Central Air Conditioner Usage Patterns in Low-Income Housing in a Hot and Humid Climate: Influences on Energy Use and Peak Demand

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Traditional wisdom suggests that mechanical cooling is unnecessary in low-income housing. However, field research from a year of monitoring ten occupied low-income homes built in South Florida reveals that while space cooling is by far the largest electrical end-use, reliance on natural ventilation alone can result in very uncomfortable conditions without improved building design. The data also suggest that very different air conditioner usage patterns are prevalent in the homes, which have a large impact on energy use. The resulting differences in thermostat settings and cooling system control can lead to wide variations in cooling energy consumption and with important implications for potential energy saving strategies. The one home using natural ventilation (with infrequent air conditioning) experienced very high internal temperatures—far above the comfort range. Surprisingly, the home which consumed the least amount of energy for space cooling used the air conditioner for the entire summer at a constant thermostat setting.

The ten homes, built by Habitat for Humanity in early 1992, are very similar in construction. Air conditioning energy use averaged 22 kWh/day from July–October of 1994. Cooling energy use varied by approximately 4:1 from the highest to the lowest consuming households. Two factors were shown to account for over 90% of the variation. Each degree centigrade lower that the thermostat was set increased daily AC use by an average of 5.0($\pm$1.0) kWh or 23%. Another significant factor was the recorded energy use of internally located appliances and associated heat gain. Each kWh of added internal appliance energy use was found to increase AC consumption by 0.39($\pm$0.35) kWh or 2%. The study suggests that programs which emphasize efficient control of space cooling systems and improved efficiency lighting and appliances may be among the most effective in reducing utility costs in such homes.

BACKGROUND

Over the last forty years, residential air conditioning has become pervasive in Florida. In 1950, virtually no homes had mechanical cooling, relying instead on vernacular architecture, landscaping, white roofs, ventilation and fans to provide comfort (Langewiesche 1950). However, the burgeoning popularity of mechanical cooling reflects the hot and humid climate and the fact that traditional methods did not always ensure comfort during the hottest periods. Historically, the percentage of air conditioned homes in the state soared from a mere 18% in 1960 to 90% in 1990 (Shrode et al. 1975, SRC 1992). Today, space cooling is considered an integral part of the Florida lifestyle. In new Florida homes, 98% reported air conditioning use between May and September of each year, while only 8% reported the use of natural ventilation during the same period (Vieira & Parker 1991). Regardless of those who may condemn its indulgence (Prins 1992), air conditioning is considered a vital necessity by most residents. As newcomers to the state say: ''. . . but of course, we couldn't live here if it wasn't for air conditioning . . .''

INTRODUCTION

As a part of a control group for a new energy-efficient development under construction by Homestead Habitat for Humanity[1], Florida Solar Energy Center (FSEC) is monitoring ten houses, previously built by the organization in Florida City. These current-practice buildings will be monitored for up to two years to compare them with energy-efficient houses in a new Habitat for Humanity community. By the beginning of November 1994, the project had collected four months of data on the air conditioning and other end uses. The recorded data from the control group homes (hence called the study homes) allows unique insight into behavioral aspects of residential space cooling.

At the end of the cooling season, the person primarily responsible for controlling the cooling system was interviewed at each home. The interview questions were designed to provide detailed information about how the cooling systems were controlled as well as the occupant's reasons for operating the systems as they do.

THE HOMES AND THEIR OCCUPANTS

The study homes are located in Florida City, south of Miami, Florida. Built in 1993, there are two similar building models in the project, both with simple rectangular floor plans. The houses with three bedrooms have a conditioned floor area of 96 m^2 (1030 square feet); the houses with four bedrooms have a floor area of 111 m^2 (1190 ft^2). The construction is conventional for South Florida: concrete block on an uninsulated slab with an exterior light colored stucco finish and A-frame roof covered by asphalt shingles. The homes generally face north or south with a small porch over the entrance. The concrete block walls are insulated with RSI-0.5 $m^2 \cdot K/W$ (R-3 $ft^2 \cdot hr \cdot °F/Btu$) insulation on the interior; the attic has RSI-3.3 (R-19) fiberglass batts over the sheetrock ceiling. The windows are single glazed units with aluminum frames and are single-hung so that about 40% of the aperature area can be opened for ventilation. Most of the homes' windows are located on north or south exposures. Several homes in the development are illustrated in Figure 1.

The mechanical cooling system in the houses consists of 7.0 kW_t (2.0-ton) air conditioners in the three bedroom homes and 8.8 kW_t (2.5-ton) air conditioners in the four bedroom units. The split systems are conventional with an interior evaporator and air handler located in a small utility room. The units have a rated seasonal coefficient of performance (SCOP) of 3.5 W_e/W_t (SEER = 12.0 Btu/W).

Figure 1. *A view of the Habitat homes in the Florida City developments.*

The cooled air is distributed through a ducted system in the attic to ceiling mounted supply registers. The air distribution system consists of approximately 15 m (50 ft) of RSI-0.9 (R-5) flex duct. Thermostat control is located in the interior hallway on an interior wall. The slide type thermostat has a set range from 10–32°C (50–90°F) with two toggle switches for mode selection (heating/off/cooling). The fan mode selection has two modes: ''on'' where the fan runs constantly regardless of the compressor operation and ''auto'' in which the fan operates only when the heat strips or compressor is energized.

The major appliances in each home are: a 154 L (40 gallon) electric resistance storage water heater, a 510 L (18 ft^3) refrigerator, an electric clothes dryer and range, and a washing machine. Several homeowners have added a chest freezer. Except for the refrigerator, all the appliances are located in a small conditioned utility room which is generally left closed. Lighting in the homes is conventional incandescent. Typical minor appliances include a living room ceiling fan, microwave oven, television, and stereo.

Occupant density in the development is fairly high. Whereas occupants number 2.4 in the average Florida household, the Habitat homes have an average of 4.6 members (University of Florida 1993). The households vary from a maximum of eight occupants per home to a minimum of three and all have one or more children of varying ages. Although income information is not available, Habitat for Humanity's mission is to provide affordable housing for low-income families. Each household has been in residence for a year or more and although the homeowners have an interest-free mortgage payment for their homes, they are responsible for payment of their monthly utility bills. We found the head of household at each house to be very aware of their monthly utility expenses. At least one family (House 4) has only very limited prior experience with air conditioning systems.

MONITORING

In April, of 1994, research engineers visited the ten sites in Florida City. The homeowners were interviewed after which each site was audited and physically measured for the instrumentation. Multi-channel data loggers and associated metering equipment was installed in late June of 1994 with the site data collection system becoming operational by mid-July.

Detailed performance data are being collected at each house, including energy use of all major appliances, meteorological conditions and interior house conditions such as temperatures, water use and window ventilation status. This includes 15-minute data on seven electrical end uses as well as total demand. A detailed description of the instrumentation and energy use patterns of non-AC appliances and equipment are contained in two other reports (Parker et. al. 1994, 1996).

A unique part of the monitoring process is the ability to detect when the home's windows are opened for natural ventilation. Contact switches were installed on the most commonly opened windows for ventilation. This allows researchers to determine the fraction of each 15 minute data interval during which the building's windows are opened for natural cooling or for other purposes.

Impacts of internal heat gains from appliances and occupants on space cooling energy use is widely acknowledged (Abrams 1986). Typically, such sensible heat must be removed from the interior to meet the thermostat setting. Another innovative part of the monitoring protocol is that all electrical end uses that take place within the potentially conditioned space are sub-metered so that interior levels of appliance heat gain can be assessed in their impact on air conditioning needs. Miscellaneous electricity use for lighting and other plug loads are obtained by taking the difference of the total recorded site electrical use from the recorded energy use of the various sub-metered major appliances. The dataloggers scan the various instruments at 5 second intervals and integrated or totalized values are output to storage every 15 minutes. Data are transferred from the dataloggers via modems and dedicated phone lines to the project mainframe computer each evening.

RECORDED ENERGY END-USES

Table 1 and Figure 2 summarizes a breakdown of measured energy end-use in the ten homes from July 24th to November 1, 1994. On average, about half of the daily 45 kWh of average summer electricity used was for air conditioning. Within the individual households AC accounted for between 44% and 61% of the total ranging from 9.3–36.4 kWh/day. These data provide insight into the magnitude of AC electricity consumption relative to other household energy end-uses during the cooling season. The next largest end-use, water heating, is much lower at 18% of the total consumption. The magnitude of the measured cooling loads in the homes suggests that technologies and architectural solutions that can reduce such loads would be highly desirable. Such measures include many which FSEC has extensively researched: light colored roofing surfaces, improved windows and window shading, whole house ventilation, and high efficiency cooling systems. However, less attention has been paid to ''human factors'' which may have equally important implications for reducing cooling energy use.

VARIATION IN COOLING SEASON ENERGY USE

Since the study homes are virtually identical and have the same models of air conditioners and appliances, the metering allows unique examination of the differences in space cooling that are attributable to occupant behavior. In installing the equipment, FSEC technicians were careful not to alter equipment settings or suggest changes to occupant behavior. Thus, within the limitations of the control group sample size, the project allows examination of how differences in space cooling energy use can be affected by household control of cooling equipment.

The variation of space conditioning demands arising from occupant behavior has been consistently noted in previous monitoring efforts. Early studies at Princeton's Twin Rivers project showed differences between otherwise identical townhouses of 2:1 in space conditioning energy (Sonderegger 1978). Similarly, a study of air conditioning use in 25 homes in Palm Beach, Florida showed a 100:1 variation in space cooling energy, mainly based on differences in ventilation behavior (Parker 1990). The variation was still 7:1 when primarily air conditioning households were considered.

Within the study homes, daily air conditioning electricity use varied by nearly 4:1 from the highest to lowest user. Mean air conditioning use among the three and four bedroom homes was similar (21.4 and 23.4 kWh/day, respectively). This suggests that factors other than intrinsic physical differences are responsible for the large variation in space cooling energy use.

Research literature suggests that the origin of these differences are behavioral in nature (e.g. Stern 1985; Kempton et al. 1992; Lutzenheiser 1992). Occupants can express differences in their methods of obtaining cooling comfort based upon ''on-off'' scheduling of the AC system, preference for interior temperature settings, ventilation and window behavior, use of drapes and blinds and zoning of supply registers.[2]

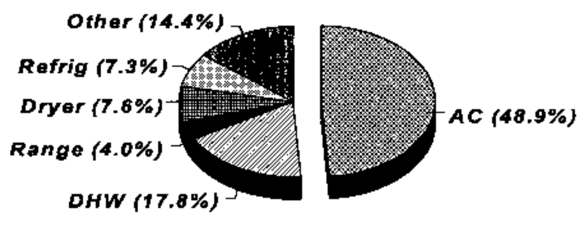
There are also indications of widespread user misunderstanding of the way in which cooling systems operate. For instance, a survey of apartment behavior in New Jersey (Kempton et al. 1992) found a common belief that the setting controlled rate of cooling rather than the thermostat. Kempton also found that many who understood thermostats believed that more extreme settings would change interior temperatures more rapidly (1986). The surveyed users also believed that the air conditioner would use more instantaneous power at cooler settings. Such misconceptions may influence the way in which AC systems are controlled.

Several previous studies have emphasized the need to understand occupant behavior as it relates to thermostat management (Gladhart & Weihl 1990; Peters 1990; Turner & Gruber 1990). Also, an earlier investigation in Florida found that control of air conditioning systems in new homes is varied and complex (Vieira & Parker 1991). For instance, although

Table 1. Energy-End Use at Habitat Sites: July 24–November 1, 1994

House ID	Bed-rooms	Occu-pants	Control Strategy	Total kWh	AC kWh	DHW kWh	Dryer kWh	Range kWh	Refrig. kWh	Freez. kWh	Miscel. kWh	Interior Temp (°C)
H01	4	8	Constant	56.2	27.1	8.3	4.6	1.4	1.7	2.9	10.2	24.4
H02	3	4	Switched/ Vent	62.1	26.8	12.9	2.3	5.0	2.3	1.2	11.6	24.6
H03	3	3	Switched/ Adjust	37.9	16.8	6.7	3.4	1.5	2.4	N/A	7.2	25.3
H04	4	8	Switched/ Vent	59.4	26.2	11.3	6.4	4.3	3.0	N/A	8.3	24.4
H05	4	3	Switched	36.6	17.0	6.7	5.0	0.9	2.1	N/A	4.8	25.6
H06	3	5	Constant	49.0	23.6	11.2	4.4	1.7	2.1	2.2	3.9	24.2
H07	3	4	Constant	38.1	23.1	5.5	2.6	0.9	1.8	N/A	4.3	25.2
H08	3	5	Constant	64.0	36.4	10.8	4.1	1.5	2.1	3.6	5.4	21.6
H09	3	3	Constant	19.8	9.3	2.8	0.5	0.1	2.6	N/A	4.4	26.7
H10	3	3	Switched/ Adjust	25.0	13.5	3.7	0.5	1.0	2.5	N/A	3.9	26.4
Avg.	3.3	4.6		44.8	22.0	8.0	3.4	1.8	2.3	1.9	6.5	24.8

Figure 2. *Energy use at ten Habitat homes. Avg: July 24–Nov. 1, 1994 = 45 kWh/day.*



the average reported thermostat set temperature in 384 surveyed households was 25.4°C (77.7°F), 15% reported switching the air conditioner on and off to achieve comfort, 44% reported adjusting the thermostat up and down to control its operation, while only 41% reported a constantly unchanged thermostat setting.

Air Conditioner Control Strategies

Scrutiny of the metered temperature and interview data from the Habitat homes cast doubt on the commonly used engineering assumption of a constant thermostat set point or schedule. Although a single daily thermostat setting was a common mode of operation, an equal number of households employed other thermostat strategies to maintain comfort. Such behavior has already been demonstrated for room air conditioners, but explicit evidence from central air conditioned homes has been lacking save in limited studies in California (Lutz & Wilcox 1992).

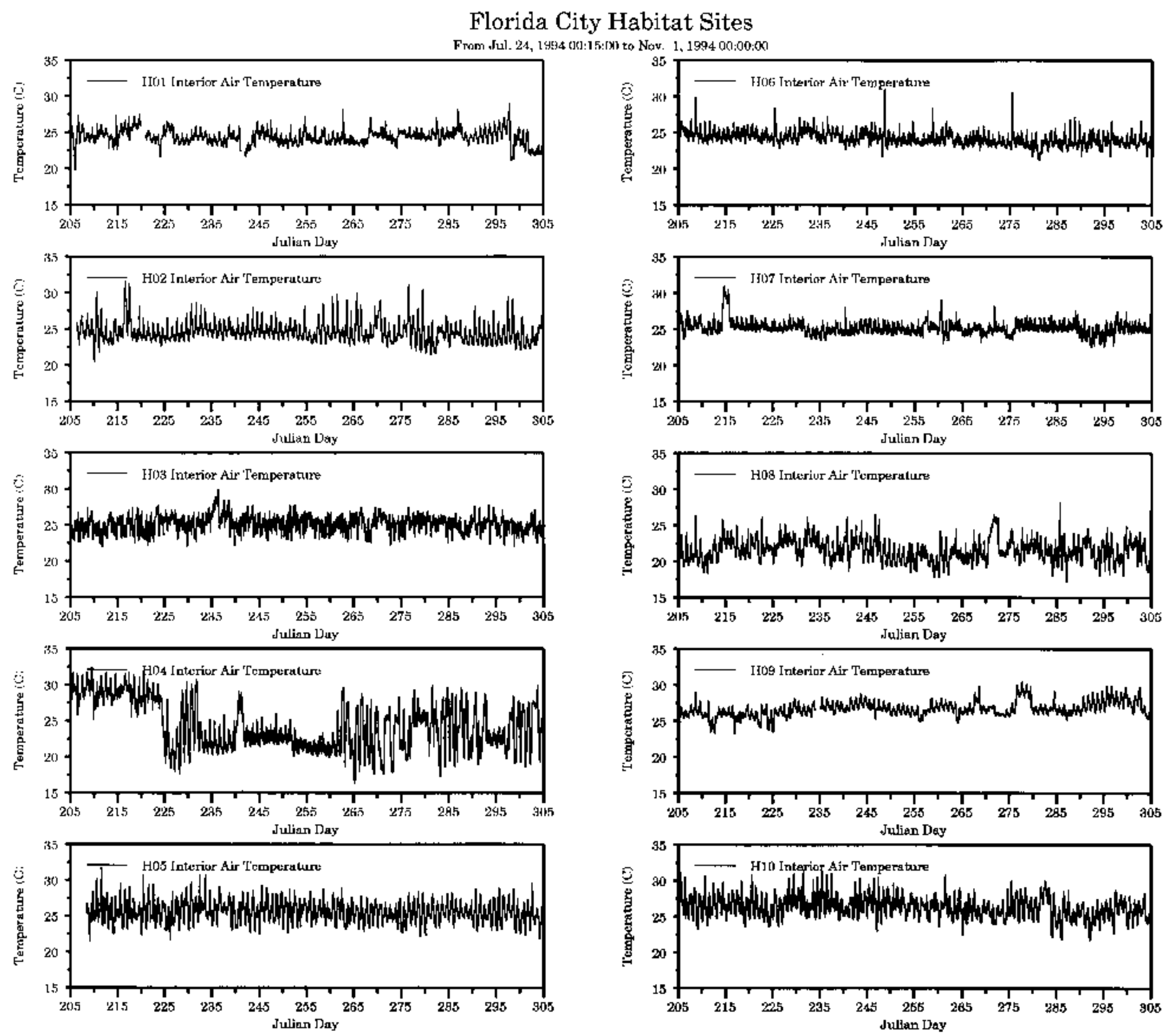
We infer two unique control strategies that were being used by the Habitat home occupants to operate their cooling systems. These were determined both from review of the instrument data as well as from a series of interviews conducted with the occupants in December 1994. There are also a number of variations on these modes of operation. Examination of daily data from the Habitat houses, as reinforced by the follow-up interview revealed two primary thermostat management strategies and a number of variants:

- Constant, daily thermostat setting (Houses 1, 6, 7, 8, 9)
- Switched or adjusted
  —On/off (House 5)
  —Thermostat adjusted (Houses 3 and 10)
  —with ventilation (House 2 and 4)

The first strategy, a constant thermostat setting was used in half the homes. Occupants following this strategy set the AC thermostat at a given temperature which is often not altered for many days. Figure 3 shows the measured interior temperatures for all ten homes over the entire monitoring period (July 24th–November 1, 1994). The recorded data show a more generally even temperature inside these houses. The exception is House 8 where the thermostat is set to 18.3°C. (65°F) which the air conditioner can seldom achieve; the temperature inside then varies throughout the day with the cooling load.

In the interview, the households following the constant thermostat strategy typically indicated that the air conditioner is left on most of the time with little change of the thermostat or opening of the house for ventilation. For instance the female head of household at House 9 said, ''I prefer the air

Figure 3. *Measured interior temperatures at ten sites: July 24–November 1, 1994.*



conditioner because I don't like to leave the windows open [for security].'' The air conditioner is not turned off, even when no one is home, ''I just leave it alone [the thermostat] and it goes off and on by itself . . . I don't turn it off and I don't change the thermostat, it always stays at 78°. . . I find it to be very comfortable at 78°. . . When I come home and come in, it's cool, not cold.''[3]

The other five houses used a ''switching'' control strategy. This involves frequent changes in the operation of the cooling system thermostat. There were three variants on this theme. In one variation, the occupants would physically turn the cooling system off, frequently when they knew they would be away from the house during the daytime hours. Said the thermostat manager at House 7, ''I leave it set at 75°—the baby has asthma and can't be too hot—and we turn it off when we're gone for the day.'' The second variation was used by House 5 and House 10 where the thermostat was set up while the occupants were away from home. Said the mother at House 10: ''I don't really like air conditioning . . . I get cold easily and like fresh air from the windows open.'' However, she admits that the major reason for not ventilating the house is due to the very warm and humid weather and the fact that her son has a medical condition which necessitates that he not become overheated. She sets up the thermostat manually when she is going to be away from the house for several hours based on the recommendation from the local utility. ''When I'm going to work, I turn it up and leave the air on so that it is not so hot when I come home.''

The third variation of the switching strategy, the use of ventilation, is common at House 4 and to a lesser extent at House 2. House 4 frequently air conditions only during evening hours when the male head of household is home, with the thermostat apparently set to 21°C (70°F) or less. During the daytime hours, although quite hot outside, the house is opened up and naturally ventilated. One of the most important findings from the project came from House 4's reliance on natural ventilation and its implications for interior air temperature. This is important since many Habitat affiliates in the Southern U.S. advocate not providing air conditioning in affordable housing and relying instead on cross ventilation.

However, in spite of having windows on three sides of the main living area, interior air temperatures greater than 31.1°C (88°F) were measured frequently at House 4 during the summer of 1994 even with windows open (the daily plots clearly indicate when windows are opened and closed at each site). The measured peak temperature during such summer natural ventilation was 32.4°C (90.4°F) with a coincident relative humidity of 63%. Temperature and humidities such as these are well beyond the established range for human comfort (ASHRAE, 1993). Excessive heat can lead to sweating, salt depletion, and heat exhaustion. As demonstrated by mortality figures during heat waves, such conditions can be fatal to infant or elderly occupants with lower tolerance to thermal extremes (Lee 1953). Moreover, numerous studies show that mental acuity falls off rapidly when subjects are exposed to temperatures greater than 30°C (86°F) (McIntyre 1980). This has implications for the acceptability of the home learning environment for school-age children. In addition, two of the households interviewed volunteered that they had members with medical conditions which required air conditioning. It is noteworthy that House 4 used natural ventilation, not from choice, but from economic necessity. They ''would use the air conditioner more, but bills are already too high [up to $200/month].''

At House 2 the home is primarily controlled by a varying thermostat setting. The mother and oldest son are at odds with each other over the desirable temperature: ''Benny turns it down,'' she gestured, ''and I turn it back up . . . Benny likes to be cold, especially at night . . . he says he sleeps better that way.'' The windows were kept closed during the hottest part of summer. However, beginning on September 14th (Julian Day 257) the AC was turned off and the windows opened several times a week. However, the reason here is not energy conservation, but ''to get rid of the stuffiness inside with some fresh air.''

Although no statistical significance can be attached to the results, segmenting the data into thermostatically-controlled and ''switched/adjusted'' groups showed 16% lower cooling energy consumption in the later group. However, segregation of the sites into these groups is somewhat arbitrary. Even sites exhibiting a ''constant thermostat setting'' often turn off the air conditioner for periods of time in which they are away and most homes adjusted their thermostats with surprising frequency. One household changed the setting on a daily basis; others changed their's weekly or at least once every month. The frequency with which thermostat settings are altered or the AC is turned off during vacant periods are noticeable in the data, but appear fairly random. Figure 3 shows a two-day vacant period in early August for Site 7 (Julian day 214) as well as two changes to the thermostat setting in the later half of the month (Julian day 230–240). House 8 left the thermostat slide switch in a very low setting at 18°C (64°F) and did not alter this control until October 14th (Julian Day 287) when the house interior temperature dropped below 17°C (63°F). The air conditioner at House 8 ran almost constantly and used the greatest amount of cooling energy of all the households (36.4 kWh/day). It is also interesting to observe that even homes with a constant thermostat setting do not necessarily maintain a constant interior temperature due to AC capacity limits and thermostat response characteristics.

THERMOSTAT SETTING

Equally as interesting as the occupant-reported reasons for selecting a control strategy were the reasons the occupants gave for selecting thermostat settings. Similar, to previous reports, our interviews revealed frequent disagreements within households on the desirable cooling temperature.[4] An example from one household (Moore, 1994):

> ''I'm always cold and she's always hot, and the thermostat keep going up and down. We agree on a lot of things, but not on thermostats. If it's too cold, I'll go outside and sit on the back porch. And when she takes off, I'll go back inside and turn the thermostat up. We go round and round . . .''

Another example comes from the circumstances at House 9. The female head of the household maintains a constant inside temperature of about 27°C (80°F)—even when away from home—and had the lowest air conditioning consumption of any of the monitored homes. However, she admits that ''my daughter is always hot and she wants the air on all the time. I ask her if she's cold if I turn it down, because I'm always cold then . . . I'm anemic and stay colder.'' Her daughter has adapted to the situation by using a portable fan in her room.

The other end of the spectrum is illustrated by the mother at House 1: ''I like it cold at about 72°.'' However, like several others, there was dissension amongst household members in terms of the favored temperature. ''I'm always hot,'' she maintained, ''my husband and my oldest child complains. He's from Panama and he doesn't care if we run the AC or not . . . I stay warmer than they do . . . I tell them to put on blankets or more clothes and socks.'' The only time she remembered the windows being opened at the home was ''for fresh air when I give it a serious cleaning . . . It's too hot outside here to open the house up.'' House 5 also reported similar disagreements. The mother likes the air conditioner, but switches the thermostat up ''to keep the bill down when no one is home.'' The thermostat is set lower when everyone returns beginning at about 3 PM. A lack of adequate breeze and security concerns prevent them from opening the front windows. ''I try my best to keep the AC at 75°,'' she said, ''but these girls—they're hot-blooded and they always want it cool all the time.'' The mother sets the thermostat up to 80°F when she is away for three hours or more. Although she is the primary thermostat manager, she admits that her daughters frequently alter the settings ''I try my best, but my daughters put it to 70°F. . . we go back and forth.''

A number of occupants reported a low temperature was important for them to get a good night's rest. The male head of the household at House 6 works evenings and must sleep during the day: ''Sometimes it [a high temperature] affects my sleeping, and you know when you get home in the morning. . . all you want to do is sleep. I can't sleep too well at 6 AM if its hot.'' House 5's members agreed; there the thermostat is adjusted frequently at least twice a day and is set down to 22°C (72°F) before bedtime. ''Its important to keep cool at night,'' the female head of household explained, ''we all like it cool to sleep.''

DETERMINANTS OF AC ENERGY USE

Figure 4 shows the AC energy use at the ten sites over the entire cooling season from July 24th–November 1, 1994. Coupled with Figure 3, the information provides a clear picture of AC usage patterns. For instance, the strange AC load profile at House 1 around julian day 287 results from the AC fan being set to the ''on'' position rather than ''auto'' so that power demand no longer falls to zero. Similarly, a period of natural ventilation without air conditioning is apparent at House 9 near the end of the monitoring period.

We used multiple regression model was used to examine how total summer cooling energy use varied with physical parameters expected to influence cooling demand. Although the sample is small, results from the model indicate that interior recorded temperature (a surrogate for thermostat setting) and measured interior appliance energy use can explain much of the observed variation from one home to the next:

$$\text{kWh} = 2.12 + \underset{[8.87]}{4.98(\Delta\text{Tint})^*} + \underset{[2.05]}{0.392(\text{kWh}_{app})^*}$$

$$R^2 = 0.933$$

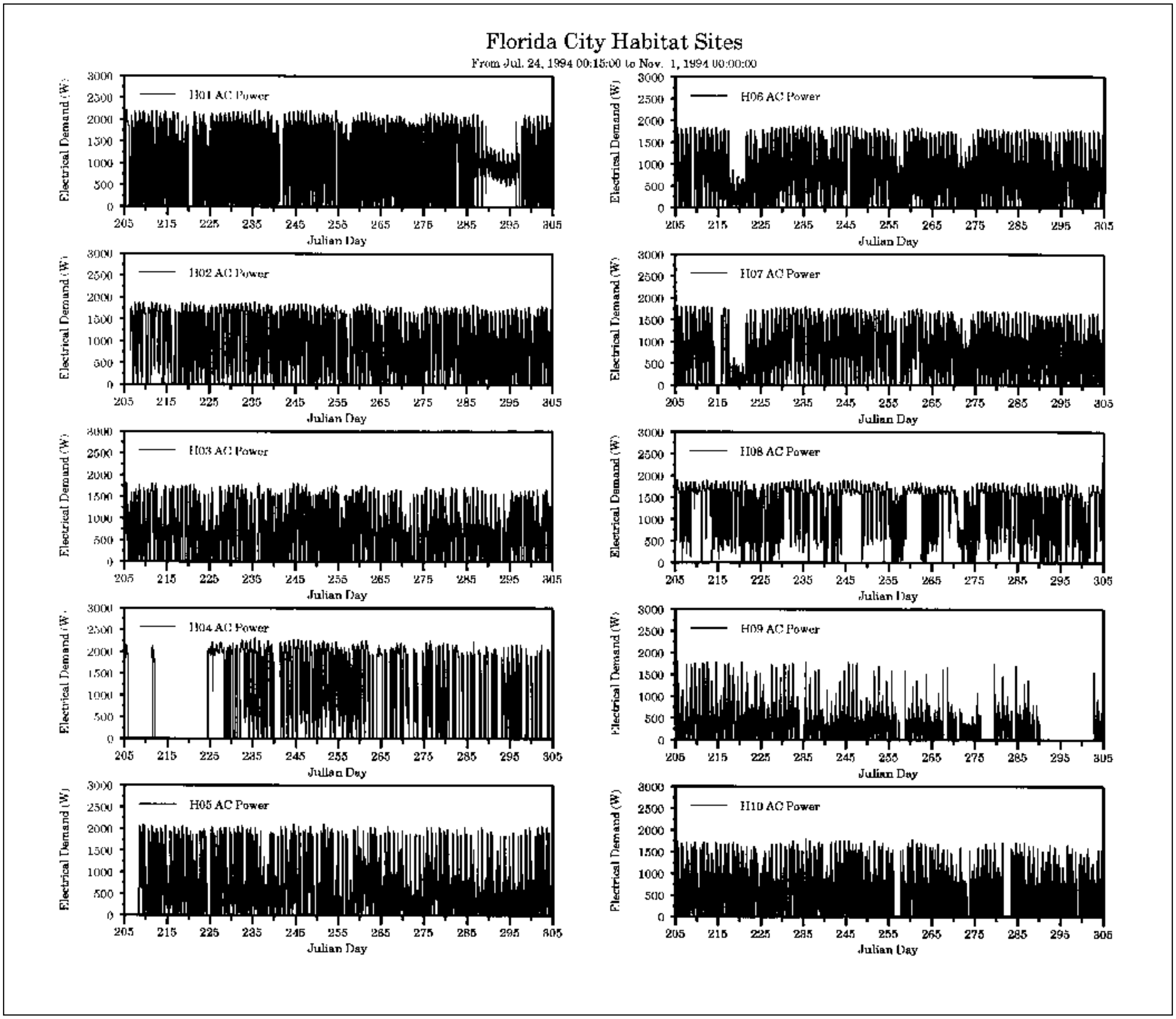
*significant at $p<0.1$ level

Where:

kWh = Daily AC electricity use (kWh; avg = 21.98]
ΔTint = temperature difference between interior and 28°C (avg = 3.16)
kWh_{app} = measured interior appliance energy use (kWh; avg = 10.49)

The values in brackets are the individual t-statistics. Various forms of the regression were attempted using strategy, numbers of bedrooms, occupants, relative humidity and other factors. However, little improvement was made to the simple parsimonious model above. This analysis indicates that the most important determinate of air conditioning energy use is the average temperature maintained within the space. Internal appliance energy use in the ten homes is also a

Figure 4. *Measured AC power at ten sites: July 24–November 1, 1994.*

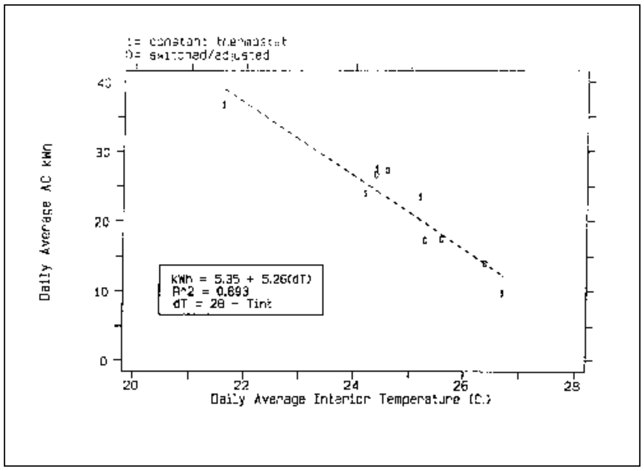


significant factor. Control strategy was not individually significant when added to the equation because it strongly influences interior temperature.

Figure 5 illustrates the pronounced relationship between interior temperature and cooling energy use. Results suggest a 23% increase in space cooling energy for each degree centigrade which the interior is cooled below 28°C. For instance, House 1 used nearly the same amount of cooling energy (27.1 kWh) as House 4 (26.2 kWh) despite the fact that House 4 used a combination of switching behavior and ventilation while the average temperatures maintained at the two sites were very similar. Significantly, House 9, which maintained approximately a 27°C (80°F) setpoint and a constant thermostat setting used the least cooling energy of all households. The thermostatically controlled sites (1, 6, 7, 8 and 9) used an average of 23.9 kWh/day for air conditioning versus 20.1 kWh/day for the ‘‘switched’’ group. A majority of this difference is likely due to conditions maintained; the switched group showed approximately a 1°C higher interior average temperature. Thus, switching behavior may be important to cooling energy use to the extent that it influences average interior temperatures.

House 4 had the most unpredictable use of air conditioning of the houses studied. On some days the air conditioner would not be used at all with the windows often opened for ventilation. Air conditioning would be most frequently used during nighttime hours. However, based on interviews with the homeowners the thermostat was set to 21°C or less

Figure 5. *Relationship of thermostat setting to seasonal AC use.*



(70°F) so that when the air conditioner was activated, it did not cycle off until it was manually switched off the following morning. On days where the AC was on continuously, the house interior temperature reached as low as 17.6°C (64°F). In several instances air conditioning was observed at House 4 while the windows were open leading to higher energy consumption. These data suggest that the household members could benefit from instruction on how to use their AC system more effectively.

INFLUENCES ON PEAK AC DEMAND

The data from the study homes vividly illustrate the importance of behavioral differences in the daily operation of the ten air conditioners. Figure 6 shows the recorded air conditioning energy and recorded interior air temperatures for all ten houses on August 18th. This date was selected for presentation as it was the August system peak for Florida Power and Light Company. Maximum power demand was between 5 and 6 PM (14,840 MWe). The weather conditions on this day were typical of those on a utility peak summer day. The average temperature was 28.3°C (83°F) with a maximum reaching 31.7°C (89°F). Conditions were sunny (average hourly insolation = 308 W/m^2) and humid (78% average relative humidity), with negligible wind.

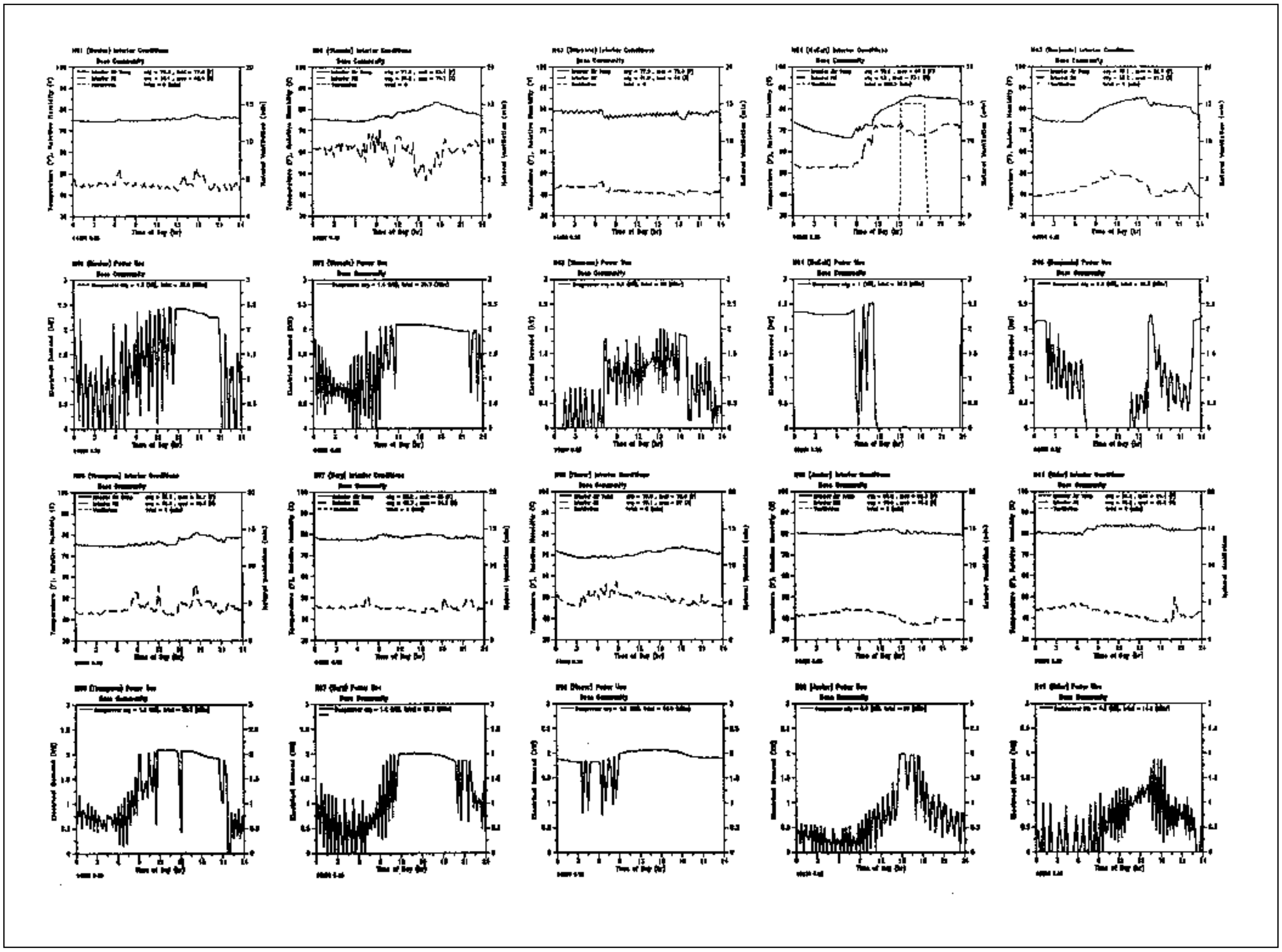
Widely ranging thermostat settings and AC operation modes were observed on the peak day. The measured daily average interior temperatures (which the plots show are sensitive enough to detect individual door openings) varied from a minimum of 21.4°C (70.6°F) at House 8 to a maximum of 27.7°C (81.8°F) at House 10. Including air handler power (which is monitored on a separate circuit), daily air conditioning consumption varied from a low of 14.2 kWh to a high of 44.7 kWh—a variation on the peak day of over 3:1. Reasons for the apparent large disparity in desirable cooling temperature is a subject of lively research debate.[5] The range of observed interior cooling temperatures also has significant implications for air conditioner sizing (Vieira et al. 1996). Most sizing procedures, such as *Manual J*, often assume a 8.3–11.1°C (15–20°F) interior to exterior temperature difference for the calculation of cooling loads. While this will result in adequate cooling system capacity for an *average* household, those desiring lower temperatures may need significantly larger units to achieve the desired temperature depression. Such circumstances provide a rationale for AC oversizing by contractors who may justifiably seek to maximize collective homeowner satisfaction while minimizing call-backs.

The coincident peak power demand on August 18th between 5 and 6 PM also varied considerably from one site to the next. AC demand was zero at House 4 where the occupants had the windows open attempting natural ventilation. However, the difficulty of using ventilation on peak days is well illustrated in this instance: interior temperatures rose to 30.1°C (86.2°F) with a 68% relative humidity using this strategy. Subsequent interviews with the occupants indicated that they would have preferred to have been air conditioning if they could have afforded it.

Although seemingly unimportant to long-term cooling energy consumption, larger air conditioner size did appear to be an important determinant of peak power demand. Here, two the homes with larger 2.5-ton air conditioners had the highest coincident peak loads, reaching approximately 2.40 kW. The 2-ton air conditioners at Sites 2, 6, 7 and 8 exhibited no diversity during the peak period, indicating they were operating at full capacity, and ran constantly at approximately 2.1 kW. House 5 had a high peak load during the hour because the homeowner had the air conditioner off while away from home during the daytime hours, only to return home at 2 PM and then turn down the air conditioner setting at approximately 4:15 PM. Table 2 displays the peak AC loads for each home between 5 and 6 PM on that day.

Excluding House 4, which did not use its air conditioner during the daytime hours on the peak day, the two homes with 2.5-ton AC units had an average demand of 2018 W during the peak hour as opposed to 1805 W for the seven homes with 2-ton systems. Interestingly, the same analysis for the long-term cooling energy consumption data showed little difference. Although not statistically representative, this suggests that AC sizing may be a larger issue for control of utility peak demand than for energy savings. This conclusion is further reinforced by examination of the daily peak AC power demand over the entire cooling period. As shown in Figure 4, the larger 2.5-ton air conditioners at Sites 1, 4 and 5 clearly had higher daily peak demands over the entire

Figure 6. *Measured interior comfort conditions and AC demand at ten sites on utility peak load day (August 18, 1994).*



monitoring period (~2200 W) than did the 2-ton units (~1,800 W).

Data for August 18th in Figure 6 show that five of the ten air conditioners ran constantly between 5 and 6 PM when FPL was experiencing their daily peak load. In these homes, the interior temperature ranged above the thermostat set point during the peak period. The homes using a relatively constant thermostat setting (Sites 1, 6, 8 and 9) used an average of 2025 W as opposed to 1714 W for those using a thermostat switching or adjustment strategy. Again, however, the differences are indicative of tendency rather than statistical significance, since the group variances were quite high. A multiple regression analysis suggested the following relationships with regard to coincident peak AC demand on the nine sites which were cooling:

$$kW = 0.493 + \underset{[2.09]}{0.095(\Delta T)^*} + \underset{[1.83]}{0.321(kW_{app})^*} + \underset{[1.27]}{0.510(AC_{tons})}$$

$R^2 = 0.656$

* significant at $p<0.1$ level

Where:

- kW = Peak hour AC demand (kW; avg = 1.852)
- $\Delta Tint$ = temperature difference betweinterior and 28°C (avg = 1.80)
- kW_{app} = measured interior appliance energy demand (kW; avg = 0.382)
- AC_{tons} = cooling capacity (tons = 3.52 kW_t; avg = 2.15)

Obviously House 4, which was naturally ventilating during the peak period had no AC demand. In the regression, the measured interior temperature likely becomes a significant carrier for switching behavior.

In summary, the analysis suggests that the magnitude of peak air conditioning demand is affected by:

- Thermostat set temperature.

Table 2. Coincident Peak Electric Demand at Habitat Sites: 5–6 PM, August 18, 1994

House ID	Bedrooms	Occupants	Control Strategy	Total Power (W)	Actual Power (W)	Percent AC of Total	Potential Max AC Demand* (W)	Runtime Fraction (%)	Interior Temperature† (°C)
H01	4	8	Constant	5160	2386	46%	2400	99%	24.6
H02	3	4	Switched/ Vent	4290	2063	48%	2070	100%	27.7
H03	3	3	Switched/ Adjusted	1620	1573	97%	2070	76%	25.1
H04	4	8	Vent	520	0	0%	2400	0%	29.8
H05	4	3	Switched	1840	1650	90%	2400	69%	28.6
H06	3	5	Constant	4080	2049	50%	2070	99%	25.9
H07	3	4	Constant	2200	1988	90%	2070	96%	26.4
H08	3	5	Constant	2270	2042	90%	2070	99%	22.8
H09	3	3	Constant	1764	1623	92%	2070	78%	26.8
H10	3	3	Switched/ Adjusted	1370	1295	95%	2070	63%	28.7
Avg.	3.3	4.6		2511	1667	70%	2169	71%‡	26.6

*These values are determined by the size of the air conditioner. Typical maximum demand for the 2-ton units was 2.1 kW; it was 2.4 kW for the 2.5 ton units.

†These values cannot be strictly interpreted as a thermostat setting. For instance, House 4 had their AC turned off and House 5 had just turned their cooling system on before the peak hour. In a number of other sites the AC was running constantly with the interior temperature slowly rising (Sites 1, 2, 6, 7 & 8)

‡The average runtime fraction over the group of sites represents the collective AC diversity during the 60-minute peak period.

- AC control strategy (set temperature vs. ''on-off'' switching).
- AC Size; larger air conditioners may lead to higher peak AC demand.
- Internal appliance energy use which increases coincident cooling demand.

CONCLUSIONS

Field research from ten monitored homes built by Habitat for Humanity in South Florida suggest that cooling energy consumption is large in magnitude—approximately half of total energy use during summer months. This implies that architectural and technology solutions (e.g., light colored roofing, improved window shading, effective cross-ventilation, etc.) which reduce cooling loads and the desire for air conditioning are attractive for reducing energy costs in low-income housing in hot climates. Also examination of collected data reveals that very different cooling system usage patterns are prevalent. Moreover, the resulting differences in thermostat settings and cooling system control can lead to wide variations in cooling energy consumption and peak demand.

The ten homes, built in early 1993, are very similar in construction and installed air conditioning equipment and appliances. There was no statistically significant difference in the air conditioning energy use of the three and four bedroom homes which averaged about 22 kWh/Day from July–October of 1994. Both the highest and lowest AC energy users were three bedroom homes. Although daily air conditioning use varied by approximately 4:1 from the highest to the lowest consuming households, two factors were shown to account for over 90% of the variation. Each degree centigrade lower that the interior air temperature was cooled below 27.2°C (81°F) increased daily AC use by an average of 4.98($\pm$1.03) kWh or 23%. One practical suggestion might be to provide large easily visible digital thermometer by the thermostat to provide useful feedback to occupants. Thermostat switching behavior was significant to the extent that it influenced maintained interior temperatures. Thus, education of low-income homeowners on proper control of cooling equipment may provide energy savings.

Another significant factor was the recorded energy use of internally located appliances which increase the sensible heat load that the cooling system must remove. Each kWh of added internal appliance energy use was found to increase AC consumption by 0.39($\pm$0.35) kWh or 2%. Accordingly, programs which improve appliance and lighting efficiency in low-income housing may provide added dividends from reduced demand for air conditioning.

Utility coincident peak demand of the larger (2.5 ton) air conditioning units was approximately 17% higher (210 W) than the 2.0 ton units. This suggests that air conditioner sizing may be a significant factor responsible for cooling related utility peak loads. Other factors found to affect peak demand were thermostat set temperature, AC control strategy, and coincident internal appliance use.

Although much of engineering analysis uses a constant thermostat set point as a fundamental basis for predicting cooling energy use, recorded data shows little evidence of such a mode of control at any of the homes. About half of the homes used a fairly constant in thermostat setting, while the others used variations of switch-based control, adjusting their thermostats at least weekly. Recorded interior temperatures, varying from 21–27°C (70–81°F), were found to be the largest factor explaining the variation observed in house-to-house air conditioning energy use. Several homes switched the AC off for prolonged periods and two homes appeared to have very low thermostat settings, resulting in constant operation when the cooling system is activated.

Even though AC energy consumption was the largest end-use, sole reliance on natural ventilation may compromise comfort in hot climates. The one house which attempted natural ventilation rather than air conditioning often saw interior temperature frequently rise above 88°F on summer days. Such temperatures can pose health risks for infants and elderly occupants and may also adversely affect the home learning environment for young children.

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ENDNOTES

1. An innovative energy-efficient residential development is being constructed in South Dade County for low-income victims of Hurricane Andrew. Developed by Homestead Habitat for Humanity, the goal of the Jordan Commons project is to achieve a model neighborhood, incorporating very high levels of energy efficiency to serve as an example for affordable community development in Florida. The 190 homes, varying in conditioned floor area from 90–140 m^2 (1,000–1,500 ft^2), will feature a battery of energy-efficiency measures recommended in a comprehensive study for the Hurricane Andrew relief effort in 1992 (Parker et al., 1992; 1994). The homes will also stress light-colored exterior surfaces and extensive landscaping as part of EPA's Cool Communities program.

2. Interviews with the occupants revealed that ceiling supply registers were seldom changed from a full open position, reflecting little attempt at thermal zoning of rooms. However, each of the houses had interior vertical or venetian blinds, all of which were left closed both during daytime and nighttime hours. Most occupants claimed to use them ''for privacy'' or ''to keep the sun out.'' Several homes had a living room or bedroom ceiling fans, most of which were operated 24-hours year round.

3. Physical examination of the thermostat setting during the interview revealed it to be at closer to 27°C (80°F) than to 26°C (78°F). The correspondence between reported thermostat settings and measured interior temperatures varied. The recorded interior temperatures averaged 1.4°C warmer than the claimed thermostat settings. A cursory analysis suggests that often the occupant-reported thermostat setting is actually the ''desired interior temperature.'' Differences are not too surprising since several sites could not maintain the low temperatures desired given the available AC thermal capacity. A enlightening commentary on the South Florida climate comes from the fact that none of the occupants had any

idea what heating setpoint they found desirable; several had never used their heating system!

4. The desire for individual control can be contentious. Reported one air conditioning contractor: ‘‘Some husbands who are electronically inclined will go out and find a thermostat that the wife can’t control. That was the situation the other day when a woman called me out to her house. Her husband had programmed the thermostat and she didn’t know how to adjust it. So we took it out and put in a regular slide switch. . .’’

5. Evidence from other studies suggest acclimatization to various cooling conditions and altered expectations from air conditioning (Busch 1992; Lovins 1992).

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