature decreases by about 1°F during the first hour and a half and then slowly declines for the rest of the evening. Indoor temperatures reach their pre-cycling levels by 11:00 or 12:00 pm. The slow decline after the initial decrease represents the recovery for dwellings with undersized units.

The other point to be made is that there is very little difference in the magnitude of the effect of the two strategies. In part that could be a function of the way units are sized. The number of units actually affected by the increase in control from 40% to 50% may not be large. Also, there may be enough variation in the control days and match days to reduce the differences.

Figure 5. *Percentages of dwellings experiencing temperatures at different times of the day, July 14, 1995.*

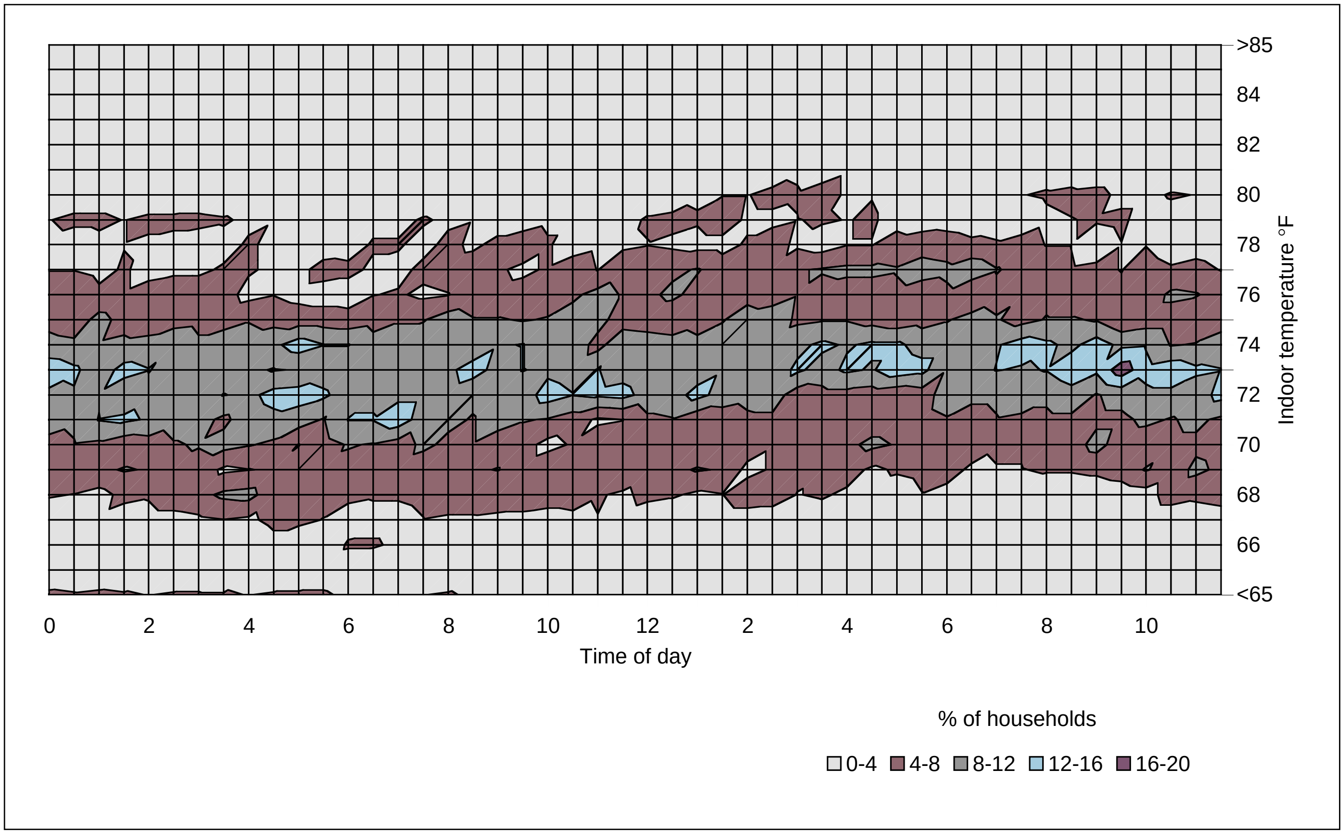


Figure 6. *Change of indoor temperature from a 50% cycling strategy on a 97°F day.*

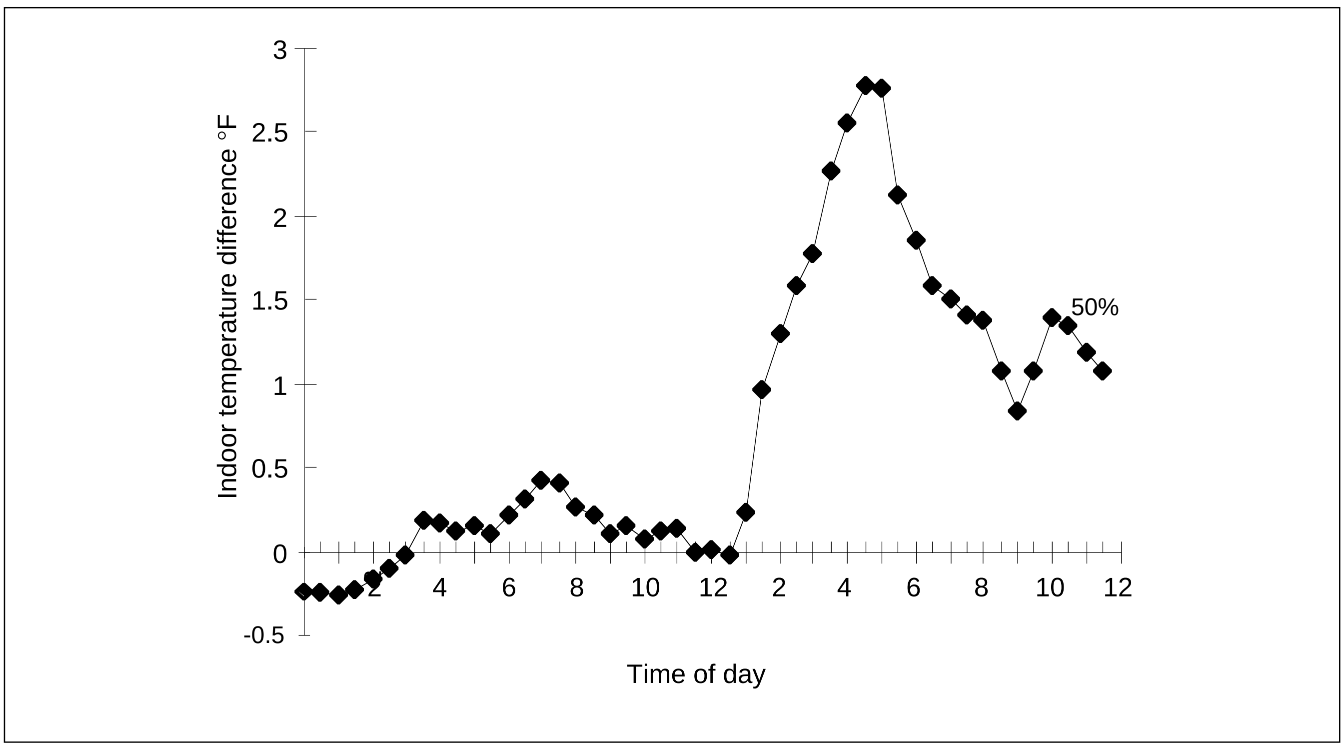


Figure 7. Change of indoor temperature from two different cycling strategies on a 90°–93°F days.

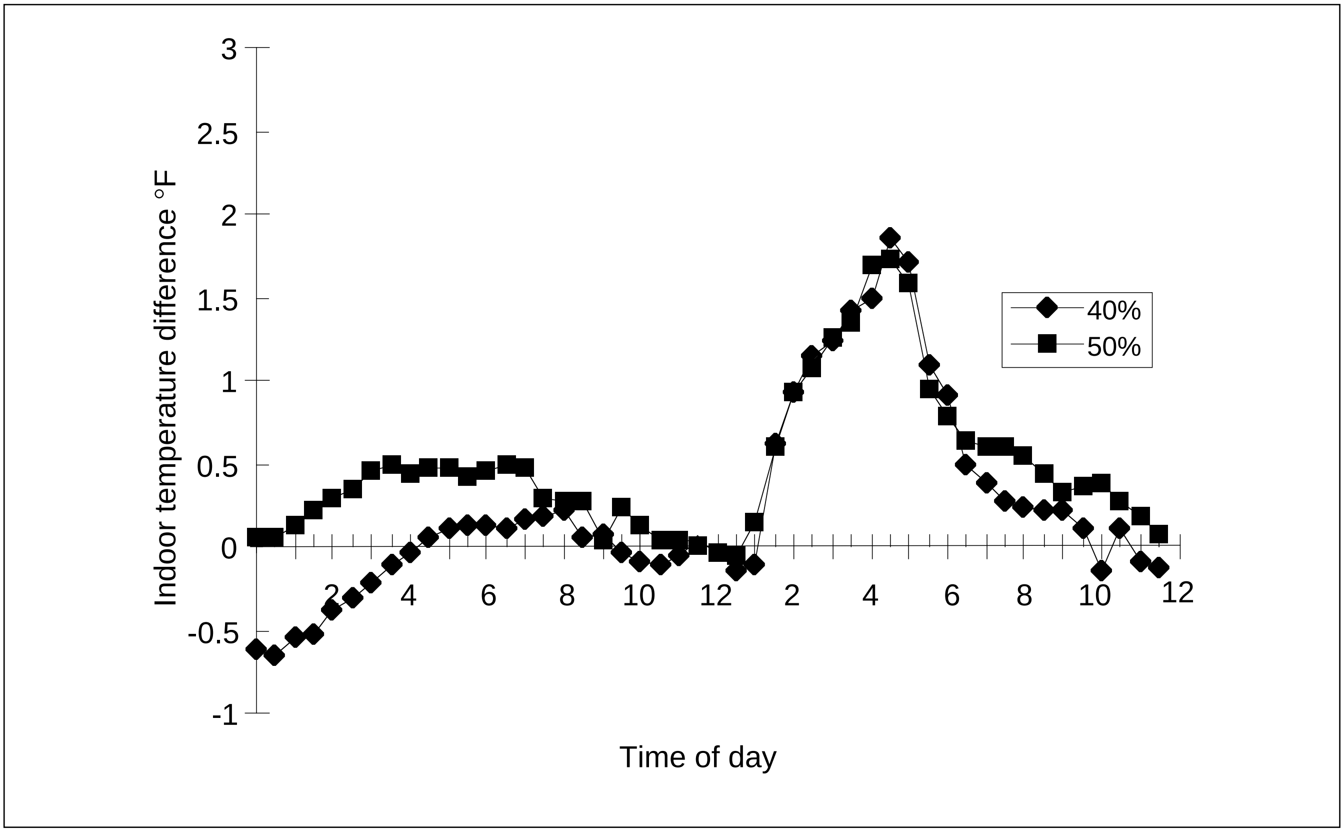


Figure 8 shows the temperature distributions in households on July 13, a 97°F control day. After viewing the figure, the reader may wish to return to Figure 5 which is for July 14, a comparable noncontrol day. When compared to July 14, the temperature distribution on July 13 shifted upward by 3° during the control period. Also, notice that on July 13 temperatures in dwellings had not fully returned to their pre-control levels by midnight.

Some 4 to 8% of households showed a slight excursion above 80° during and just after the control period. However, this is not dissimilar to what happened on the noncontrol day. Less than 1% of these households had a temperature that exceeded 85°. Also, it should be observed that roughly a sixth of the homes experienced temperatures that exceed 76°F during the control action.

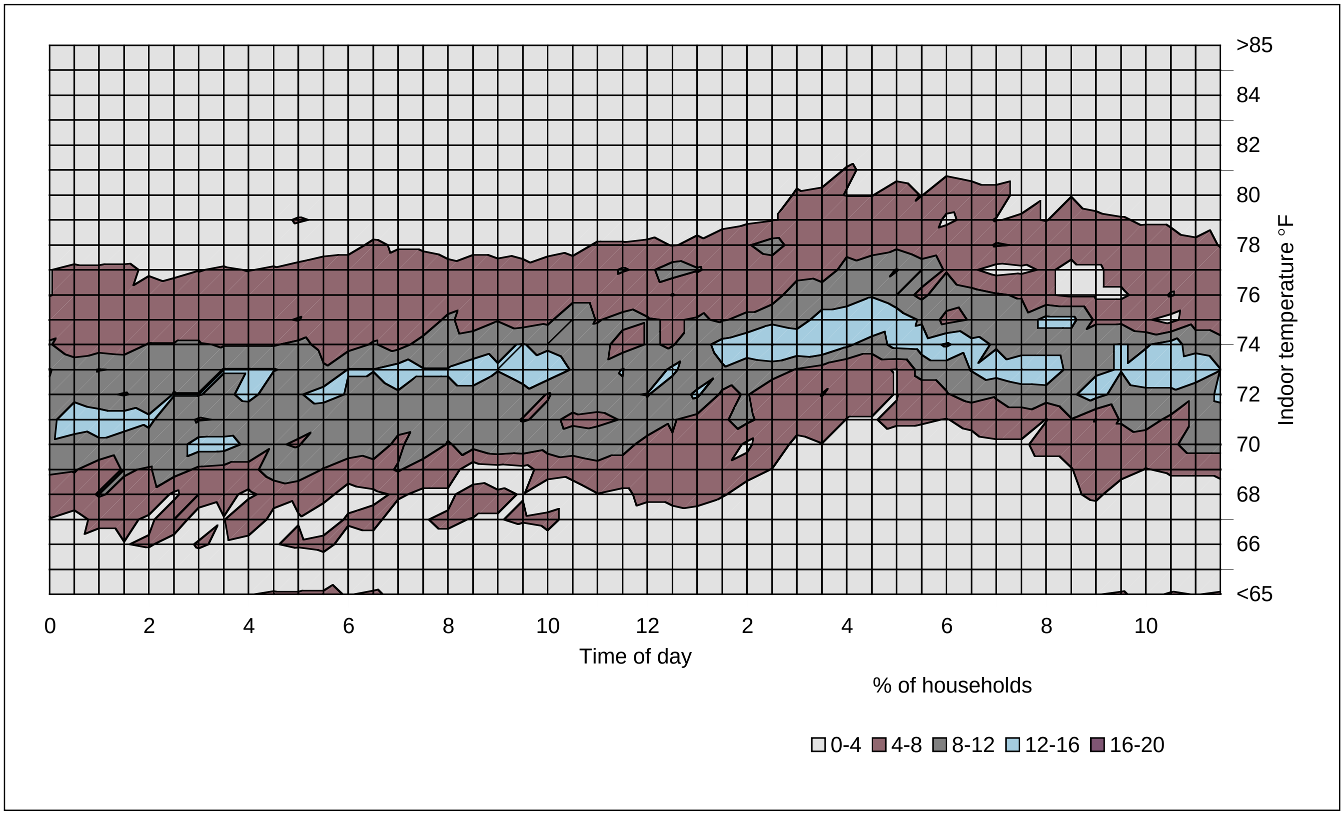
SUMMARIZING THE EFFECTS OF DIFFERENT CONTROL STRATEGIES, DIFFERENT HOURS OF THE DAY, AND THE EFFECTS OF INDOOR TEMPERATURES

Table 1 summarizes the effects on indoor temperature of the various control actions that were implemented during the summer of 1995. The table is organized by hours of control, daily maximum temperature category, and intensity of control. The maximum temperature change is the largest average temperature change in a half-hour period during the control period. The average temperature is the average temperature change during all 30-minute intervals for the control period (usually four hours).

The data show that the average maximum temperature increase in response to control was less than 2°F except for two days, one which was a very hot 97°F when the intensity of control was 50% and another which was a cooler 84° day, but where the intensity of control was higher, 75%. The average temperature increases for all control actions were less than two degrees.

Careful inspection of the values in this table lead to the conclusion that there is not a perfectly linear relationship between outdoor temperature, control strategy, and temperature reduction. Although there is not room to develop the point here because of space limitations, the effects of control, including temperature impacts, are driven by how householders use their air conditioners. Outdoor temperature is a necessary condition in the decision making process but the context of the weather in the days prior to control also play a substantial role.

Figure 8. *Temperature shift on July 13, a control day.*



CUSTOMER REACTIONS TO CONTROL

We have already seen that temperature swings in households in response to control are in the range of one to two degrees except on the hottest days. The question is, ‘‘How did customers respond to control?’’ The answer to this question depends on whether customers physically sense changes in temperature and having sensed a change in temperature, assign meaning and or importance to the change.

In this program, the controls were installed so that the indoor fan could run in the absence of the compressor. If during the control period the thermostat called for cooling, the fan ran even though the compressor did not. Customers would continue to sense air flow even if the temperature increased.

Customers had a relatively high general awareness that CPCo was cycling their central air conditioner during the summer of 1995. Over two-thirds (69%) of the respondents reported that CPCo had cycled their air conditioner during the summer. Seven percent said that they did not think that their unit had been cycled and 25% did not know whether or not CPCo had cycled it (Table 2).

Customers who said that they were aware that CPCo had cycled their air conditioner were asked how many days it was cycled. As shown in Table 2, 80% of respondents did not know how many days their air conditioner had been cycled. Among those who did, the largest percentage said it had been cycled between 60 and 90 days. Air conditioners were actually cycled on 32 days. Lack of awareness is probably not surprising since there would be days when customers did not have their air conditioning running or the duty cycle of the machine would be low enough so that households would either not know that control had taken place or would not have experienced any significant effects of control.

When customers were asked how they knew whether there was cycling, the most frequent response was that the house was not as cool as it usually was on some days (reported by 26% of respondents) or that they did not hear the air conditioner turn on as often (24%). Less than one percent customers in the sample said that their house got uncomfortably warm.

When asked directly if their house got uncomfortably warm during the summer because of having their air conditioner cycled, fewer than 17% of those responding (20 customers) said ‘‘yes’’ (Table 3). Customers who used their air condi-

Table 1. *The Effects of Different Load Control Strategies at Different Hours of the Day on Days with Different Temperatures*

Time of control period	Temper- ature range	Strategy	Maximum average temper- ature increase	Control period average temper- ature increase
1–5 pm	77-79F	40%	0.18	−0.06
	77-79F	75%	1.04	0.67
	80-83F	40%	1.38	0.96
	80-83F	75%	1.82	1.07
	84-86F	40%	1.57	0.97
	84-86F	50%	1.07	0.60
	84-86F	75%	1.38	0.88
	87-89F	33%	0.40	0.20
	87-89F	40%	0.89	0.59
	90-93F	40%	1.85	1.07
	90-93F	50%	1.72	1.10
	94F +	50%	2.78	1.68
3–7 pm	77-79F	75%	1.84	1.14
	80-83F	40%	0.78	0.48
	80-83F	50%	1.53	1.03
	84-86F	33%	1.10	0.70
	84-86F	40%	1.27	0.84
	84-86F	50%	0.86	0.56
	84-86F	75%	2.27	1.49
	87-89F	33%	1.00	0.82
	87-89F	40%	1.03	0.66
	90-93F	50%	1.74	1.26

tioner on a daily basis were no more likely than those who used it less frequently to say that their house got uncomfortably warm during cycling. Customers who reported their house got uncomfortably warm because of cycling were asked how many times that occurred. For one-third of these 20 customers, the house got uncomfortably warm only one or two times while for another one-fourth of these customers the house was uncomfortably warm three to four times.

SUMMARY AND CONCLUSIONS

This paper reports indoor temperatures for the summer of 1995 for 200 households in Grand Rapids, Michigan, and discusses the effects of direct control of air conditioners on indoor temperatures. The average half-hourly uncontrolled indoor temperature, as measured in the return air plenums, typically fell within the range of 70°–75°F. Average indoor temperatures exceeded 75° on some warm, but not hot, days when air conditioning was not being widely used. Inspection of distributions of the average half-hourly temperatures revealed that only one or two homes had temperatures that exceeded 85° on a 97° day. For any half-hour interval on that same day, 1–5% of homes had temperatures between 80° and 85°, and the remaining homes had temperatures below 80°. Some people set their thermostats higher during working hours and reduced them in the late afternoon and early evening before raising the setting again in the evening.

On days when air conditioning was controlled, the maximum half-hourly change in average indoor temperature was about 2.7°F. This was for a 50% control strategy on a 97° day. A more severe strategy on a similar temperature day would have caused a larger temperature change. The average temperature change for the four-hour control periods was less than 2°F. In most households, temperatures returned to pre-cycling conditions within one to two hours after control was completed for the day except on days when the temperature exceeded 90°. On those days, indoor temperatures in some homes did not return to pre-cycling conditions for four to six hours.

While customers were generally aware that they were being cycled, very few were able to specifically pinpoint how often they were cycled. Also, only about a sixth of customers indicated that they became aware of the cycling because of indoor temperature changes. Furthermore, many of those who indicated that cycling had made their dwellings warmer said this had occurred on four or fewer occasions. This would be consistent with the control on the hottest days.

These data indicate that for these households and for the control strategies that were used, the effects of control on indoor temperatures were not large and there were not widespread reports of discomfort.

Table 2. *Customer Awareness of Air Conditioner Cycling*

Awareness issue	Percent of households
Were you aware that your air conditioner had been cycled in 1995?	
Yes	69
No	7
Don’t know	25
N	175
If aware, how did you know it was being cycled?	
House was not as cool as it usually was on some days	26
Didn’t hear the air conditioner go on as often	24
Couldn’t really tell when it was being cycled	23
Looked at the control box on the air conditioner	5
Called CPCo to check if the unit had been switched off	3
Noticed the bill credit	2
Don’t recall	10
N	120
If aware, how many days was your air conditioner cycled?	
2 days or less	2
3 to 5 days	2
6 to 19 days	2
20 to 29 days	3
30 to 39 days	3
40 to 59 days	2
60 to 90 days	7
Don’t know	80
N	120
Average number customer-recalled days	40
N	24

Table 3. *Reported Problems with Air Conditioner Cycling*

Reported Problem		Percent of Households
The house got uncomfortably warm as a result of cycling		17
	N	120
The number of times my home got uncomfortably warm		
	1 to 2 times	35
	3 to 4 times	25
	5 to 6 times	15
	7 to 10 times	5
	10 or more times	10
	Don't know	10
	N	20

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