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A FIELD STUDY ON RESIDENTIAL AIR-CONDITIONING PEAK LOADS DURING SUMMER IN COLLEGE STATION, TEXAS

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EXECUTIVE SUMMARY

Severe capacity problems are experienced by electric utilities during hot summer afternoons. Several studies have found that, in large part, electric peak loads can be attributed to residential air-conditioning use. This air-conditioning peak depends primarily on two factors: (i) the manner in which the homeowner operates his air-conditioner during the hot summer afternoons, and (ii) the amount by which the air-conditioner has been over-designed. Whole-house and air-conditioner electricity use data at 15 minute time intervals have been gathered and analyzed for 8 residences during the summer of 1991, six of which had passed the College Station Good Cents tests. Indoor air temperatures were measured by a mechanical chart recorder, while a weather station located on the main campus of Texas A&M university provided the necessary climatic data, especially ambient temperature, relative humidity and solar radiation. The data were analysed to determine the extent to which air-conditioning over-sizing and homeowner intervention contributes to peak electricity use for newer houses in College Station, Texas.

The measured data and various analysis approaches described were able to qualitatively reveal whether the AC was oversized or not but exact quantification was not possible. The same held true in terms of being able to identify the presence of human behavior on thermostat operation (and thus, on whole-house electricity peaks). Consequently, we were unable to quantitatively determine the amount of peak shaving potential in these houses.

The results of this study were as follows:

(a) A methodology was developed in order to determine the electricity use of the air handler fan by only measuring whole-house and AC compressor use. This is advantageous in that it simplifies the experimental hardware requirements in projects of the sort undertaken here.

(b) The base loads, i.e., the minimum electric load due to refrigerator, lights and other equipment which run all the time, of the non-Good Cents houses are about 0.5 kWh/h while those of the Good Cents houses are about 0.15 kWh/h- a four-fold difference.

(c) Average daily AC use and whole-house electricity use in different houses in College Station during August, the hottest month of the year were compared. It was found that except for one house where the homeowner sets up his thermostat before going to work, the AC use accounted for 65% to 80% of the whole-house electricity use. Also, the manner in which the homeowner operates his AC affects the average use more significantly than does the manner in which the house is constructed (i.e., whether it is a Good Cents house or not). Finally, our analysis found that all the homes satisfied the Good Cents criteria that AC equipment should be sized assuming heat gains of not more than 12,000 Btu/h per 1000 square feet of conditioned space.

(d) The analysis strengthened our belief that whole-house peaks during the peak afternoon periods are largely due to AC use. This was done by generating load duration curves of whole-house electricity use and concurrent AC use and quantifying the interdependence by computing the correlation coefficients between both. These coefficients were very high -- between 0.8 and 0.98. Another observation was that the AC contribution to the whole-house peaks range from a low of 25% to a high of almost 100% in the sample of houses studied.

(e) We also presented different classes of regression models, based on physical heat transfer equations capable of predicting AC use from various physical drivers. The temperature difference is the most important driver though other drivers are not negligible. The R^2 values of the models when applied to the data at hand varied from a low of 0.44 (in a house where the thermostat is controlled frequently) to a high of 0.80 (in houses where the thermostat is essentially left alone) over the houses investigated. How these values of R^2 could be used to detect the presence of human control on thermostat operation was also discussed: a low R^2 value implying significant intervention and vice versa. These trends in model R^2 and what they imply in terms of human control are novel features of this study.

(f) How scatter plots of AC use versus temperature difference could qualitatively yield information regarding both AC oversizing and homeowner intervention were discussed and the underlying conceptual scientific framework was also presented. The table shown below presents a summary of our qualitative observations of all 8 houses studied. Preliminary indications are that only one house has an undersized AC, two houses have correctly sized ACs, while the remaining five houses have oversized ACs. Only one house had excessive homeowner control while five houses seem to have little or no control at all. Experiments planned for the summer of 1992 should provide more definitive, and hopefully, more quantitative results.

Qualitative observations drawn from our analysis of August 1991 data.

	H1	**H2**	**H3**	**H4**	**H5**	**H6**	**H8**	**H9**
Floor area of house (ft^2)	2201	2650	2105	1397	1637	2609	3635	2000
No. of ACs	1	2	1	1	1	2	2	1
Average Internal loads during peak period (kWh/h)	0.75	0.50	1.5	1.0	1.0	0.75	1.7	1.75
Max. installed AC capacity (including air handler) (kWh/h)	3.5	>5.0	>5.0	2.75	>4.5	>6.5	>7.5	4.5
AC sizing?	Correct	Over	Over	Under	Over	Over	Over	Correct
Homeowner control?	None	Moderate	Little	Little	None	Little	None	Excessive

The results of this study were generally inconclusive because the two major objectives, namely to ascertain whether and by how much oversizing of ACs is prevalent and to determine the extent to which whole-hose electricity peaks can be reduced by proper sizing and operation of the ACs, could not be satisfactorily addressed. Whether this deficiency can be overcome by redesigning the experimental set-up to include electronic (and more accurate) measurements of indoor air temperature and the run-time of the ACs, will be explored in a subsequent study planned for the summer of 1992.

List of Figures

List of Tables

Table Of Contents

1.0 INTRODUCTION

Texas is the nation's leading state in electricity consumption, accounting for nearly 9% of the nation's total electric usage of about 2.8 trillion kilowatthours in 1989 (EIA, 1990). Peak demand in Texas is roughly 48 Gigawatts (Zarnikau et al., 1992) of which about 19 Gigawatts is attributed to the residential sector peak. Electric utilities in many parts of the country experience severe capacity problems during hot summer afternoons (see for example, EPRI, 1985a or Kahn, 1988). Several studies have indicated that residential air conditioning (AC) load is a significant component of electric utility peak demand on these hot summer afternoons (for example, Kempton et al., 1991; Reddy et al., 1991). ACs are a major factor in electricity use in Texas, contributing 90% of the residential peak (Zarnikau et al.,1992). Consequently, utilities are designing and implementing programs -- referred to as "Demand-Side Management programs (DSM) (EPRI, 1985b) -- to reduce or limit the growth in consumption and especially demand (which is essentially consumption over a short time interval, often taken as 15 min.) of residential customers during these peak demand periods. These programs include diverse activities ranging from audit and non-audit information supplied by utilities to their customers to various incentives and load control programs, and the use of thermal storage systems (George, 1988).

The Bryan Municipal Utility in Bryan, TX has a program which offers a rebate of $200 to any homeowner who installs an AC with a Seasonal Energy Efficiency Ratio (SEER) of 10. The rebate increases by $200 for every unit increase in SEER, terminating at a rebate of $1200 for a SEER of 15. The College Station Municipal Utility in College Station, TX encourages energy efficient construction and high efficiency ACs through a DSM program which certifies new houses built to specified efficiency standards as "Good Cents" homes. The criteria for qualification as a "Good Cents" home require: (i) proper sizing of the AC equipment through a calculated heat gain of not more than 12,000 Btu/hr per 1000 square feet of conditioned space, and (ii) the total energy requirement for heating, cooling and water heating be approximately 50 % less than a conventionally built home (Schertz and Stracener, 1986). Texas Utilities Electric Company offer rebates to customers who install thermal storage systems (Barakat and Chamberlain, 1990). This program has been called the most successful and aggressive thermal storage program in the U. S.

AC peak demand depends primarily on two factors: the size or capacity of the AC and the manner in which the homeowner operates the AC. For example, a home in which the owner constantly changes his thermostat setting or operates his AC in an interruptive mode would experience high peak loads more frequently than a home where the AC is run constantly with fixed thermostat setting. The amount of peaking would depend on the capacity of the AC. In turn, the capacity of the AC is based on the maximum thermal loads of the house (the ambient and indoor temperature difference being the most influential), on the efficiency or COP of the AC unit and, finally, on the degree of oversizing. A practical rule of thumb for estimating AC capacity in these parts of the country is 400-500 square feet of living area per ton of AC (Abrams, 1986), while, as mentioned earlier, the Good Cents home criteria is half this amount,i.e.,1 ton per 1000 square feet. The trend in improved house insulation and air tightness has probably resulted in AC oversizing. The use of large safety factors by home builders is another reason. A third factor for overdesign is that when sizing calculations are done following accepted ASHRAE procedures (ASHRAE, 1989), it is assumed that the thermal load due to air leakage is simply that given by the enthalpy difference between indoor and outdoor air. Claridge and Bhattacharyya (1990) have shown that this is only an upper limit which is probably not reached in most homes, meaning that even a careful calculation of thermal loads using engineering procedures is likely to result in the use of an oversized AC unit.

Economic and comfort consequences of oversizing are severe, both in commercial buildings and in residences (Abrams, 1986). Intentional oversizing is unjustified because:

(i) it creates comfort problems. Because of over-capacity, run time of the system decreases, so the blower has less time to mix the inside air. This leads to hot spots in places such as

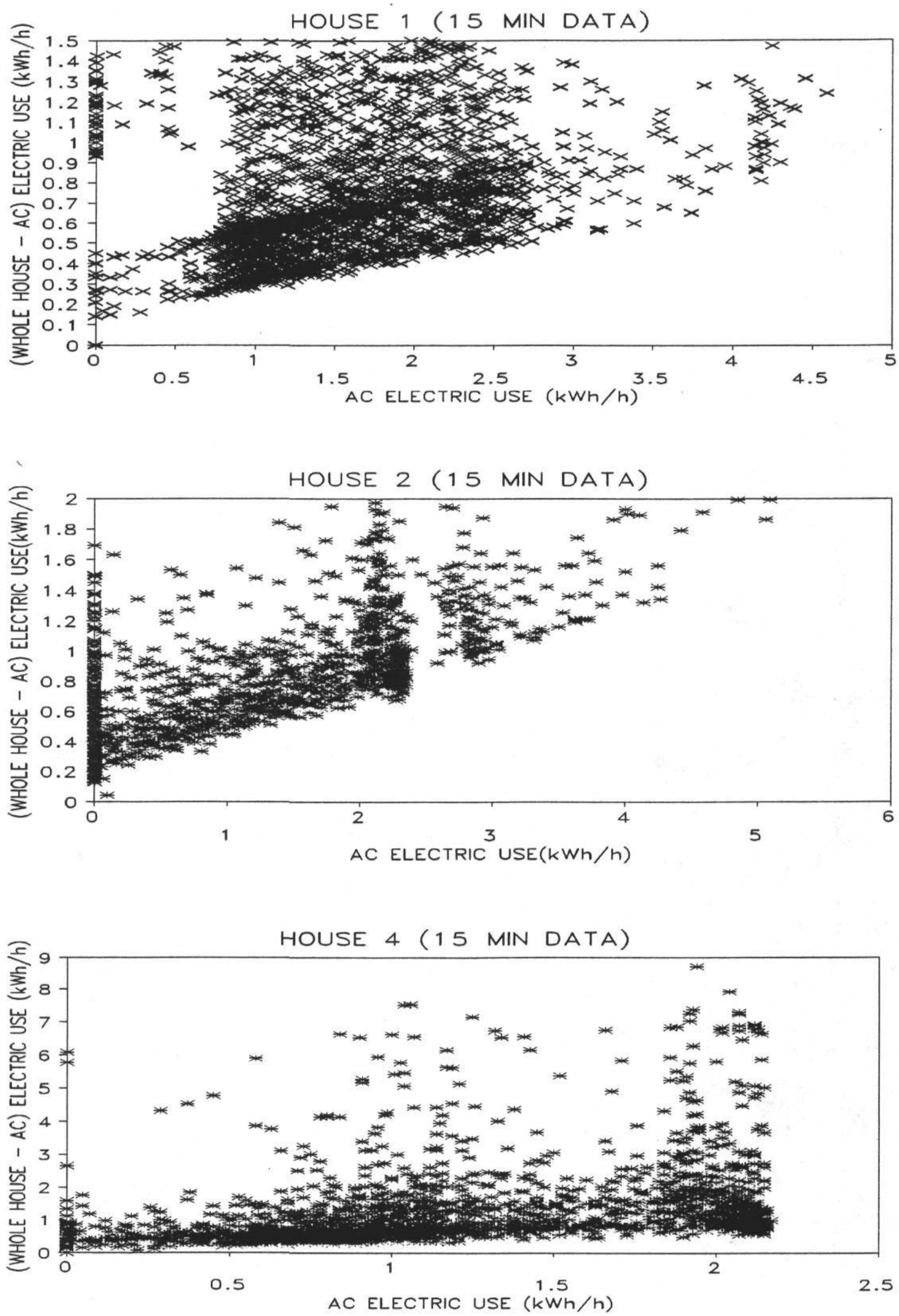


Fig. 1. Scatter plots of whole-house minus compressor electricity use versus compressor electricity use during August 1991. Electricity consumed by the air handler can be ascertained by means of a regression line through the lower boundary of the scatter plot.

kitchens or rooms with large sunlight exposures.

(ii) it reduces the dehumidification capacity of the system. Again because of reduced run time, there is not enough opportunity for water vapor in the air to be removed by the cooling coils.

(iii) it causes wear and tear on AC equipment. The bearings in electric motors and compressors are severely stressed due to frequent start and stop cycles.

(iv) more power than a properly sized unit is consumed due to frequent cycling. This is because an AC uses more power when it first starts than when it is running steadily.

(v) higher initial equipment and installation costs as well as increased maintenance costs.

The specific goals of this study, initiated in early summer of 1991 and performed in collaboration with the College Station Municipal Utility, were to perform independent measurements in the newer residences of College Station in order to:

(a) gauge the extent to which whole-house electricity use during the summer months is dictated by the AC, specially during the peak hours of the day,

(b) ascertain the degree to which observed AC use can be attributed to physical causes ,i.e., climatic and other variables as against home-owner intervention,

(c) determine whether and by how much oversizing of ACs is prevalent,

(d) determine the extent to which whole-house electricity peaks can be reduced by properly sizing and operating the AC. (From the utility's perspective, it is more relevant to study the net peak shaving in a group of residences. However, given our rather limited database, this study confines itself to evaluating electric peak shaving potential in individual houses.)

The summer peak period for College Station is during the late afternoons. For this study, we have chosen this period to be the four hours from 2 to 6 p.m. Though weekend-weekday diurnal electric use patterns are different in residences which are largely unoccupied during the working hours of the day (Reddy, 1989), such a separation was not done in this study because many, if not most, residences in College Station are occupied during the peak hours of the day.

2.0 EXPERIMENTAL DESIGN

Given the preliminary nature of this study and due to the limited financial resources available, it was decided to select a small number of test residences in College Station and monitor their whole-house electric use and the AC electric use at 15 minute time intervals along with concurrent indoor air temperatures and pertinent climatic data. These issues are elaborated below.

2.1 House Selection

Other than a strong willingness of the home-owner to participate in this study, the following house selection criteria were also adopted:

(i) the houses should be newly built during or after 1989;

(ii) some of them should have passed the College Station Good Cents Program;

(iii) the sample should, if possible, include houses of different sizes, i.e. different heated/conditioned square footage;

(iv) sample should, if possible, cover homes built by different builders.

Of the original list of approximately 60 Good Cents homes and 140 non-participant homes, only eleven houses were finally selected as test homes (see Table 1). Half were Good Cents homes. However, the average size of the homes selected was bigger than the typical College Station house which is about 1600 square feet. Recent trends in College Station area housing market have skewed the size of homes built during the last few years. As a result, the average size for our sample was 2100 square feet for the Good Cents homes and 2628 square feet for the non-participant homes.

Table 1. Characterisitics of sample houses selected

House	Cooled Sq. Ft.	Builder	Good Cents	No. of ACs	Data Analyzed
1	2201	Borski	Yes	1	Yes
2B	2650	Ranier	Yes	2	Yes
3	2105	Husfield	Yes	1	Yes
4B	1397	Lege	Yes	1	Yes
5	1637	Thomas	Yes	1	Yes
6	2609	Thomas	Yes	2	Yes
7	3449	Signature	No	2	No
8C	3635	Willems	No	2	Yes
9A.	2000	Mariott	No	1	Yes
10	2447	Lightsey	No	1	No
11	1607	Willems	No	1	No

Notes: (i) Avg. sq. ft. of Selected houses = 2340
Avg. sq. ft. of Good Cents Houses = 2100
Avg. sq. ft. of Non-Participants = 2627.6

(ii) An "A". "B". etc. after the house number denotes the selection of an alternate house, "A: being the first alternative, etc.

2.2 Instrumentation

The selection and installation of the equipment used in the data collection included the following:

(a) Whole house and air-conditioning electric power demand (i.e. average consumption over 15 minute time intervals) were measured by a Class 200, 240 V, Sangamo J5S watt-hour meter and a single phase Data Star Recorder (DS-100). Installation of the recorders (one per house) and meters (one per AC) were done in July 1991 for all eleven houses. Note from Table 1 that of the eleven houses selected, five had two ACs.

(b) Using the Sangamo ST-PCT software and the internal modem of the Sangamo Data Star Recorder, the data were retrieved weekly from the monitored houses. The recorders were installed and programmed as "phone-home" recorders. The recorder modem would, at a designed time during the non-active phone hours (e.g. 2-4 a.m.), call the "home location"- a remote PC installed at a central location and left on overnight in order to receive incoming calls.

(c) Due to financial constraints it was decided to monitor indoor air temperatures using a mechanical chart recorder. We selected the Dickson SC4 Recorder, a dry-stylus, battery operated 4" circular chart with a range of 45 ^{o}F to 90 ^{o}F with an accuracy of 2% full scale. These were used to measure indoor temperature over a week after which the recorded chart was replaced with a fresh chart by the homeowner. The recorders were placed in a central location of the house (usually the den/living room) at a mid-range level away from windows and AC vents. Constant contact with the participants was maintained through weekly visits to the homes to pick up the recorded temperature charts.

(d) Measurements of climatic data relevant for our purpose essentially included: ambient dry bulb temperature, relative humidity (from which absolute humidity could be deduced), solar radiation and wind speed. Because the test homes were within a few miles of the weather station used in one of the LoanSTAR buildings (Turner, 1990) and because the two climatic parameters which are most affected by the local house environment, namely solar radiation and wind, are parameters whose influence on the thermal loads in well shaded homes (such as those in our sample) is small, it was decided to simply use the climatic data from the weather station instead of measuring them on site for each house individually. Note that the weather station records climatic data on an hourly time scale as against the 15 minute time scales which have been adopted to measure whole-house and air-conditioner electric use in the test homes.

3.0 DATA SCREENING AND PRELIMINARY ANALYSES

3.1 Data Screening

As described earlier, 15 minute electric use of the whole house (E_{WH}) and of the air-conditioner (E_{AC}) for all houses was monitored from July to October of 1991. However, data from Houses 7, 10 and 11 had to be discarded because of instrumentation problems. Lightning knocked out two of the data loggers and configuration problems in the third house led to no data being gathered during August. Unfortunately, this resulted in only two of the final eight houses retained for analysis to be non-Good Cents houses. Further, in order to decrease the amount of effort involved in the data conversion and screening process, it was decided to limit our analysis to one month only. August is considered the hottest month in College Station and a close look at the hourly ambient dry-bulb temperatures for 1991 confirmed this fact. Because air-conditioner use is strongly influenced by outdoor-indoor temperature difference, we deemed it relevant to simply study the August data for the eight houses indicated in Table 1. At different stages of our analysis, we have chosen to study the data either at 15 minute or at hourly time scales. Reasons for these choices are discussed at the appropriate juncture.

Another unfortunate fact was that the summer of 1991 was a cool summer in terms of average temperature levels of outdoor air. ASHRAE (1989) proposes a value of 96.8°F for the 2.5% design value (corresponding to 150 hours at or above this value) for the ambient dry bulb temperatures in Bryan, TX . The highest hourly temperature recorded during summer 1991 was about 94°F, which is close to the 5% design value. Consequently, the ACs, even if designed properly, may still be running at part-load conditions and results of our data analysis could turn out to be inconclusive.

3.2 Accounting for Air Handler Electricity Use

The instrumentation measuring AC electricity use actually measures the electricity consumed by the compressor of the AC unit only. All the test houses have central AC and consequently the electric use of the air handler should be regarded as an inherent part of the AC use itself. The air handler electricity use was, however, not measured explicitly because of increased installation costs. (Typically, the air handler is located in the attic far away from the compressor unit.) Consequently we had to infer it from E_{WH} and E_{AC} values as described below (Haberl, 1991). An energy balance on the entire house yields:

WH use = Base load + AC use + Air handler use + Miscellaneous use

or

$$E_{WH} = E_{BL} + E_{AC} + E_{AH} + E_{Mis} \tag{1}$$

where

E_{AC} is the load drawn by the compressor of the air conditioner,
E_{BL} consists of the minimum electric load due to the refrigerator, lights and other equipment,
E_{AH} is the load drawn by the air handler fan,
and E_{Mis} consists of intermittent loads due to apparatii operated momentarily, e.g. TV, dishwasher, washing machine, lights, etc.

The fact that the AC and the air handler cycle at the same frequency (i.e., the air handler operates only slightly longer than does the compressor of the AC) suggests the following:

$$\frac{\text{Actual air handler use } (E_{AH})}{\text{Air handler installed capacity}} = \frac{\text{Actual compressor use } (E_{AC})}{\text{Installed AC capacity}} \tag{2}$$

The capacity of the air handler and that of the AC can be assumed to be constant to a first order approximation, in which case, actual air handler electric use would simply be a multiple of actual AC electric use. The terms in eq. (1) can be re-arranged into:

$$(E_{WH} - E_{AC}) = E_{BL} + (b * E_{AC}) + E_{Mis} \tag{3}$$

where b is the multiplying constant, which physically represents the ratio of air handler electric capacity to AC compressor electric capacity.

Figure 1 depicts scatter plots of $(E_{WH} - E_{AC})$ vs. E_{AC} for three houses using 15 minute data. A very distinct lower bound emerges in all houses which can be attributed to instances when the miscellaneous loads are zero. (Note that the use of 15 minute data is recommended because it reveals a far more distinctive pattern than data averaged over longer time scales. The smear caused by the miscellaneous loads is drastically reduced at 15 minute time scales than at hourly time scales.)

A linear fit through the lower bound of the data scatter of Fig. 1 essentially implies dropping the term E_{Mis}, therby modifying eq. (3) into:

$$(E_{WH} - E_{AC}) = a + b * E_{AC} \tag{4}$$

where the intercept or constant 'a' is the base load of the house, i.e., E_{BL}, and the slope 'b' is the multiplying constant discussed earlier.

Finally, the total AC electricity use (E_{ACT}) is computed:

$$E_{ACT} = E_{AC} + E_{AH} = E_{AC} * (1 + b) \tag{5}$$

Such a corrective procedure was applied to all houses at the 15 minute time scale. Those houses which had two ACs also had two air handlers. Consequently, it was found that the above procedure could be directly applied to the electric use of both ACs combined rather than having to do so for each AC separately.

Table 2 assembles the values of the coefficients a and b of eq. (4) for all houses. We note that generally the base load is between 0.1 to 0.2 kWh/h , exceptions being the two non-Good Cents homes, namely H8 and H9, which are much higher- about 0.5 kWh/h. There does seem to be a four-fold difference, with the Good Cents homes having less base load. The values of b (which physically denote the ratio of the installed electric capacities of the air handler to the AC compressor) are between 0.14 and 0.25. There does not seem to be any difference between the non-Good Cents and the Good Cents homes in this regard.

Table 2. Regression coefficients of the model (E_{WH} - E_{AC}) = a + b*E_{AC} using 15 minute data during August 1991. This is necessary to determine electricity used by the air handler.

House	a kWh/h	b (1/h)
1	0.13	0.138
2	0.15	0.265
3	0.18	0.160
4	0.09	0.240
5	0.16	0.154
6	0.14	0.198
8	0.55	0.141
9	0.52	0.187

We also draw attention to the distinct differences in the scatter plots of the three house shown in Fig. 1. E_{AC} for House 1 (H1) is generally between 0.7 and 2.75 kWh/h, peaking to about 4.25 kWh/h at times. On the other hand in H4, the AC compressor seems to be operating at its maximum load of about 2.1 kWh/h quite frequently. This indicates either a certain amount of under-sizing of the AC or very frequent intervention of the homeowner on either the thermostat setting or on the AC itself. H2 has two ACs, the second of which only cools one bedroom and is operated infrequently, while the first runs continuously. The empty band in the data points around 2.5 kWh/h separates periods where one AC as against both ACs operate.

3.3 Average AC Contribution to WH Electricity Use

Figure 2 presents ratios of E_{ACT} to E_{WH} during August 1991 for all houses. Two ratios are shown for each house, one for all hours of the day (i.e., the daily total values) and the other for the peak period only (i.e., during 2 to 6 p.m. only). Except for H9 whose home owner sets up his thermostat before leaving to work each day, the ratios are between 0.65 and 0.8. Also, the peak period ratios (except for H9 due to the same reason mentioned above) are a few percentage points higher than the daily totals.

Figure 3 shows how the monthly average daily total AC consumption per square foot of living area varies from house to house. Surprisingly,the AC in H9, despite the thermostat set-up, consumes a lot more energy per square foot of living area than do the ACs in many of the other houses. Except for H2 and H3, the ratios are around 0.020 and 0.025 kWh/ft^2/day. This implies that in College Station a house of 2000 ft^2 would consume on an average from 40 to 50 kWh/day during August, the hottest month of the year. The rule-of-thumb sizing for ACs in this part of the country, namely 500 ft^2 per ton (Abrams, 1986), can also be assessed. For a 500 ft^2 house, a ratio of 0.020 kWh/ft^2/day translates into 0.42 kWh/h. A capacity of 1 ton is 3.5 kW thermal which for an AC with a COP of 3.5, turns out to be about 1 kW electric. Only for average AC run-times of about 40%, will the hourly electric mean usage values be consistent with those of Fig. 3. On the other hand, the criteria that Good Cents homes should

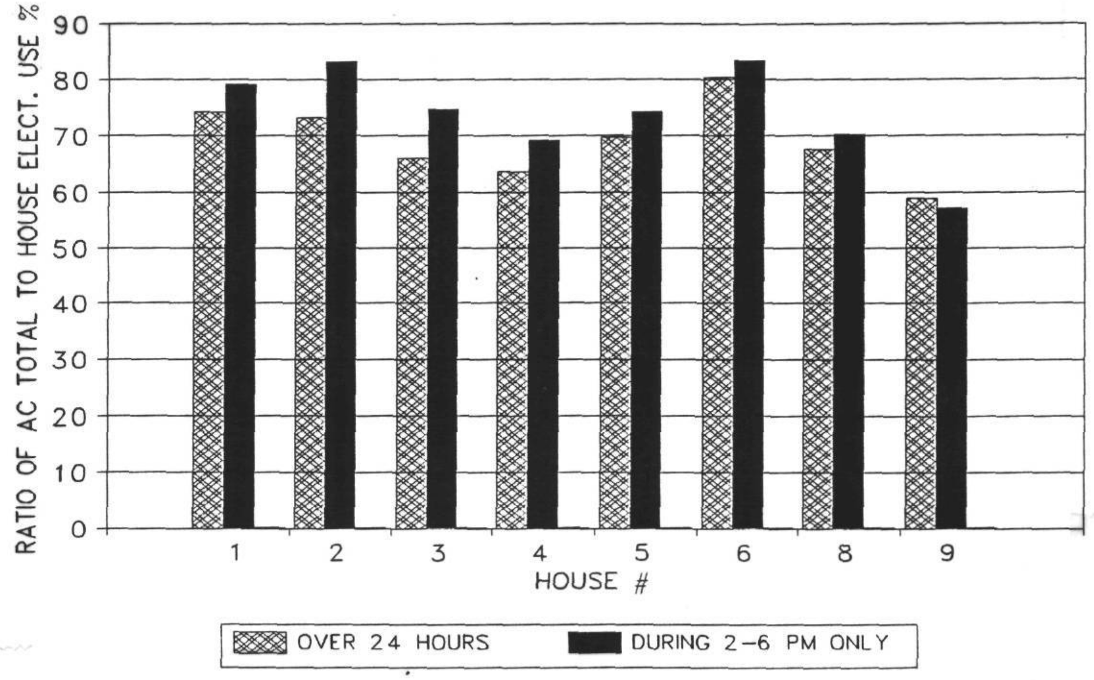


Fig. 2. Ratios of total air-conditioner to whole house electicity use during August 1991 for all houses. Ratios are shown separately for the entire 24 hour period and for peak perios only (i.e. from 2-6 p.m.).

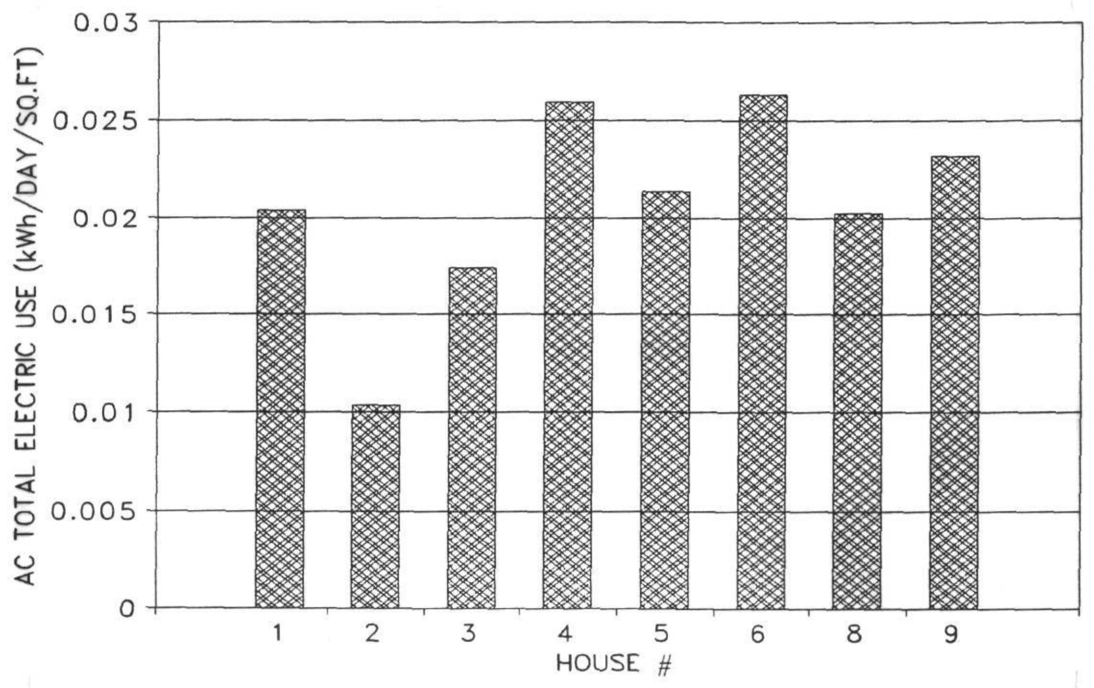


Fig. 3. Average air-conditioner use per day divided by floor area of the house during August 1991.

require no more than 1 ton per 1000 square feet of conditioned space seems to be better supported by the results shown in Fig.3.

Area normalized AC electric use values in H2 are lower by a factor of 2 than the other houses because of the physical zoning which seems to occur in the house due to only one of the two ACs running continuously and the second switched on only when needed. As a result, the temperatures of the two zones may be rather different, a fact which we are unable to assess from our data because only one temperature recorder was used.

It is also obvious that in H8 and H9, the two non-Good Cents houses in the sample, the AC use is, in fact, on the low side compared to some of the other houses. This is unexpected because Good Cents houses were supposed to be more energy efficient, thereby requiring less AC use. Though the sample is small, it is clear that the manner in which the homeowner operates the AC (as in H2 and H9) affects the average use more significantly than the manner in which the house is constructed.

4.0 INTERDEPENDENCE OF AC AND WH LOADS DURING PEAK PERIODS

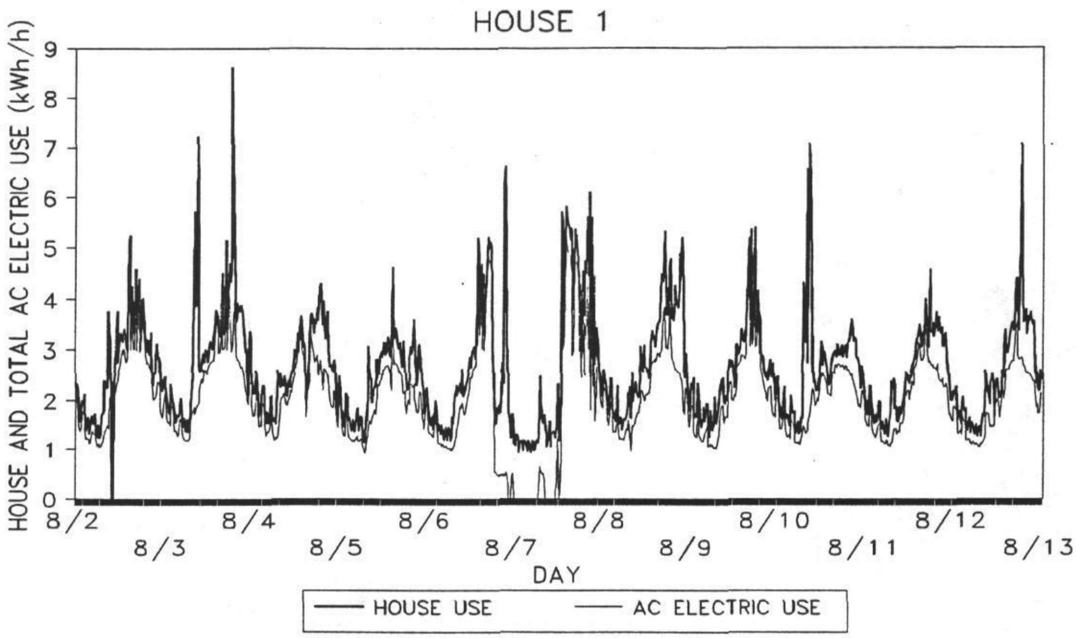
Before studying the effects of AC oversizing on WH electric loads during utility peak periods and ways of alleviating the problem, we should ascertain from our data the extent to which E_{ACT} and E_{WH} occur concurrently during the peak periods. Though previous studies have addressed this issue (for example, Kahn, 1988; Fitzpatrick, 1977), we shall, nevertheless, verify this fact with the data at hand.

One way of doing this is to look at time plots of E_{ACT} and E_{WH}, as shown in Fig. 4 for two houses. Though one can certainly distinguish concurrent spikes during the peak periods, there seem to be other equipment as well that contribute to the peak whole-house electricity use. Equipment like range/oven, dishwasher, washer/dryer, etc.. obviously contribute to the peak as well. These are momentary and a more detailed analysis is required in order to ascertain their individual contributions on whole-house peaks. We shall limit ourselves to AC peaks only in the discussion that follows.

There are other ways of plotting the data in order to bring out the dependence between E_{ACT} and E_{WH} more clearly. Figure 5 shows a scatter plot of E_{WH} and E_{ACT} for three houses using 15 minute data for loads occurring during the peak hours of 2 to 6 p.m. Though the time series behavior and day-to-day cyclic patterns are lost, the extent to which E_{WH} is dictated by E_{ACT} can be more clearly visualized. Because a tight band along the 45 ^{o} line indicates strong interdependence, we note that E_{WH} for H1 and H2 is predominantly the result of AC electric consumption while that for H4 is far less so.

An alternative way is to generate the load duration curve (which is the classical manner in which electric utility analysts tend to study load data (Kahn, 1988) of E_{WH} and plot it alongside the concurrent E_{ACT} values (see Fig. 6). A small spread in E_{AC} values and a close match between E_{WH} and E_{ACT} values throughout the entire range indicate a very strong dependence. This seems to be so for H2 where the AC accounts for almost the entire whole-house peak of 8 kWh/h. However, for H4, the interdependence for most of the range (except for the lower end of E_{WH} values) is poor. The AC contributes only 2.5 kWh/h of the total whole-house peak of 9 kWh/h. The wide plateau in the E_{ACT} plot suggests gross undersizing of the AC. The plots of the two houses shown in Fig. 6 illustrate extreme patterns. Similar plots for other houses do not seem to have such distinctive trends and it is generally difficult to infer from such plots whether the AC is undersized or not. However, what these plots undeniably illustrate is the interdependence between E_{WH} and E_{ACT}. The reader can refer to Appendix B for the load duration curves of whole-house electricity along with concurrent AC use for all the homes analyzed.

In order to qualify this interdependence, correlation coefficients (see any basic statistics book, for example Sachs, 1984) between whole-house and air-conditioner electricity use have been computed using 15 min. data during the peak period. These are tabulated in Table 3. We note that except for H4, all other houses exhibit strong correlation coefficients, between 0.8 and 0.98. H2 has the highest value while H4 has the lowest, which support physical arguments made earlier.



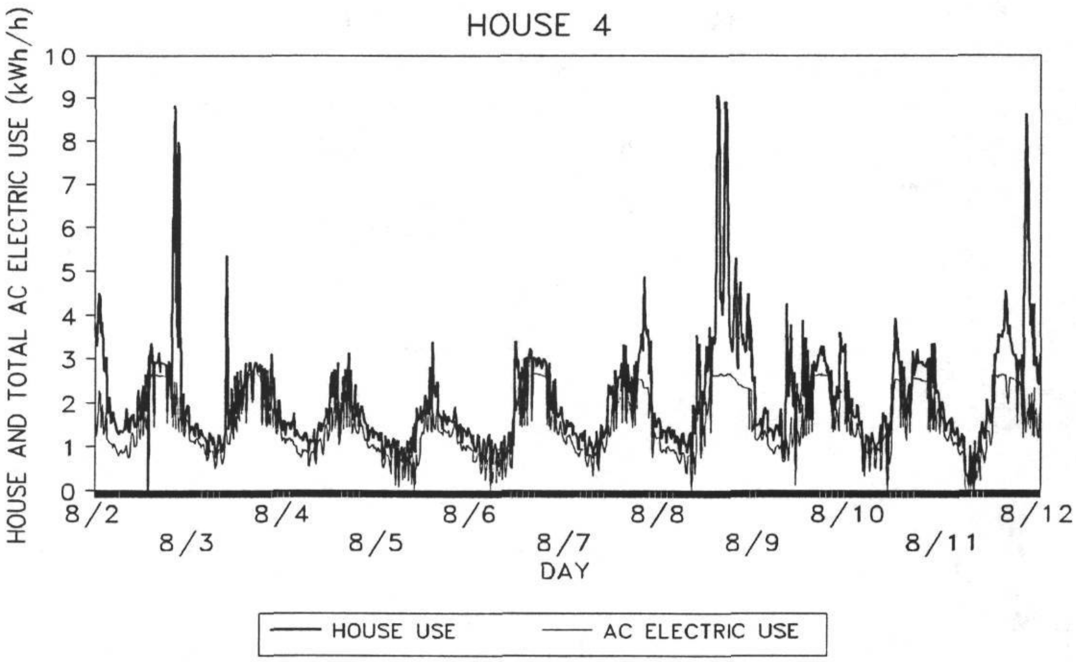


Fig. 4 Sample time plots of whole-house and air-conditioner electricity use.

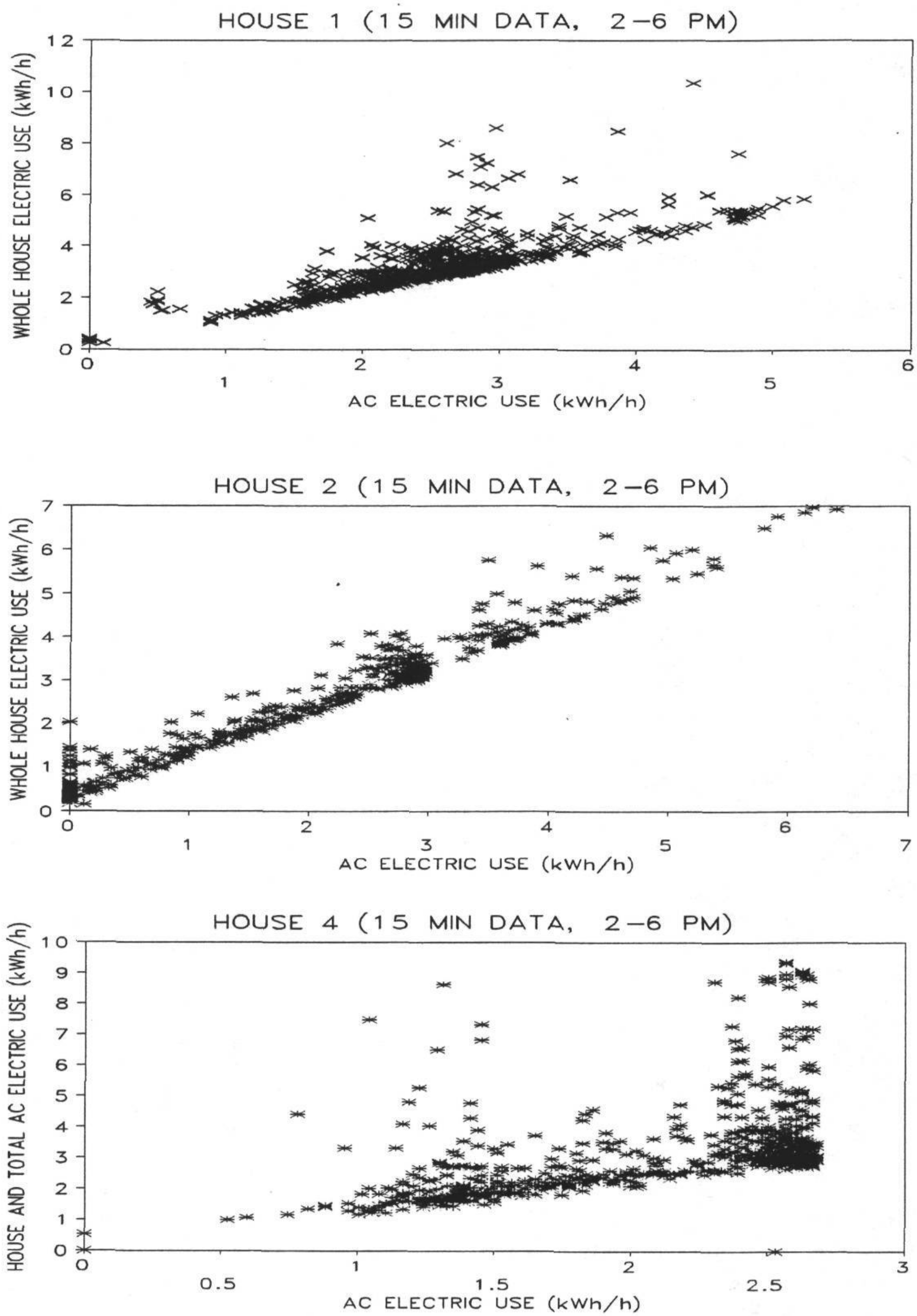
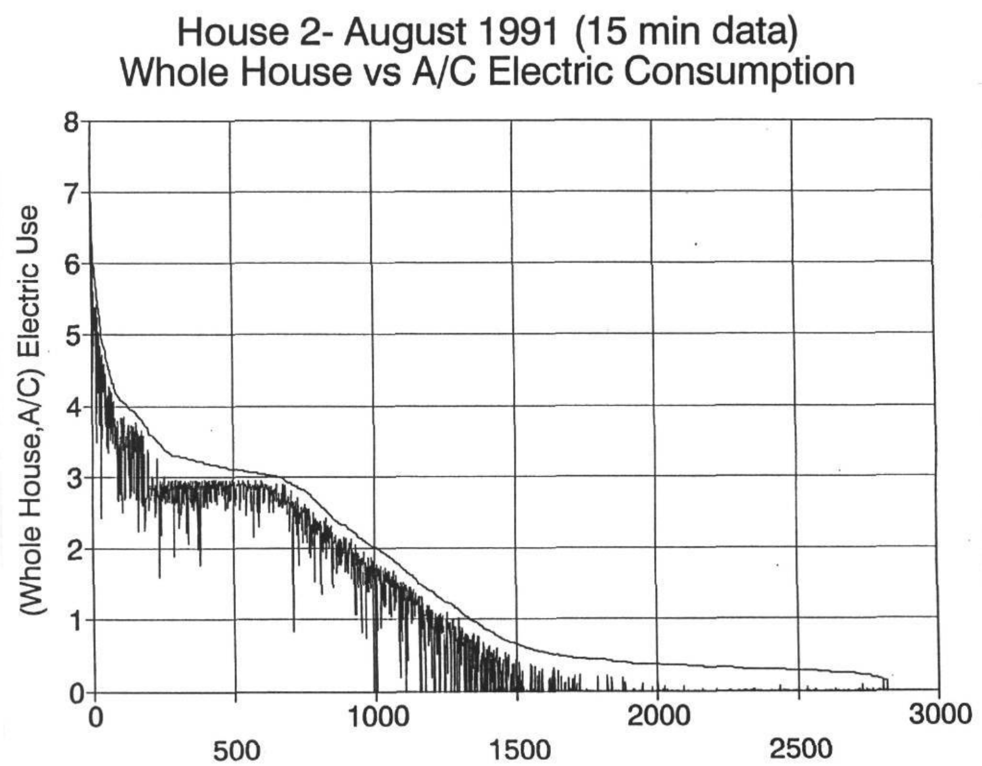


Fig. 5. Scatter plots of whole-house and air-conditioner electricity use during the peak period (i.e., from 2 -6 p.m.) for August 1991.



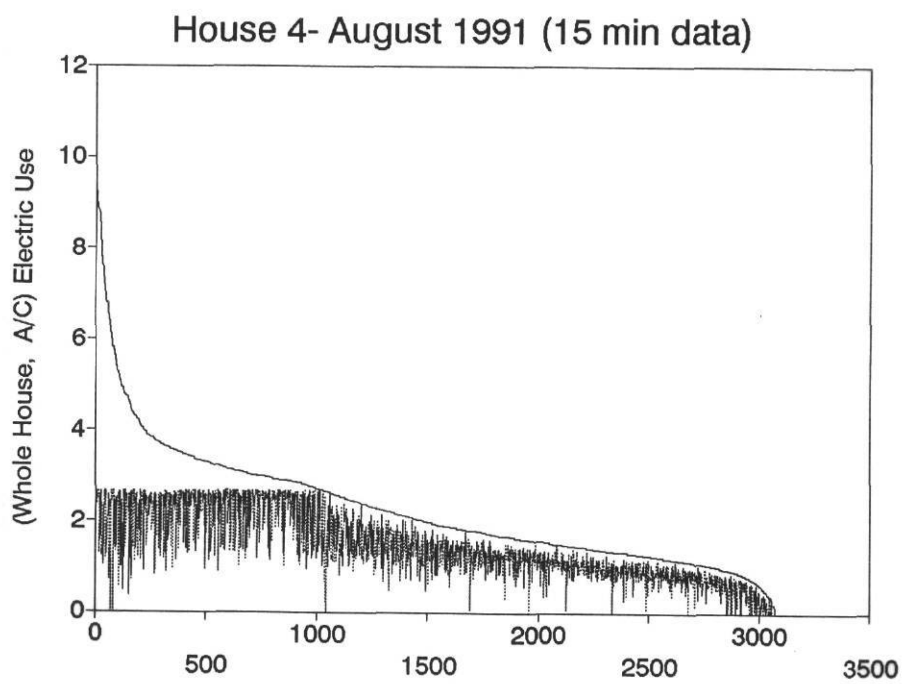


Fig. 6. Load duration curves for whole-house electicity use along with concurrent air-conditioner use for August 1991.

Table 3. Correlation coefficients between whole house and concurrent air conditioner electricity use during the peak perios (2-6 p.m.) using 15 minute data.

House	Correlation Coefficients
1	0.787
2	0.983
3	0.942
4	0.508
5	0.887
6	0.795
8	0.856
9	0.913

To conclude, we have demonstrated that whole house electric use in certain of the newer residences of College Station during peak utility periods could largely be the result of air conditioning use. In the sample of houses studied, the AC contribution to the whole-house peaks ranged from a low of 25% to a high of close to 100%. Hence, identifying factors which contribute to the AC peak and studying ways by which these peaks can be avoided is relevant to our objective of shaving summer utility electric peaks in residences.

5.0 EFFECT OF PHYSICAL PARAMETERS ON OBSERVED AC USE

In this section, we shall seek to ascertain the extent to which observed AC use can be attributed or explained by physical drivers (i.e., climate and other variables). This would enable us to determine how much of the observed AC use in the residence is unexplained or occupant dependent. Rational calculation procedures to size AC for design purposes have been extensively discussed in the published literature and the industry norm is to adopt the guidelines suggested by ASHRAE (1989). Essentially, the thermal loads of the building depend on the following: building type, type of construction, climatic conditions, interior operating conditions and internal loads (occupants, lighting and equipment).

Figure 7 depicts time plots, over one week, for 3 houses of the total (i.e., compressor plus air-handler) AC electric use (E_{ACT}), of whole-house loads (E_{WH}), of indoor dry-bulb temperature (T_{in}) and outdoor dry-bulb temperature (T_{out}). We detect distinct diurnal patterns in all houses. For H9, T_{in} has a large diurnal swing while the thermostat in H1 keeps the indoor temperature constant throughout (except for a day when the AC broke down). The building loads tend to be variable with sharp momentary peaks, especially in H1 and H4. The low AC use in H9, as explained earlier, is attributed to the homeowner setting up his thermostat level before leaving for work every day.

The variation of E_{ACT} can be viewed as the time response of a system subject to deterministic as well as random inputs. The latter may be due to both homeowner intervention (on AC operation as well as on internal loads) and to physical parameters whose influence was left out of the deterministic model. Statistical treatment of such signals is best done by adopting principles of digital filtering which includes the processes of smoothing, predicting, differentiating, integrating, separating of signals and removal of noise from a signal (Hamming, 1989). In this study, we have adopted an approach of regressing measured data in the framework of a physical model representing the thermal behavior of the residence. Such an approach cannot adequately treat abrupt on-off changes in the thermostat setting and other types of "noise". The goodness-of-fit of the model, quantified by the Adjusted Coefficient of Determination R^2 would then be indicative of how much of the observed variation in E_{ACT} can be attributed to physical causes.

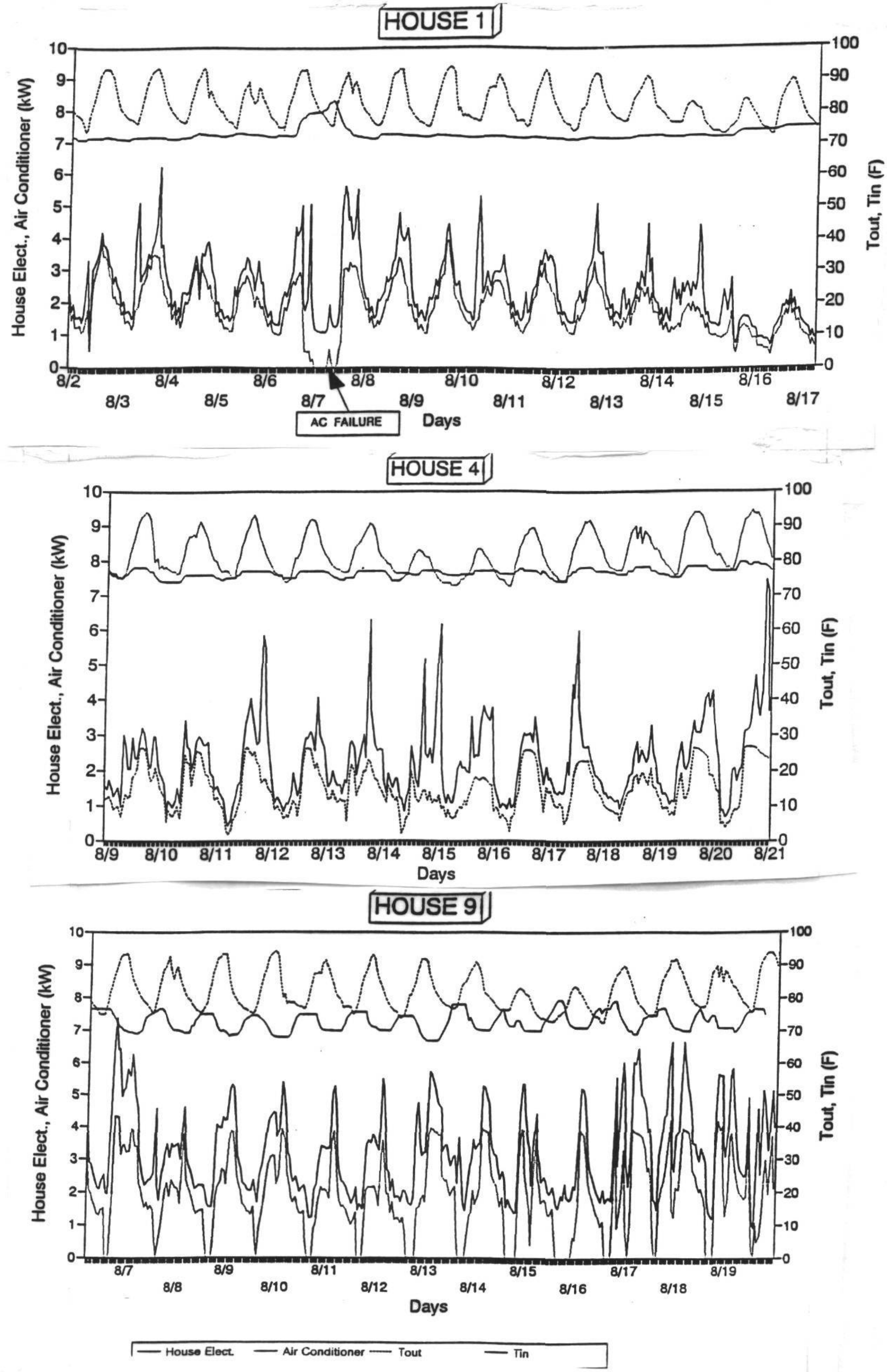


Fig. 7. Sample time plots of whole-house and air-conditioner electricity use along with outdoor and indoor dry blub temperature.

Neglecting humidity effects (which we justify by noting that a stepwise regression consistently discarded the specific humidity driver as a parameter influencing E_{ACT}), a simplified thermal balance on the house yields:

$$MCp\frac{dT_{in}}{dt} = UA*(T_{out} - T_{in}) + E_{Int} + A_s * Q_{sol} - (COP) * E_{ACT} \tag{6}$$

where MC_p is the heat capacity of the house,
(UA) is the total heat loss coefficient,
A_s is the "effective" solar aperture,
Q_{sol} is the solar irradiation on a horizontal surface, and
COP is the Coefficient of Performance of the AC.

The COP varies with operating temperatures. The effect of small temperature variations on the COP can, to a good approximation, be evaluated by assuming proportionality with the Carnot efficiency corresponding to the evaporator and condensor temperatures (McQuiston and Parker, 1988). Thus, the COP ratio of actual to rated:

$$\frac{COP}{(COP)_{Rated}} = \frac{\left(T_{cond} - T_{evap}\right)_{Rated}}{T_{cond} - T_{evap}} \tag{7}$$

With the approximation that $T_{cond} = T_{out} + \Delta T$ and $T_{evap} = T_{in} - \Delta T'$, where ΔT and $\Delta T'$ denote temperature differences, we have:

$$COP = (COP)_{Rated} * \frac{(T_{out} - T_{in})_{Rated} + a''}{(T_{out} - T_{in}) + b'} \cong \frac{a'}{(T_{out} - T_{in}) + b'} \tag{8}$$

where a', b' and a" are constants.
Introducing this in eq. (6), we have the following functional form of the regression model:

$$\begin{aligned} E_{ACT} &= a + b*(T_{out} - T_{in}) + c*E_{Int} + d*Q_{sol} + e*(T_{out} - T_{in})^2 \\ &\quad + f*E_{Int}*(T_{out} - T_{in}) + g*Q_{sol}(T_{out} - T_{in}) + h*\frac{dT_{in}}{dt} \\ &\quad + i*(T_{out} - T_{in})\frac{dT_{in}}{dt} \end{aligned} \tag{9}$$

where a, b, c, d, e, f , g ,h and i are regression coefficients.

Three classes of model structures can be identified from eq. (9):

(a) <u>Model A</u>: Thermal mass is neglected and COP is assumed constant.

The following model structures are then obtained:

$$
\begin{aligned}
&\text{A1: } E_{ACT} = a + b * T_{out} \\
&\text{A2: } E_{ACT} = a + b * (T_{out} - T_{in}) \\
&\text{A3: } E_{ACT} = a + b * (T_{out} - T_{in}) + c * E_{Int} \\
&\text{A4: } E_{ACT} = a + b * (T_{out} - T_{in}) + c * E_{Int} + d * Q_{sol}
\end{aligned}
\tag{10}
$$

where a, b, c and d are regression coefficients.

(b) Model B: Thermal mass is neglected but variation of COP with operating temperatures is considered.

$$
\begin{aligned}
E_{ACT} &= a + b * (T_{out} - T_{in}) + c * E_{Int} + d * Q_{sol} + e * (T_{out} - T_{in})^2 \\
&\quad + f * E_{Int} * (T_{out} - T_{in}) + g * Q_{sol} (T_{out} - T_{in})
\end{aligned}
\tag{11}
$$

(c) Model C: Thermal mass and varying COP are considered.

This class of model uses eq. (9) directly with the derivative of T_{in} evaluated according to a forward-difference scheme of numerical differentiation.

Table 4 presents the R^2 values of the various models for four houses using hourly data. A stepwise regression scheme has been used instead of multiple regression to ensure that only significant regressor variables are chosen by the regression model. Model C regression results were no better than those of Model B and hence results of this model have not been included in Table 4. This is rather surprising because thermal mass effects of residences can, and often are, important (Reddy et al., 1991). A possible reason for this may be the rather crude manner by which T_{in} data were measured.

Table 4. Adj-R^2 values of hourly regression models for E_{AC} using stepwise regression.

Model	Regressor Variables Retained	H1	H2	H4	H9
A1	T_{out}	0.611	0.404	0.631	0.00
A2	$(T_{out}-T_{in})$	0.754	0.498	0.631	0.111
A3	$(T_{out}-T_{in})$, E_{Int}	0.760	0.525	0.686	0.169
A4	$(T_{out}-T_{in})$, E_{Int}, Q_{sol}	0.795	0.580	0.707	0.442
B	$(T_{out}-T_{in})$, E_{Int}, Q_{sol}, $(T_{out}-T_{in})^2$	0.797	0.604	0.714	0.451

We note from Table 4 that there is more variation in R^2 across houses than across models. Not surprisingly, there is a gradual improvement as a higher level model is used in Class A models. Temperature or temperature difference is certainly the most influential driver but E_{Int} is an important secondary driver while the influence of solar effects is also manifest. Notice the low R^2 values of 0.11 for model A2 in H9 while inclusion of solar increases R^2 significantly. This large increase may not necessarily be due to Q_{sol} itself but due to time of day occupant effects (like switching on the AC at a particular hour of the day) for which the solar load could be a good surrogate. There is but little improvement in R^2 values when model B is used instead of Model A4. Hence, accounting for variable COP does not seem to be worth the added complexity. We see that R^2 values in H1 are highest, about

0.8, while the lowest occur in H9 (R^2 = 0.44). (Recall that a quantitative interpretation of say R^2 = 0.8 implies that 80% of the observed hourly variation in E_{ACT} values can be attributed to the physical parameters appearing in the model.) This is again physically consistent, because the resident of H9 systematically varies his thermostat setting every day while the resident of H1 leaves his thermostat fixed at a constant level.

On the whole model, A4 seems to be the most appropriate choice across all houses. How well this model predicts the observed E_{ACT} values for H1, H4, and H9 can be gauged from Figure 8. As expected (see Table 4) the model seems generally sound for H1 and H4, though it is unable to satisfactorily predict the peaks. The coefficients of the stepwise regression models using model structure A4 are given in Table 5. We note that Q_{sol} coefficients are negative which is physically inconsistent because increased solar loads should result in increased AC loads and vice versa. This suggests inter-correlated regressor parameters, which is indeed the case as testified by the correlation coefficients shown in Table 6. The proper manner to deal with such data sets is to resort to Principal Component Analysis (Ruch and Claridge, 1991; Wu et al. ,1992). Theoretically, such an approach ought to circumvent the problem associated with collinear data sets and enable robust and physically meaningful regressor coefficients to be identified. Such a PCA analysis was attempted on our data, but surprisingly did not improve our regression results. This aspect of the analysis seems to warrant more careful scrutiny and has been left aside for the time being.

Table 7 presents values of the regression coefficient of (T_{out} - T_{in}) versus E_{ACT} for the 4 houses normalized by the cooling or floor area of the particular house. These normalized values are close to within 20% of each other; in the range $5.7\text{x}10^{-5}$ to $8.5\text{x}10^{-5}$ in units of (kWh/h/^{o}F/ft^2).

To summarize, we found that of all the model structures investigated, model A4 seems most appropriate. The need to include thermal effects and varying COP of the AC has proven to be unnecessary. This is a surprising result and could be due to the crude manner in which internal air temperatures were measured. Model R^2 values were found to vary from about 0.8 for a residence with little or no homeowner intervention on AC operation to a low of 0.45 for one where the AC operation was systematically controlled every day.

Table 5. Regression coefficients obtained by stepwise regression of hourly E_{ACT} values using model structure A4.

	Units	H1	H2	H4	H9
Constant	-	0.439	0.360	0.6417	0.8882
(T_{out}-T_{in})	°F	0.1247	0.1827	0.1122	0.1711
Q_{sol}	$\frac{W}{m^2}$	-0.00126	-0.00250	-0.00043	-0.00263
E_{Int}	$\frac{kWh}{h}$	0.0766	0.7510	0.1619	-0.09081

Table 6. Correlation coefficients of the various regressor variables.

Variables	H1	H2	H4	H9
(T_{out}-T_{in}) and Q_{sol}	0.67	0.65	0.64	0.44
(T_{out}-T_{in}) and E_{Int}	0.04	-0.02	-0.05	0.34
Q_{sol} and E_{Int}	-0.02	-0.11	-0.03	0.45

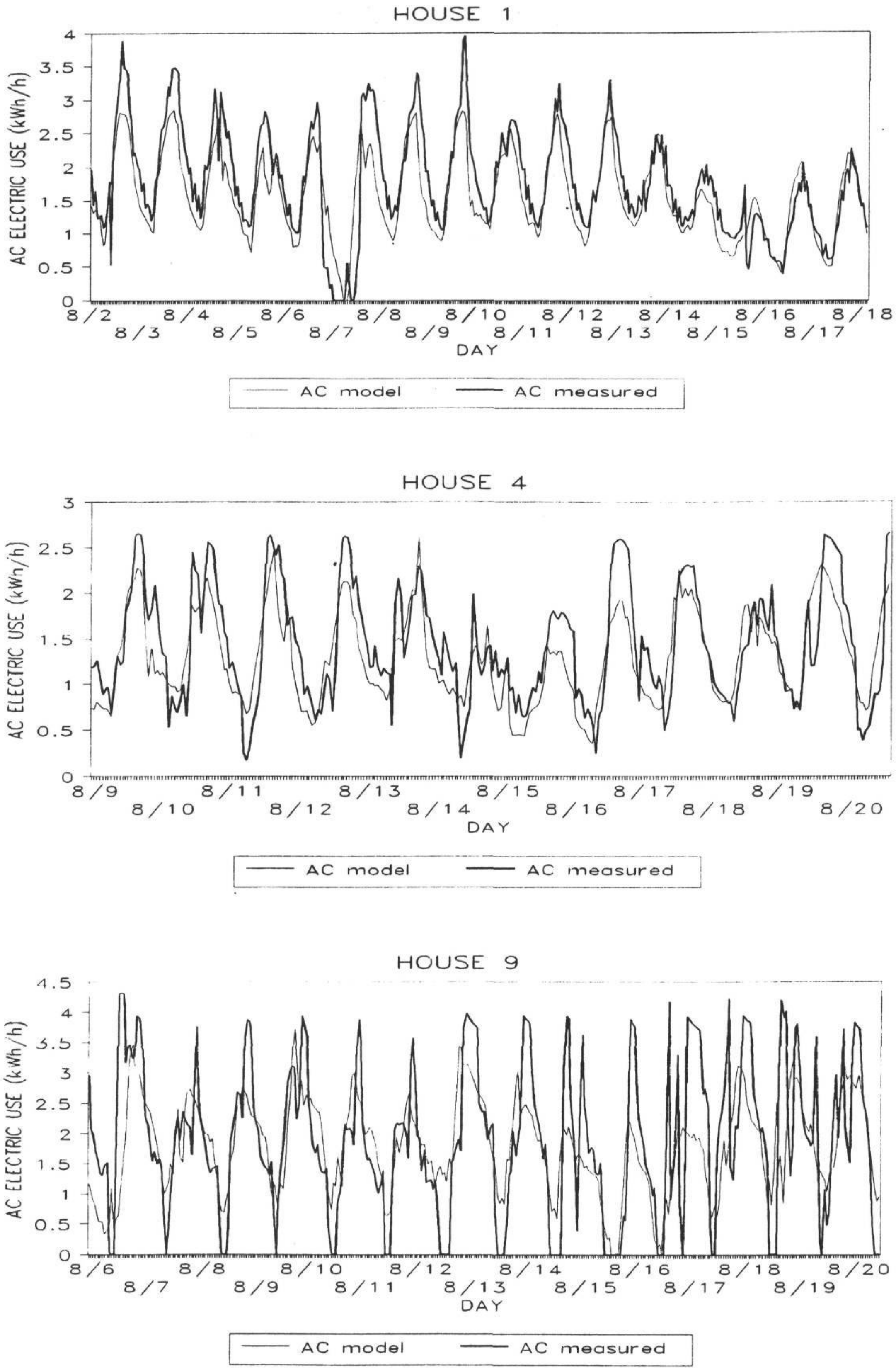


Fig. 8. Tracking ability of the regression models for three residences.

Table 7. Floor area normalized values of the regression coefficient of outdoor-indoor temperature difference with hourly E_{ACT}.

Coefficient	Units	H1	H2	H4	H9
$(T_{out}-T_{in})$	°F	0.1247	0.1827	0.1122	0.1711
Floor Area	ft^2	2201	2650	1397	2000
Normalized	$\frac{kWh}{°F\text{-}h\text{-}ft^2}$	5.7×10^{-5}	6.9×10^{-5}	8.0×10^{-5}	8.5×10^{-5}

6.0 EFFECT OF AC SIZING AND CONTROL ON AC PEAK USE

We now address the specific goals (c)and (d) listed in Section 1, namely to determine whether and by how much the ACs have been oversized, and to determine the extent to which actual AC control and sizing have resulted in high AC electric demand during the afternoon periods. We shall do this by two different approaches, as presented below.

6.1 Approach Involving Scatter Plots of AC Use and Temperature Difference

Appendix A, taken from Reddy and Claridge (1992), provides a conceptual scientific framework by which one is able to ascertain from AC use (E_{ACT}) and outdoor minus indoor temperature difference (T_{out} - T_{in}), whether (i) the AC is correctly sized, and (ii) whether human behavioral determinants affect AC use.

Though temperature difference is by far the most important driver for E_{ACT}, the other drivers, namely E_{Int} and Q_{Sol}, are not negligible. Consequently, a scatter plot of E_{ACT} versus (T_{out} - T_{in}) may not accurately convey the extent to which E_{ACT} is actually influenced by the deterministic physical drivers. Nevertheless, such a plot is widely adopted by data analysts, and as seen below, can yield useful insight. Figure 9 is such a scatter plot for four houses. For H4 and H9, there is a distinct upper boundary to the E_{ACT} values with a slight dependence on (T_{out} - T_{in}) denoting that maximum AC capacity has been reached. H2, which has 2 ACs with one running continuously, also has such a bound at about 2.5 kWh/h, even at relatively low temperature differences. H1, on the other hand, does not seem to exhibit such an upper bound.

It is seen from Figure 9 that the upper bound has a slight positive slope which is due to the fact that COP decreases with increasing outside air temperature, resulting in higher AC power consumption. The mere presence of this upper bound is not evidence enough to conclude that the AC is undersized. Only if the upper boundary stretches to relatively low values of (T_{out} - T_{in}) can we conclude homeowner intervention on either the thermostat or the AC itself. This is clear in H9 where we know that the occupant turns down his thermostat after returning from work in the late afternoons. On the other hand, no such intervention occurs in H4 and maximum AC capacity is reached as a result of AC undersizing.

What is most unfortunate from Figure 9 is our inability to identify the normal operating line of AC, i.e., line AE of Figure A2. It is clear that either the inherent inability of such a representation to account for other physical drivers, or the error introduced as a result of our rather crude T_{in} measurements, has resulted in excessive noise which swamps out any underlying pattern. We have also generated such scatter plots over different time intervals, ranging from 15-minute to 24-hour intervals, but there was no marked improvement in our ability to more accurately identify the normal AC operating line. In turn this

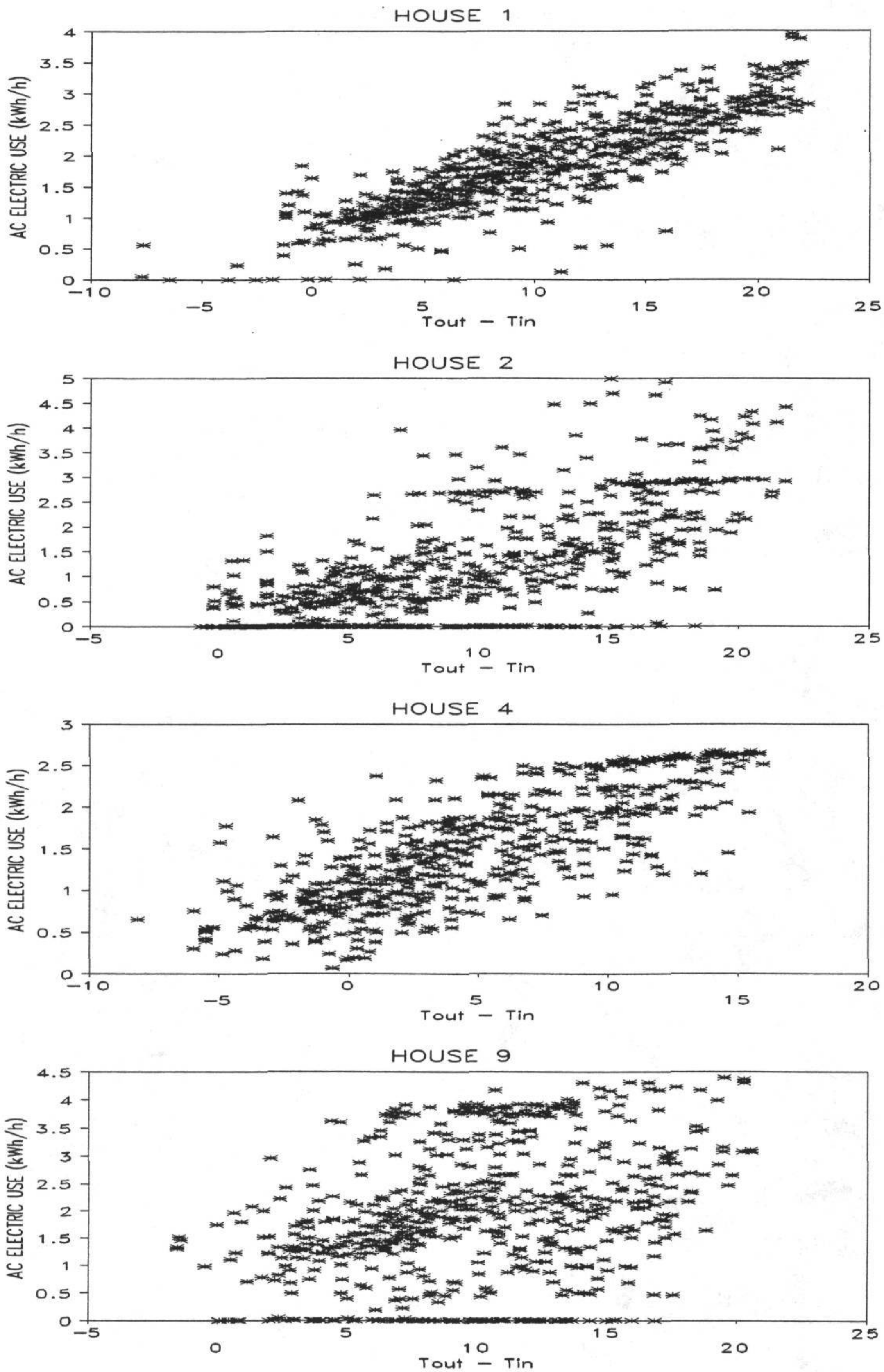


Fig. 9. Scatter plots of hourly total air-conditioner use versus temperature difference between outdoors and indoors during Agust 1991.

deficiency has prevented us from ascertaining whether the AC is oversized or not because point B (see Figure A2) could not be properly identified. Thus, the scatter plot approach seems unable to provide us with a satisfactory means of ascertaining proper AC sizing.

6.2 Approach Involving Mean AC Diurnal Variation During the Hottest Days

A second approach investigated in this study paralleled that adopted by Reed (1991). He generated mean diurnal duty cycles (defined as the proportion of time the AC operates in a fixed time period, 1 hour in our case) of several houses and compared them against model predictions based on information from a simple energy audit of the home information about the AC and temperature data. The scope of this study is more modest and we have limited ourselves to studying only the diurnal patterns. Also, we chose to look at mean AC use itself rather than duty cycle. We selected 8 of the hottest week days during August 1991 and averaged the hourly T_{out} data and E_{ACT} data of all houses. These profiles are shown in Figure 10. A number of interesting features can be noted:

(i) The profiles of T_{out} and E_{ACT} in a number of houses seem to peak at slightly different times. This is contrary to the regression model results of Section 5 which indicated that inclusion of the heat capacity term did not improve model R^2 values, implying that temperature difference drivers and AC use should not be out of phase.

(ii) The more hour-to-hour variation, especially around the peak period from 2:00 to 6:00 p.m., in AC use, the more likely the AC is to be oversized. This is true for H2 and H6 which have two ACs. This seems to be also true for H3 and H5. H8 also has two ACs, but its diurnal variation is smooth and follows the diurnal T_{out} variation. This suggests little or no homeowner activity on thermostat control.

(iii) The homeowner is H9 is known to control his thermostat extensively. This is apparent from the profile which indicates abnormally low AC use during the morning and early afternoon hours.

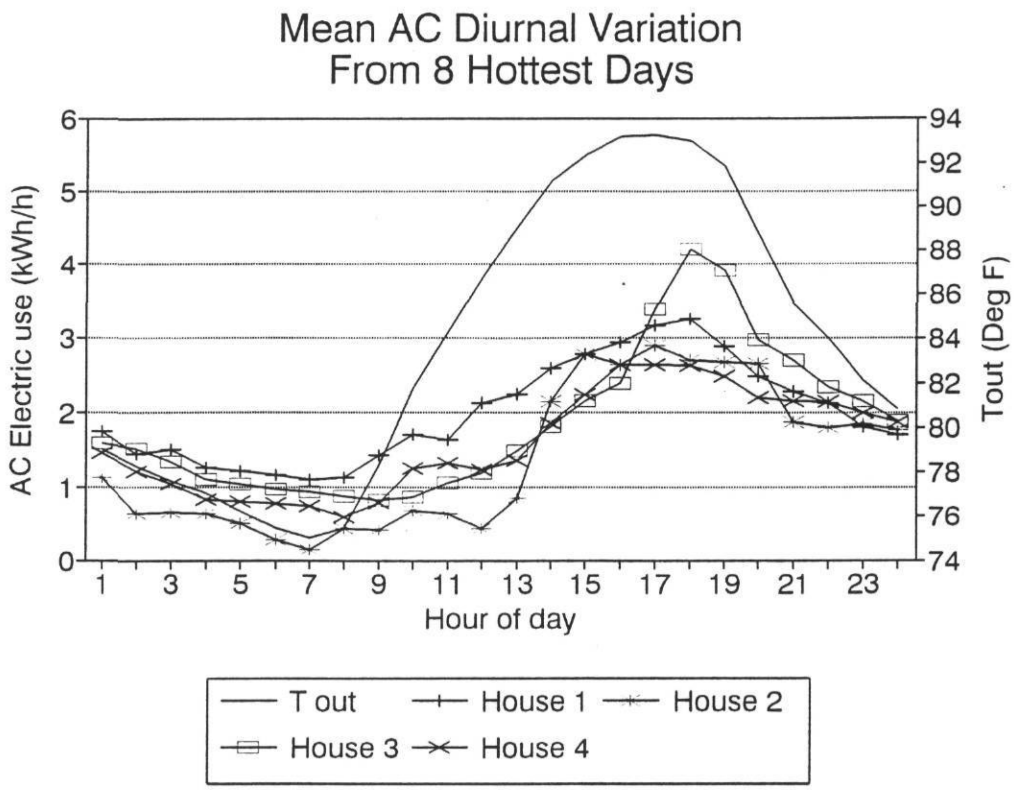
Other than the above features, no further insights into (a) whether the ACs were oversized or not, and, (b) if there were,to what extent, were gained during this analysis approach.

7.0 OVERALL SUMMARY AND FUTURE WORK

The results of this study were generally inconclusive because the two major objectives, namely to ascertain whether and by how much oversizing of ACs is prevalent and to determine the extent to which whole-hose electricity peaks can be reduced by proper sizing and operation of the ACs, could not be satisfactorily addressed. The various approaches were able to qualitatively reveal whether the AC was oversized or not but exact quantification was not possible. The same held true in terms of being able to identify the presence of human behavior on thermostat operation (and thus, on whole-house electricity peaks). Consequently, we were unable to quantitatively determine the amount of peak shaving potential in these houses. Whether this deficiency can be overcome by redesigning the experimental set-up to include electronic (and more accurate) measurements of indoor air temperature and the run-time of the ACs, will be explored in a subsequent study planned for the summer of 1992.

The positive results of this study were as follows:

(a) A methodology was developed in order to determine the electricity use of the air handler fan by only measuring whole-house and AC compressor use. This is advantageous in that it simplifies the experimental hardware requirements in projects of the sort undertaken here.



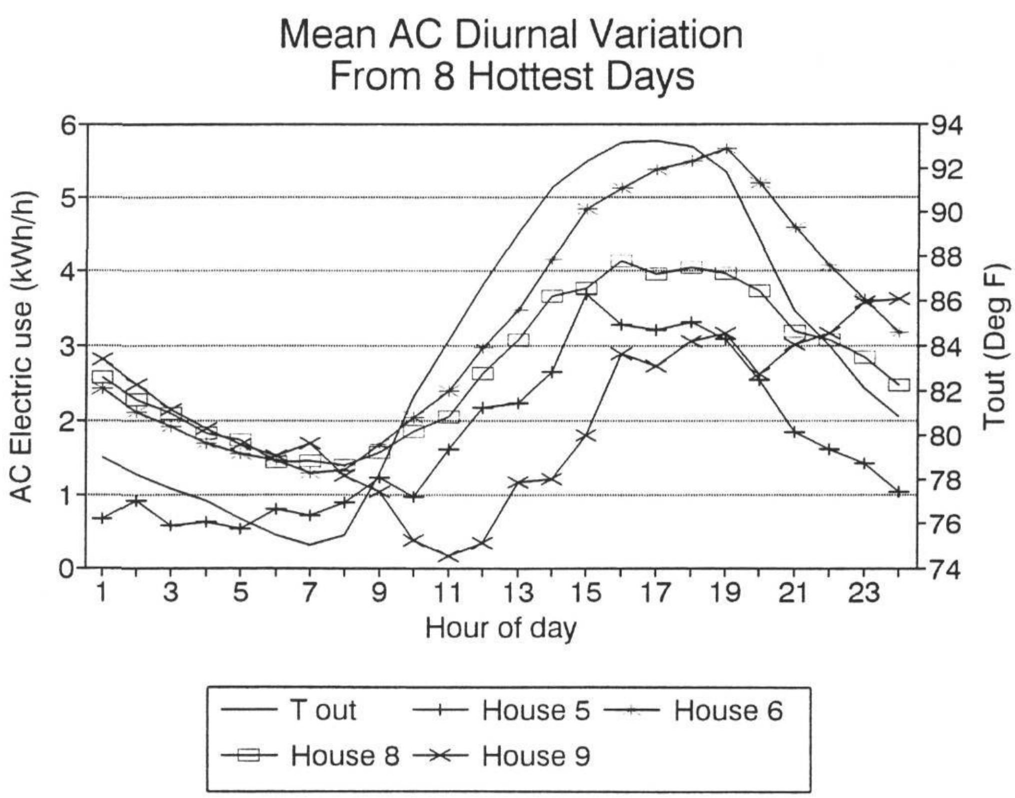


Fig. 10 Mean diurnal outdoor temperature and total AC use in each of the eight houses. The profiles have been found by averaging over the 8 hottest weekdays of August 1991.

(b) The base loads, i.e., the minimum electric load due to refrigerator, lights and other equipment which run all the time, of the non-Good Cents houses are about 0.5 kWh/h while those of the Good Cents houses are about 0.15 kWh/h- a four-fold difference.

(c) Average daily AC use and whole-house electricity use in different houses in College Station during August, the hottest month of the year were compared. It was found that except for one house where the homeowner sets up his thermostat before going to work, the AC use accounted for 65% to 80% of the whole-house electricity use. Also, the manner in which the homeowner operates his AC affects the average use more significantly than does the manner in which the house is constructed (i.e., whether it is a Good Cents house or not). Finally, our analysis found that all the homes satisfied the Good Cents criteria that AC equipment should be sized assuming heat gains of not more than 12,000 Btu/h per 1000 square feet of conditioned space.

(d) The analysis strengthened our belief that whole-house peaks during the peak afternoon periods are largely due to AC use. This was done by generating load duration curves of whole-house electricity use and concurrent AC use and quantifying the interdependence by computing the correlation coefficients between both. These coefficients were very high -- between 0.8 and 0.98. Another observation was that the AC contribution to the whole-house peaks range from a low of 25% to a high of 100% in the sample of houses studied.

(e) We also presented different classes of regression models, based on physical heat transfer equations capable of predicting AC use from various physical drivers. The temperature difference is the most important driver though other drivers are not negligible. The R^2 values of the models when applied to the data at hand varied from a low of 0.44 (in a house where the thermostat is controlled frequently) to a high of 0.80 (in houses where the thermostat is essentially left alone) over the houses investigated. How these values of R^2 could be used to detect the presence of human control on thermostat operation was also discussed: a low R^2 value implying significant intervention and vice versa. These trends in model R^2 and what they imply in terms of human control are novel features of this study.

(f) How scatter plots of AC use versus temperature difference could qualitatively yield information regarding both AC oversizing and homeowner intervention were discussed and the underlying conceptual scientific framework was also presented. Table 8 presents a summary of our qualitative observations of all 8 houses studied. Preliminary indications are that only one house has an undersized AC, two houses have correctly sized ACs, while the remaining five houses have oversized ACs. Only one house had excessive homeowner control while five houses seem to have little or no control at all. Experiments planned for the summer of 1992 should provide more definitive, and hopefully, more quantitative results.

Table 8. Qualitative observations drawn from our analysis of August 1991 data.

	H1	H2	H3	H4	H5	H6	H8	H9
Floor area of house (ft^2)	2201	2650	2105	1397	1637	2609	3635	2000
No. of ACs	1	2	1	1	1	2	2	1
Average Internal loads during peak period (kWh/h)	0.75	0.50	1.5	1.0	1.0	0.75	1.7	1.75
Max. installed AC capacity (including air handler) (kWh/h)	3.5	>5.0	>5.0	2.75	>4.5	>6.5	>7.5	4.5
AC sizing?	Correct	Over	Over	Under	Over	Over	Over	Correct
Homeowner control?	None	Moderate	Little	Little	None	Little	None	Excessive

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Useful discussion with our colleagues J. S. Haberl and S. Katipamula are acknowledged. Thanks also to Mr. P. Teinert and others of the City of College Station for their assistance in providing technical support during the instrumentation phase. This research was sponsored in part by (i) by the National Science Foundation, (ii) the Texas Higher Education Coordinating Board under the Energy Research and Applications Program (ERAP) project #222 and (iii) the City of College Station.

NOMENCLATURE

AC	Air conditioner
A_s	Effective solar aperture
a, b...	Regression coefficients
COP	Coefficient of Performance
E	Electric energy
MC_p	Heat capacity of the house
Q	Thermal energy
R^2	Coefficient of determination
T_{in}	Indoor air temperature
T_{out}	Outdoor air temperature
t	Time
UA	Total heat loss coefficient of the house

SUBSCRIPTS

AC	Air conditioner, usually compressor only
ACT	Total air conditioner, compressor plus air handler fan
AH	Air handler
BL	Base load
cond	Condenser
evap	Evaporator
Int	Internal loads
Mis	Miscellaneous
sol	Solar
WH	Whole-house

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APPENDIX A

How Does AC Control By Homeowner Result In Excess AC Power Demand

Figure A1 illustrates how AC control by the homeowner can result in peak or excess AC power demand. Let T_{in} * be the design indoor air temperature. The base case would be one where the thermostat is left entirely alone. Then T_{in} *, neglecting the small temperature fluctuations due to the thermostat dead band, would be essentially constant as shown in the upper half of Figure A1. Under these circumstances, the AC would operate normally, cycling repetitively as shown at the right hand side of the lower half of Figure A1.

Let us consider homeowner control of the thermostat. Though there are several ways by which such control can occur, let us assume the most basic case wherein the AC was originally switched off and the indoor air temperature T_{in} is left to float depending on the thermal loads of the residence. In Figure A1, this is illustrated by a variable line above the T_{in} * line. If the AC is now switched on, it would take the AC a certain time interval, represented by Δt in Figure 1, for it to lower T_{in} to T_{in} *. During this period, the AC would draw the full installed power which would be in excess of the electric power under normal cyclic operation. Thus, homeowner intervention of normal thermostatic AC operation has resulted in a period Δt during which excess electric power was drawn. This amount of excess electric power is what results in electricity peak loads in the residence, which taken over several residences, lead to electric utility peaks.

Let us now discuss how AC oversizing imparts peak demand. Several parameters, both climatic and apparatus design values, affect the performance of an AC, which is essentially a vapor compression refrigerator device. Of the climatic parameters, the ambient or outdoor dry bulb temperature T_{out} is probably the most influential because it affects both the heat loads of the residence and the refrigerator capacity via the condenser temperature. Even in an unconditioned home, because of the thermal mass of the building, diurnal variation of T_{in} will be much smaller than T_{out}. Hence the driver $(T_{out} - T_{in})$ is, in practice, dictated more by T_{out} than by T_{in}.

Because the coefficient of performance (COP) of the AC tends to decrease with increasing values of $(T_{out} - T_{in})$, the AC power, E_{AC}, at full refrigeration capacity, i.e., assuming no cycling of the AC, will exhibit a slight positive slope. ACs of different full-load capacities would be represented by a family of lines such as CD and FG of Figure A2. However, the actual AC electric use is dictated by the thermal loads of the residence. If we assume $(T_{out} - T_{in})$ to be the sole driver, the actual AC electric use will increase linearly with $(T_{out} - T_{in})$, as shown by line AE in Figure A2. Note that the effects of cyclic operation of the AC are inherently contained in line AE.

The industry practice of proper sizing of an AC to match the loads in a particular residence involves choosing the full capacity line among the family of lines which intersects line AE at a point, shown as B in Figure A2, corresponding to the design T_{out} value recommended by ASHRAE (1989) for that specific geographic location. This practice would require that a constant T_{in} * value be selected which, due to internal loads of the residence, is closer to the balance point temperature (Mitchell, 1983) of the house rather than the actual indoor air comfort temperature. Because T_{in} * is taken as an average constant value, the temperature difference driver is shown in Figure A2 as ΔT design. In short, line CD represents AC power consumption at full capacity, while line AB represents actual power consumption. At a temperature difference other than the design value, sayΔT, the ratio (OR/OS) would represent the fractional time that the AC is on.

Let us now discuss how improper control of the AC or AC oversizing can lead to excess AC power demand. In our simplified visualization given by Figure A2, actual or measured AC use without homeowners control on the thermostat should fall on line AB for ΔT values less than ΔT design, and if the AC is well designed on line BD for ΔT values greater than ΔT design. This electric use is altered by homeowner control. If the AC were initially off, and if the homeowner switches it on when the temperature difference is, say ΔT, the measured E_{AC} value would be OS and not a value close to OR. Consequently, an excess electric demand represented by RS on Figure A2, would result. It is clear that if the AC is over-designed to begin with, as represented by say FG, the excess demand would be higher still, as represented by RT. Hence, it is clear that thermostatic control by homeowners will result in an electric excess demand or peak, the magnitude of which is related to the degree of AC over-design.

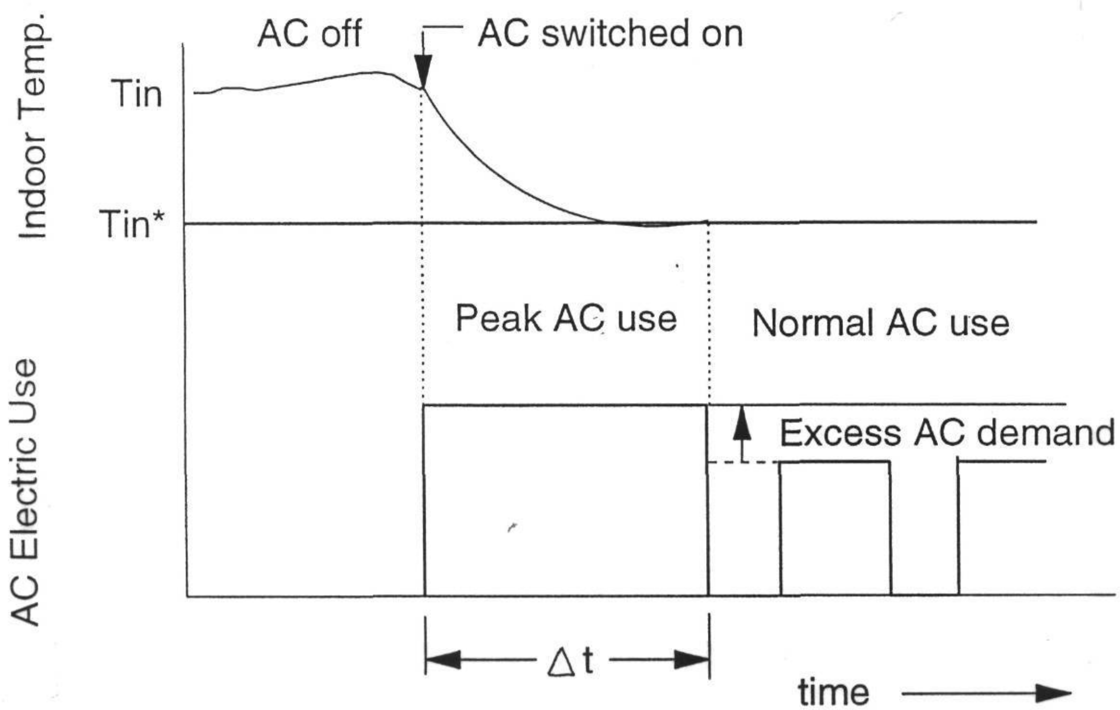


Fig.A1. Schematic illustrating how air-conditioner control by homeowner can result in excess air conditioner power demand.

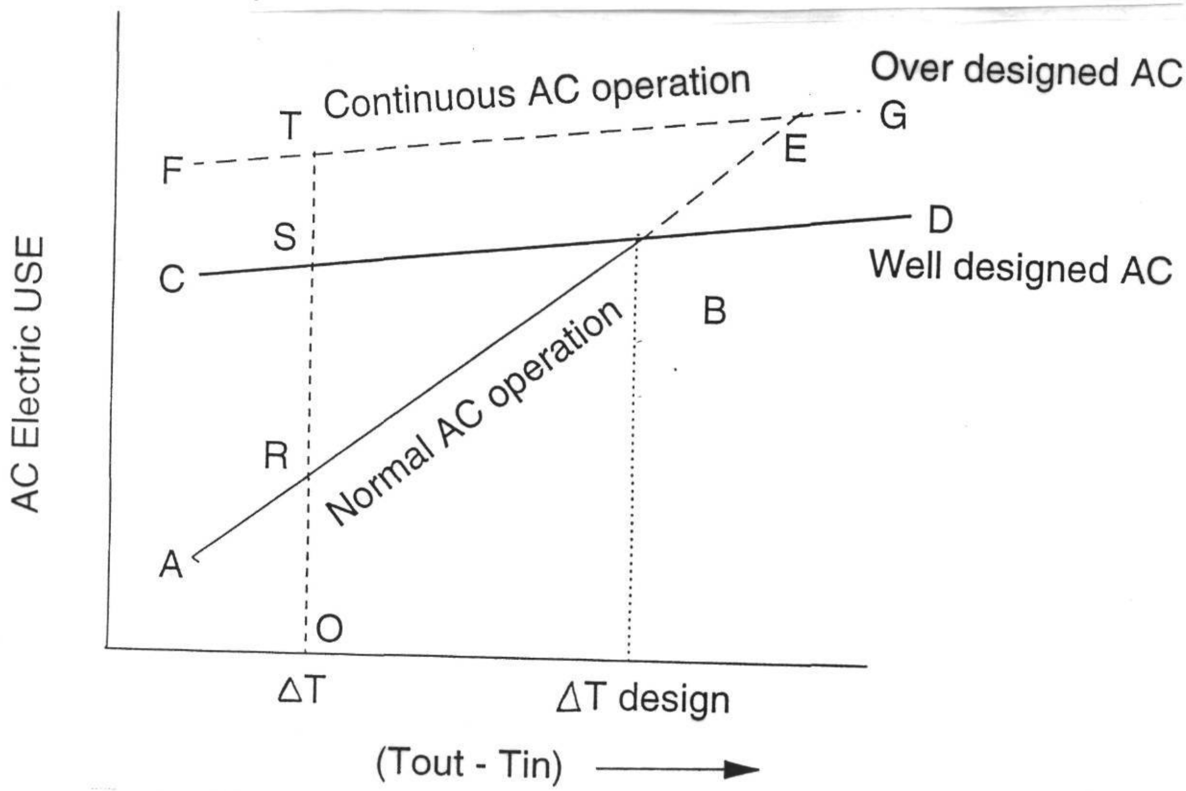


Fig.A2. Conceptual figure illustrating how air-conditioner electricity use varies with temperature difference.

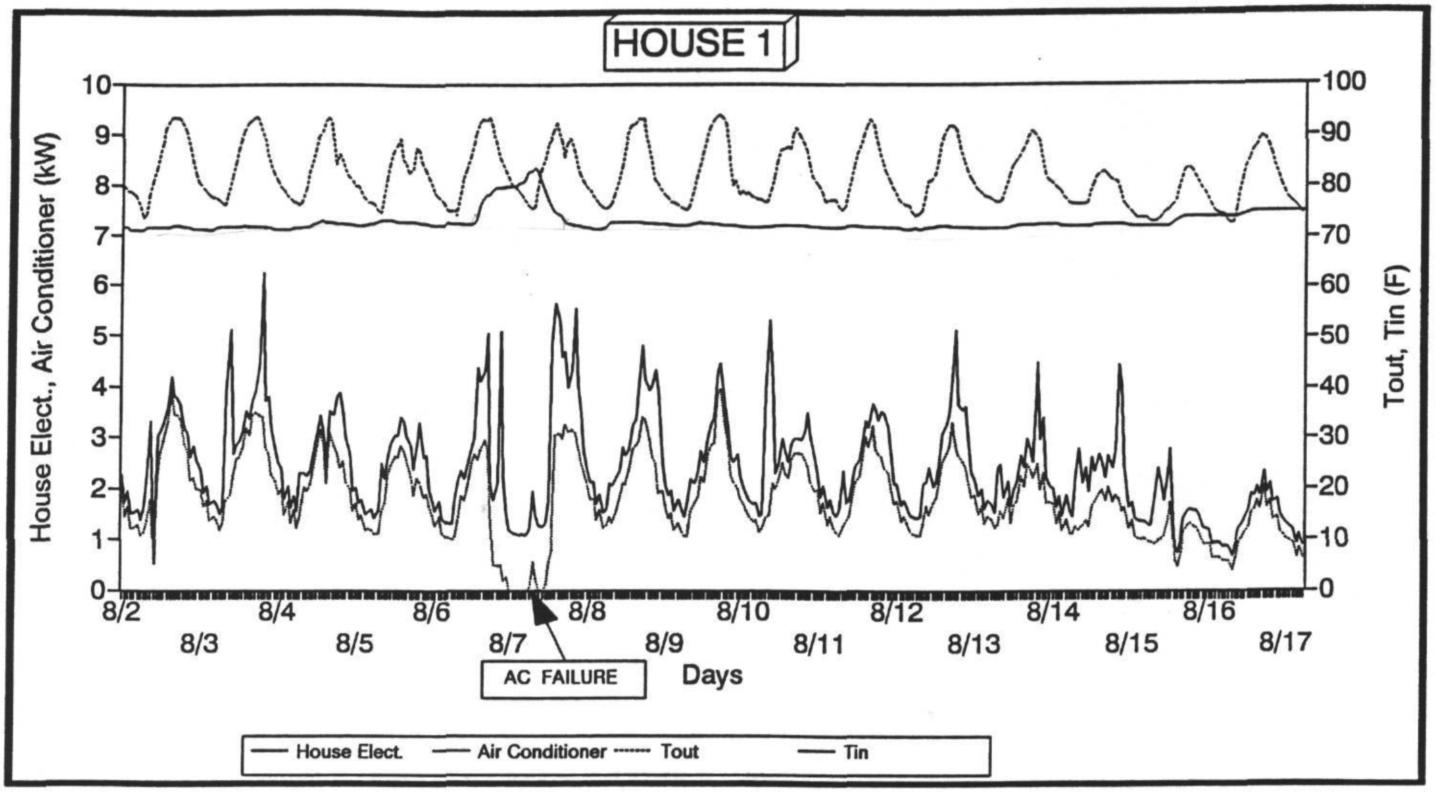
Appendix B

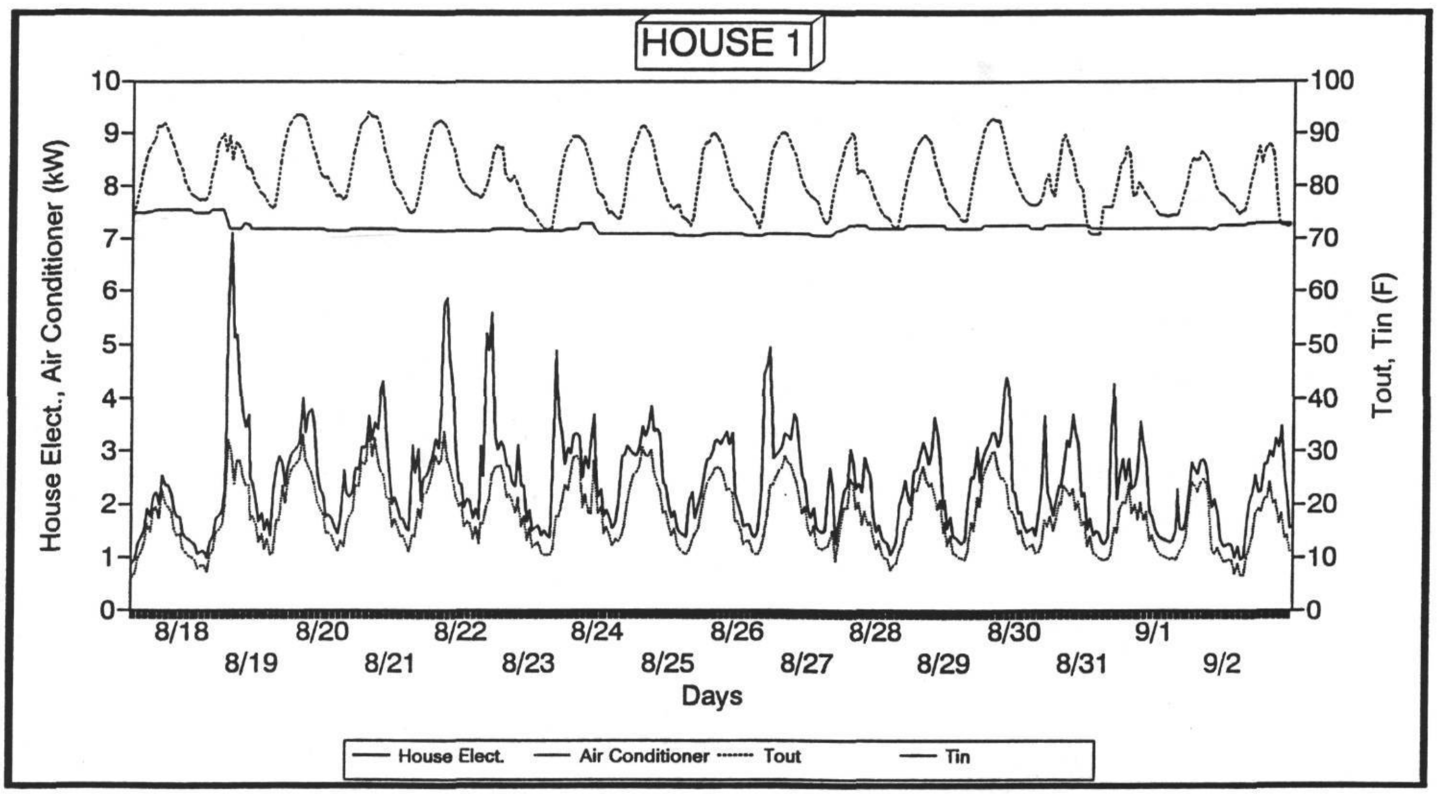
Set B1: Time plots of whole-house electric, air-conditioner electric, outdoor and indoor temperatures.

Set B2: Load duration curves of whole-house electricity use along with concurrent air-conditioner use for August 1991.

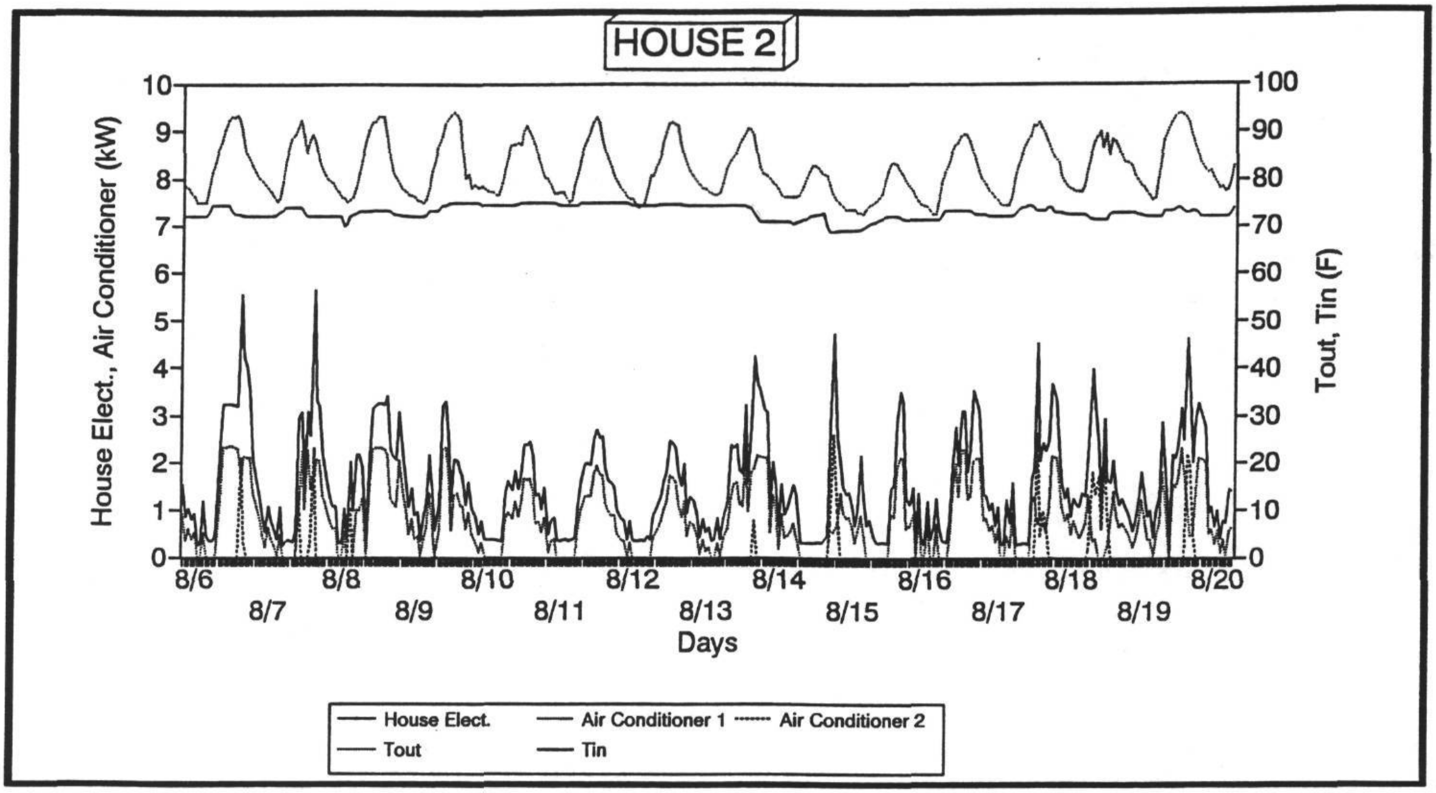
Set B3: Scatter plots of AC use versus outdoor temperature and versus outdoor-indoor temperature difference

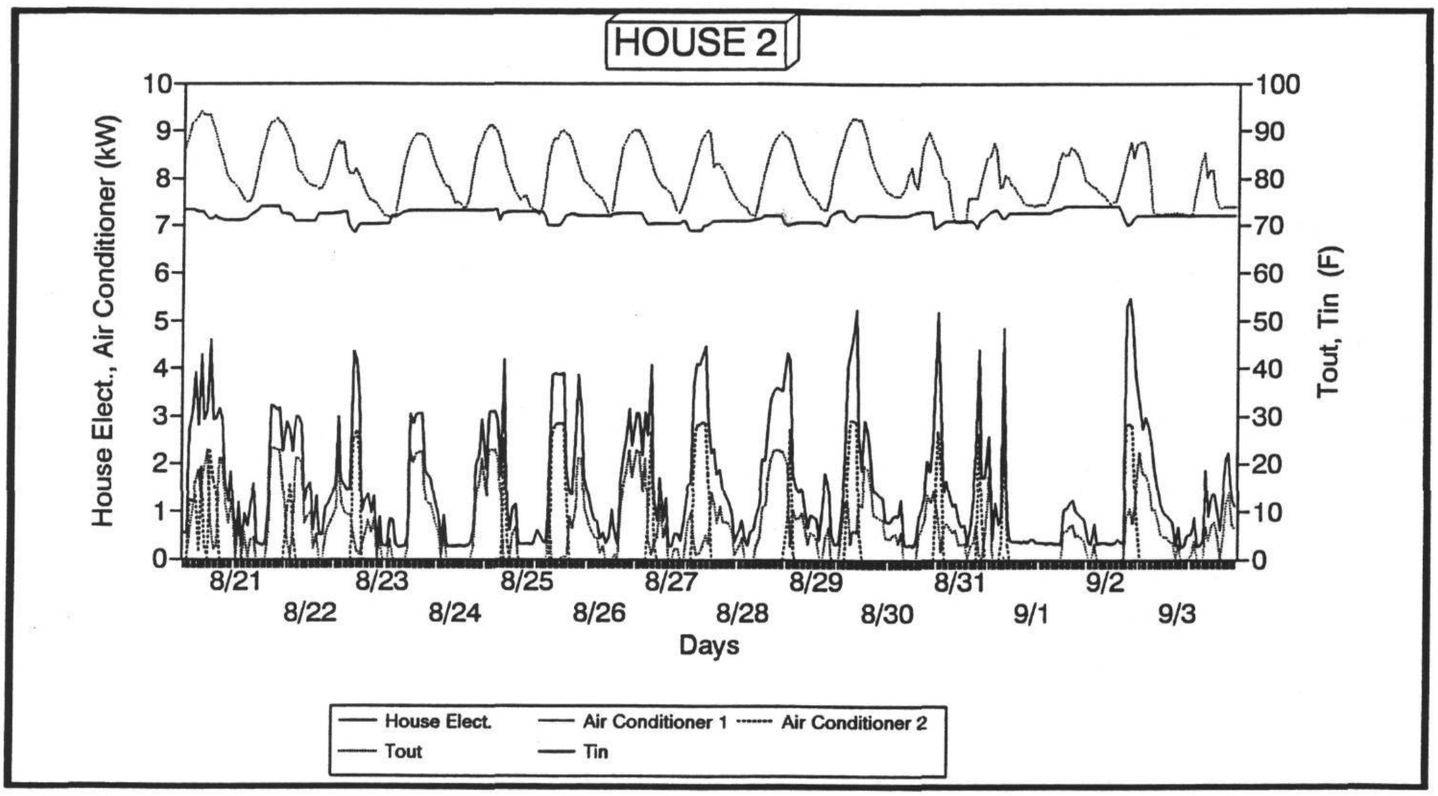
Set B4: Mean diurnal trends over 8 hottest weekdays of various important physical parameters.



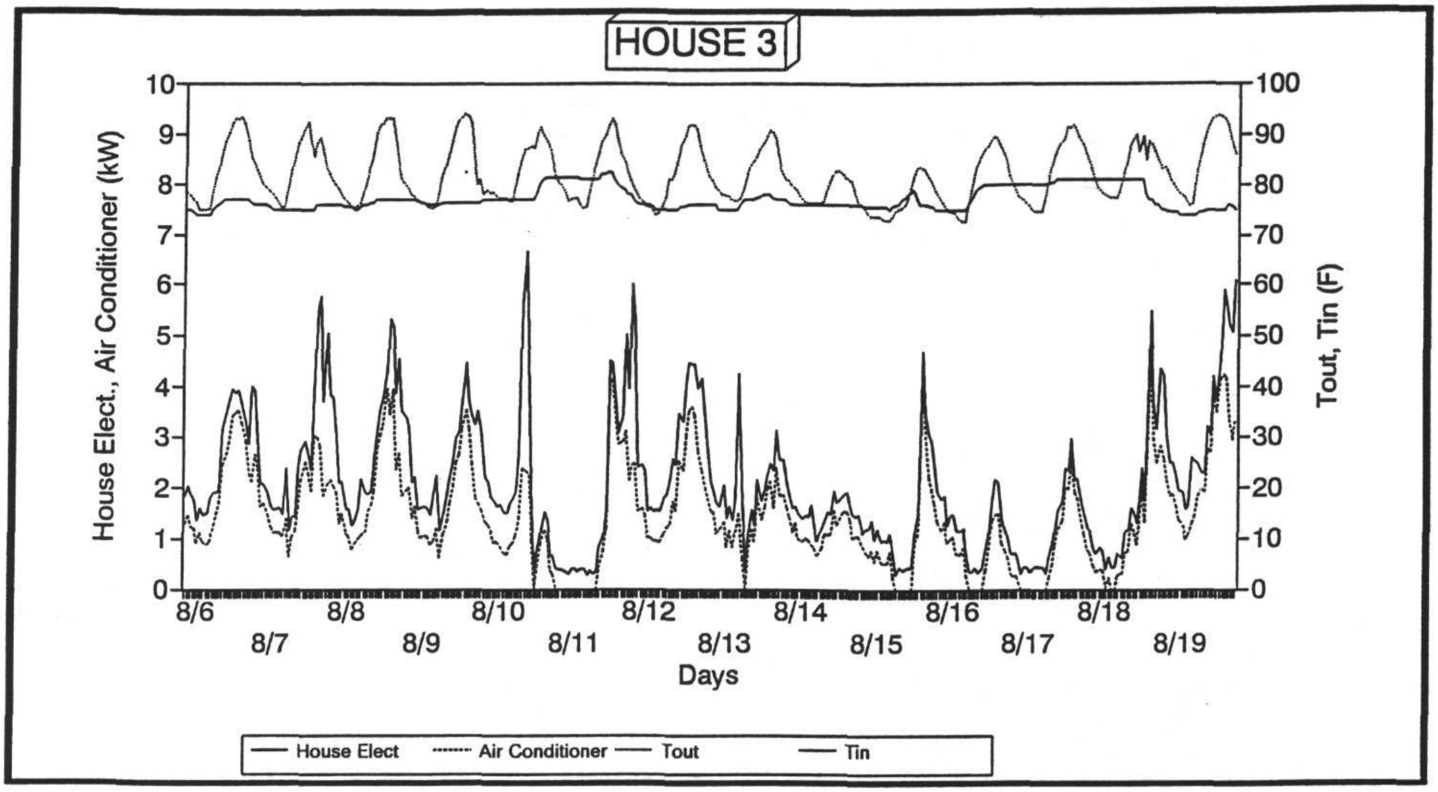


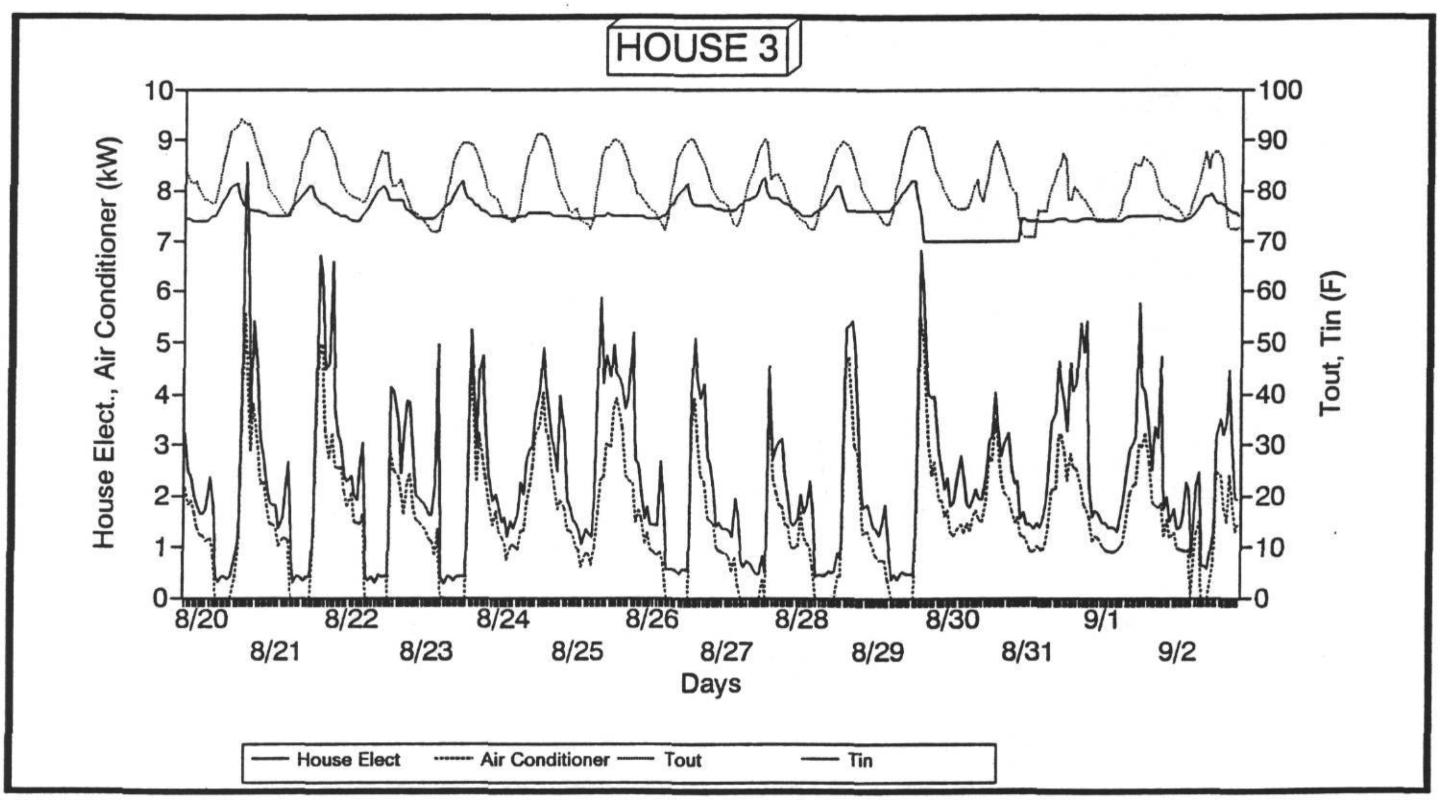
Air conditioner and whole house electricity use in kW are shown for August 2 - September 2, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.



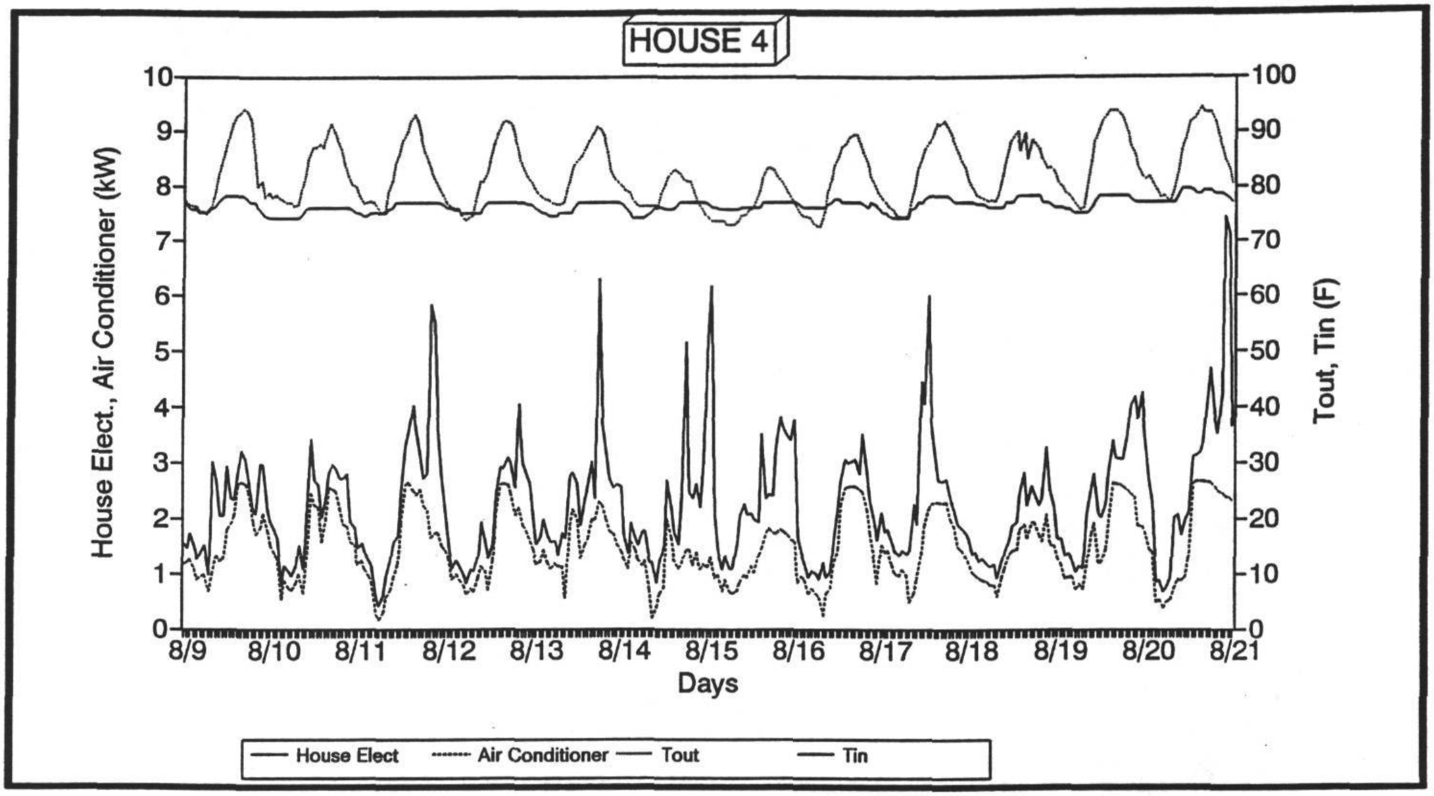


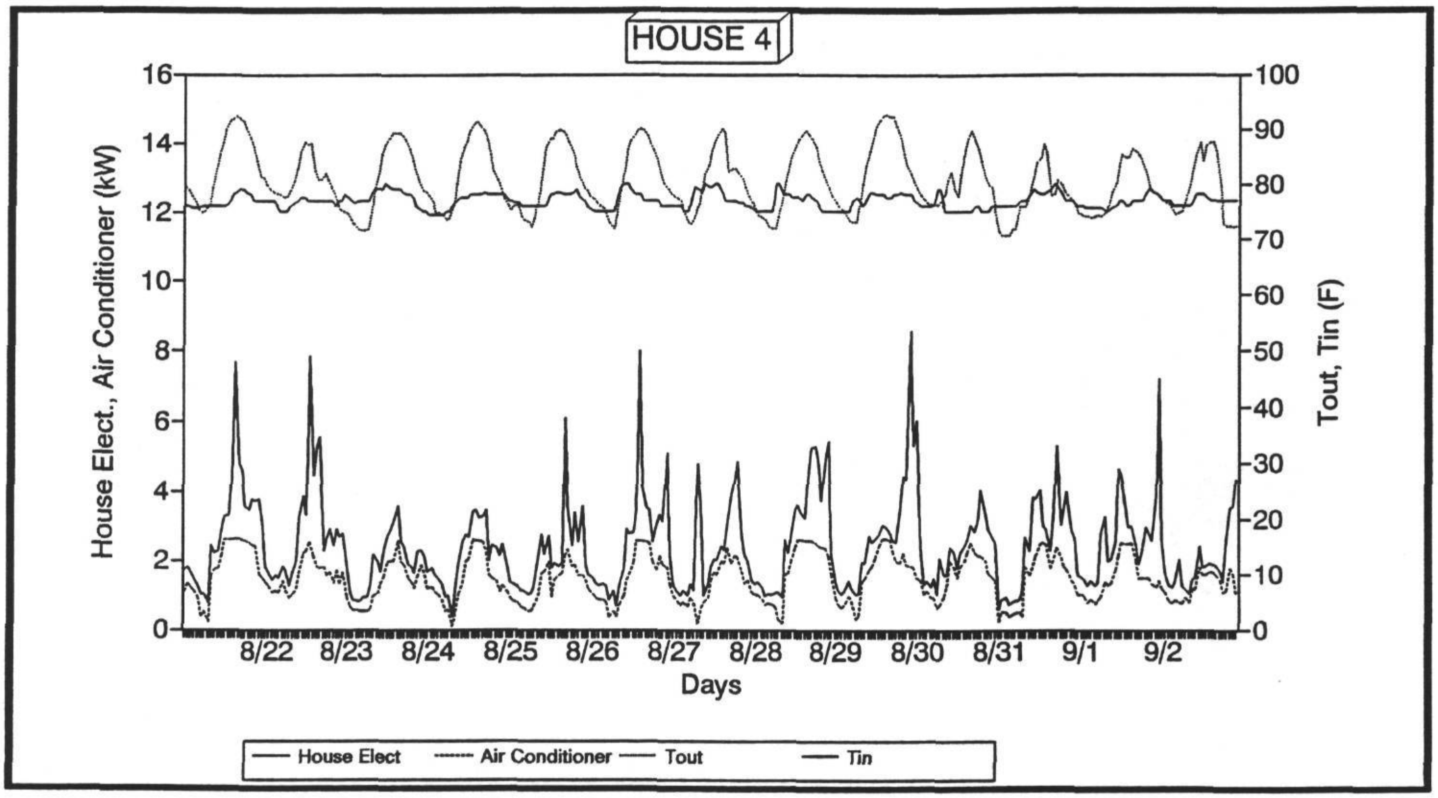
Air conditioner and whole house electricity use in kW are shown for August 6 - September 3, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.



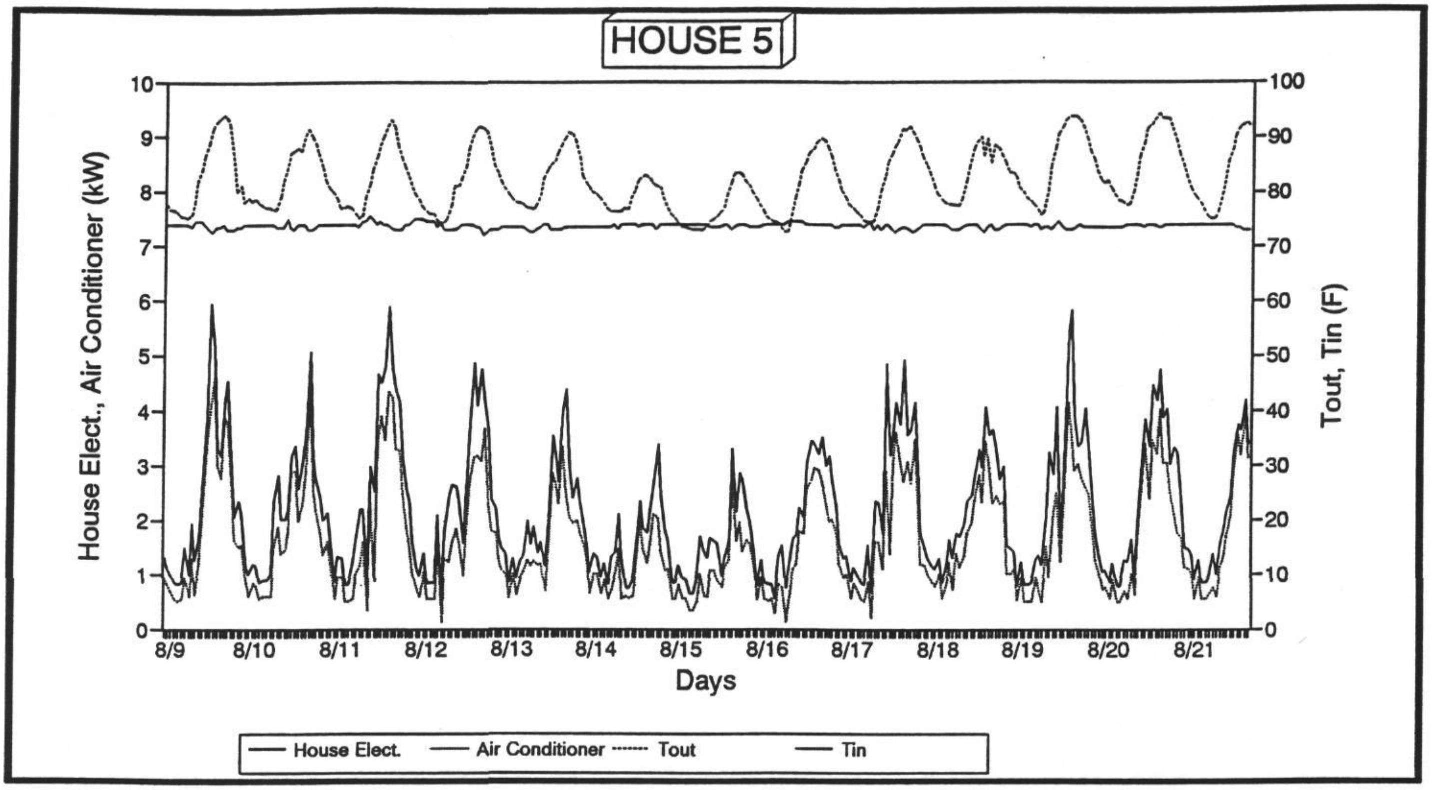


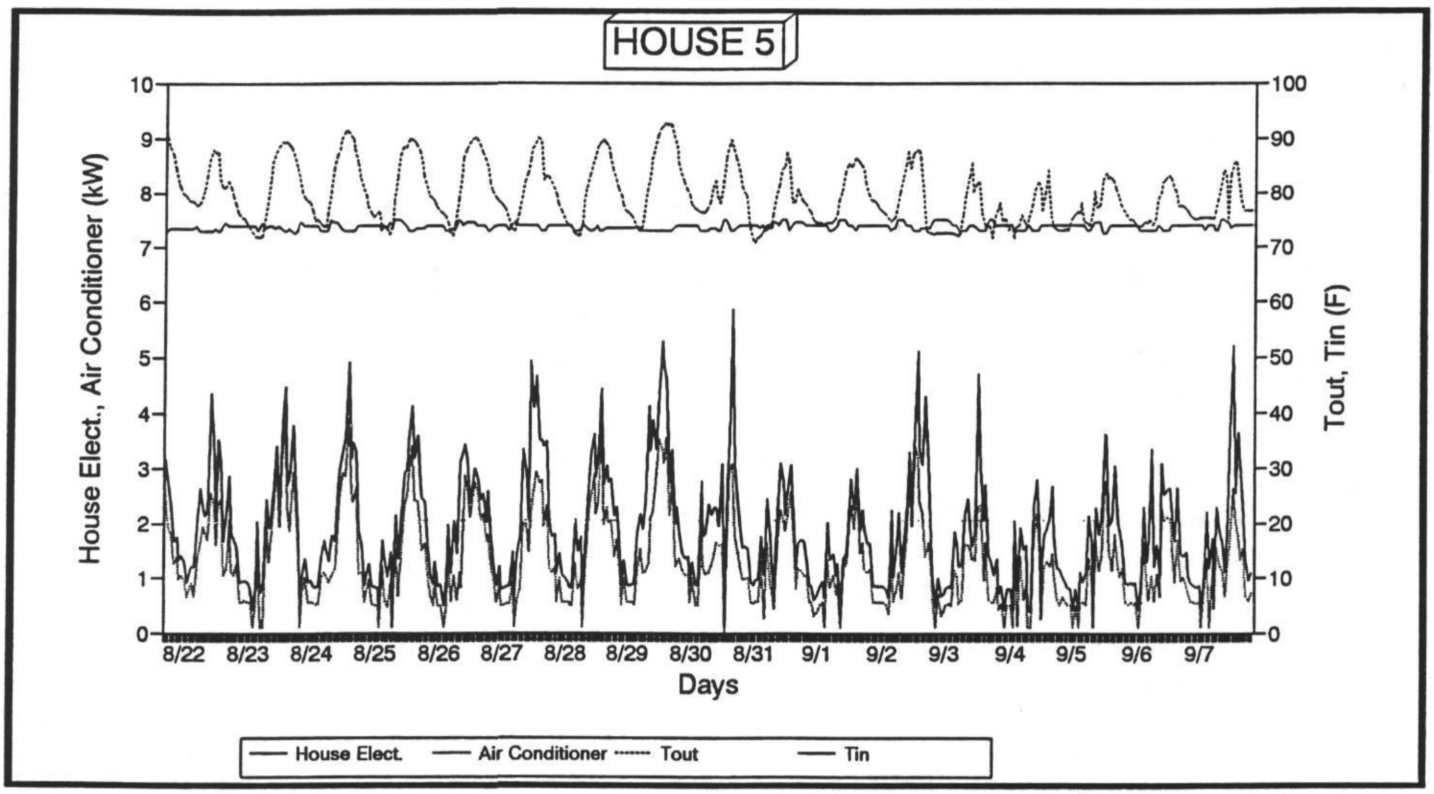
Air conditioner and whole house electricity use in kW are shown for August 6 - September 2, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.



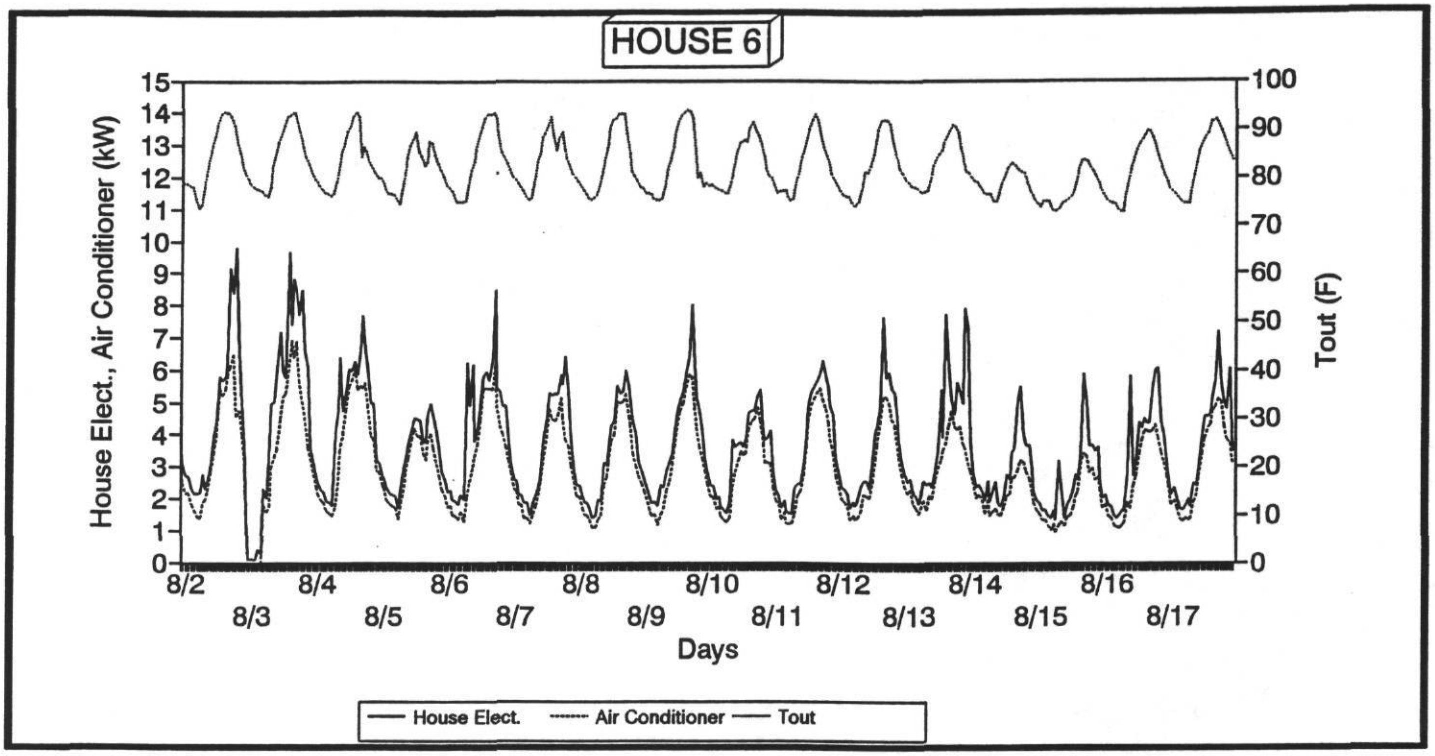


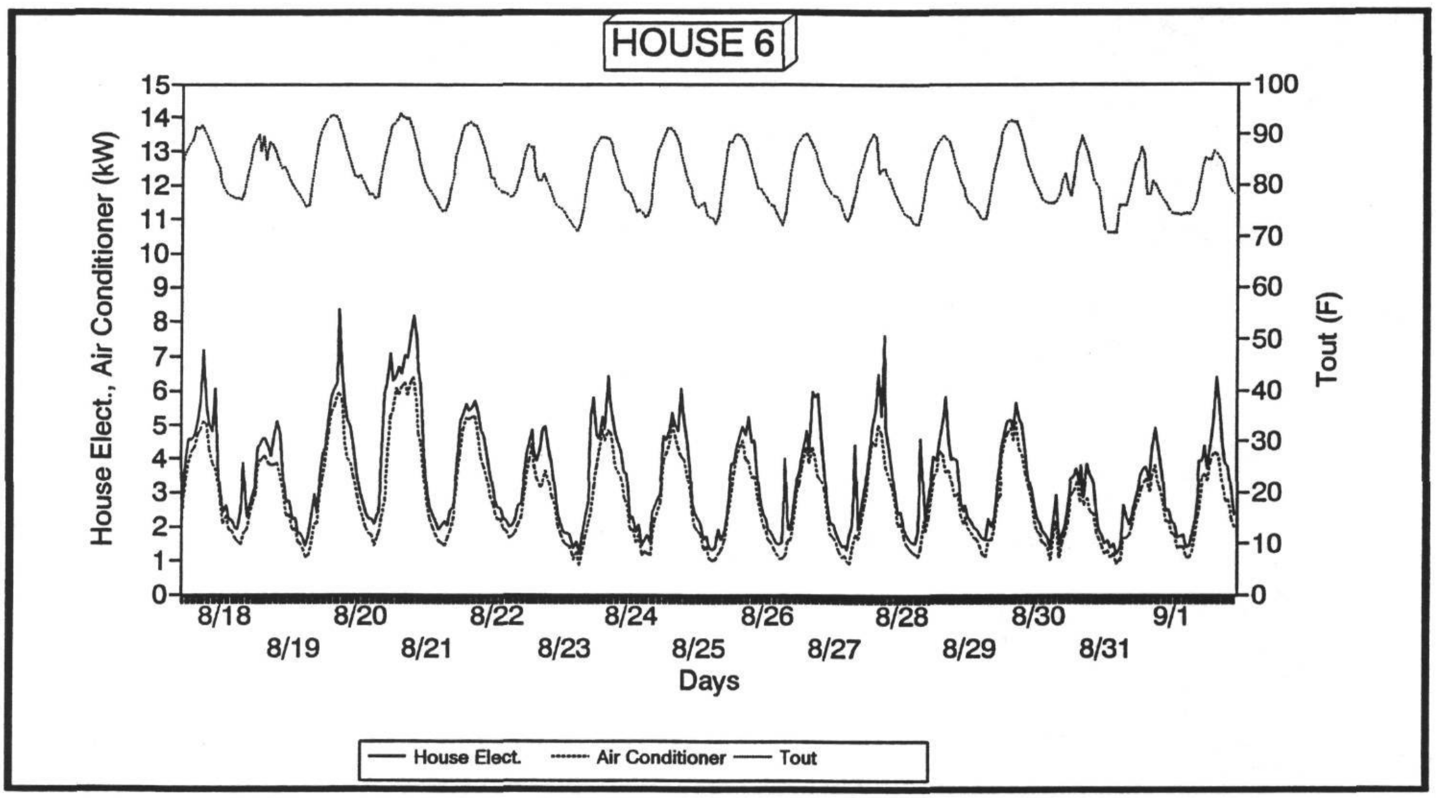
Air conditioner and whole house electricity use in kW are shown for August 9 - September 2, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.



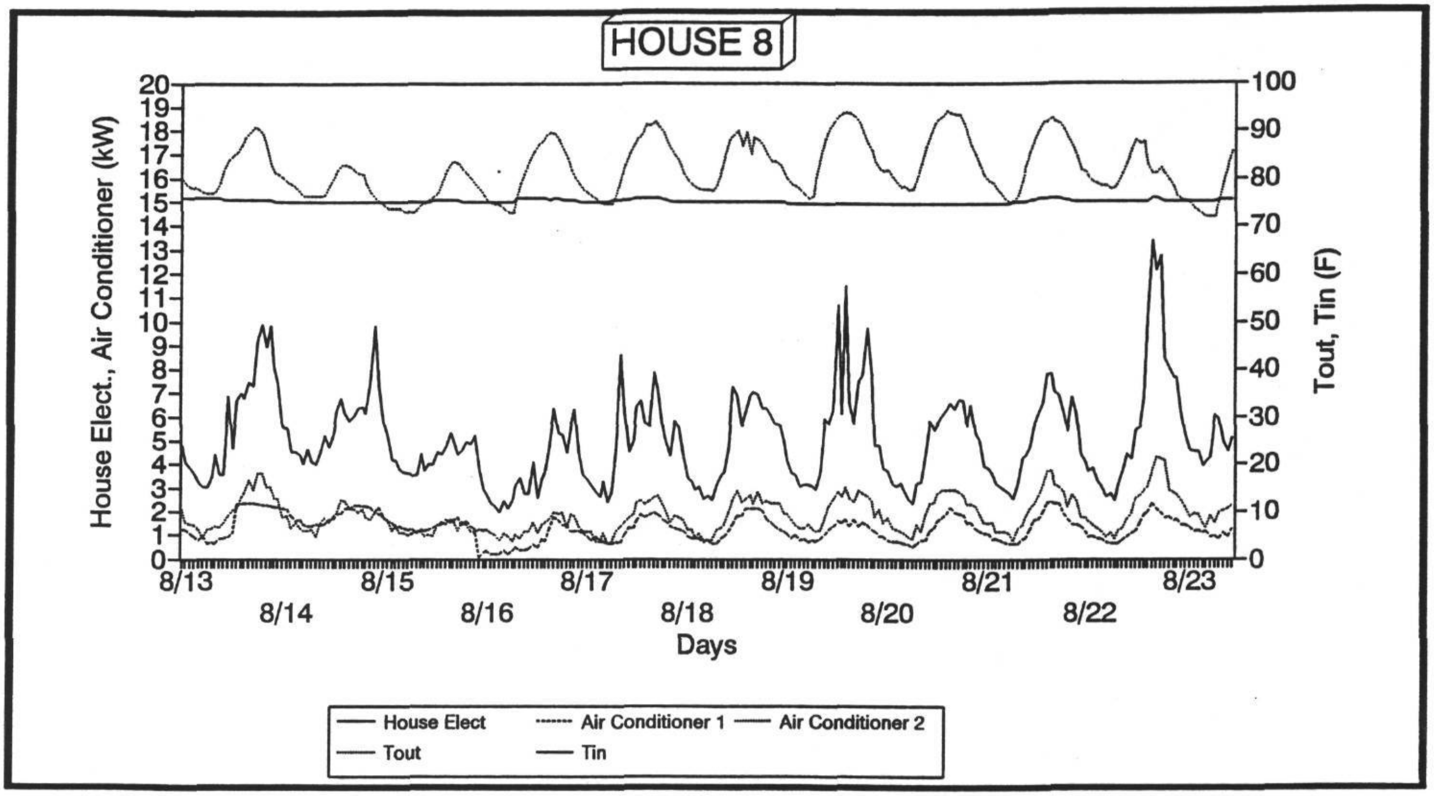


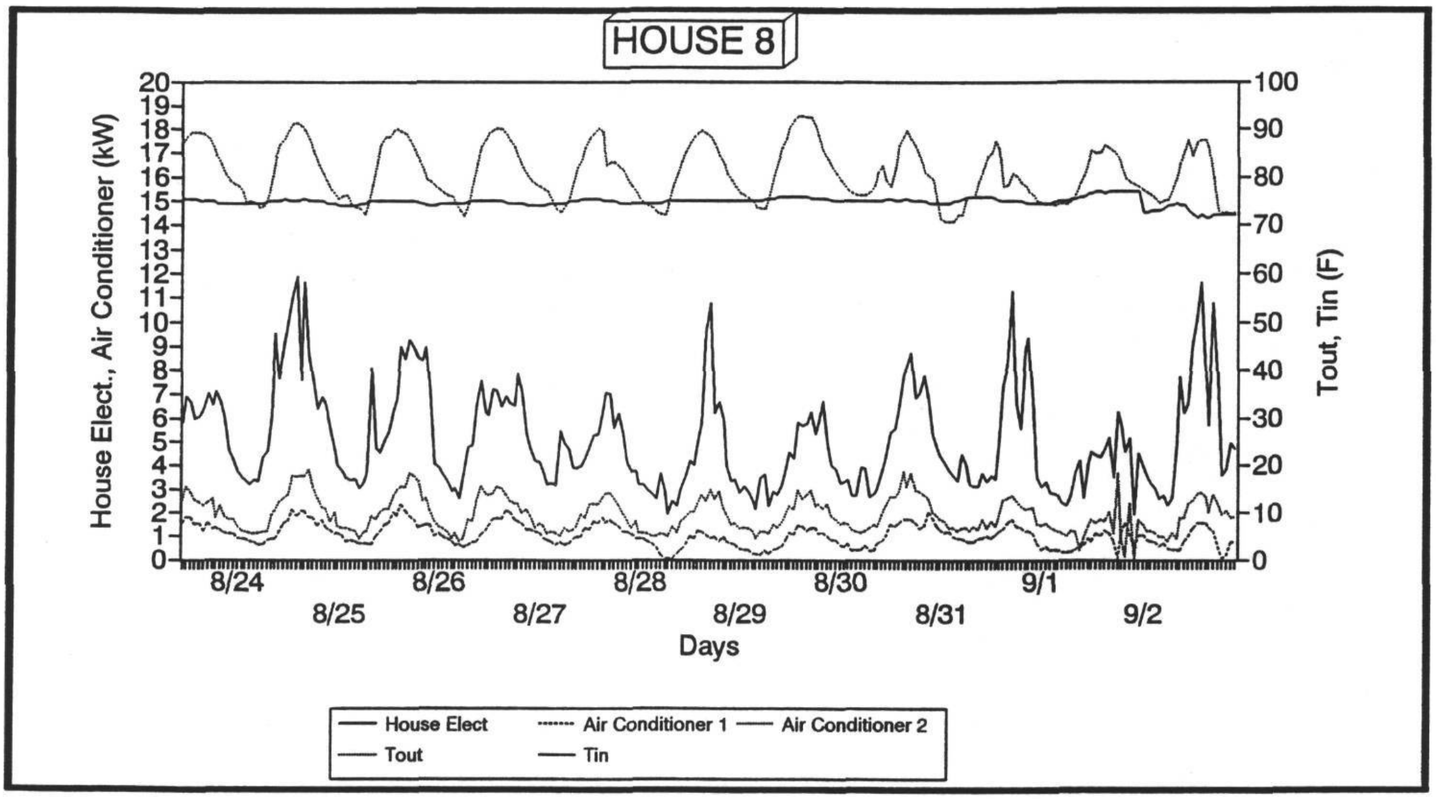
Air conditioner and whole house electricity use in kW are shown for August 9 - September 7, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.



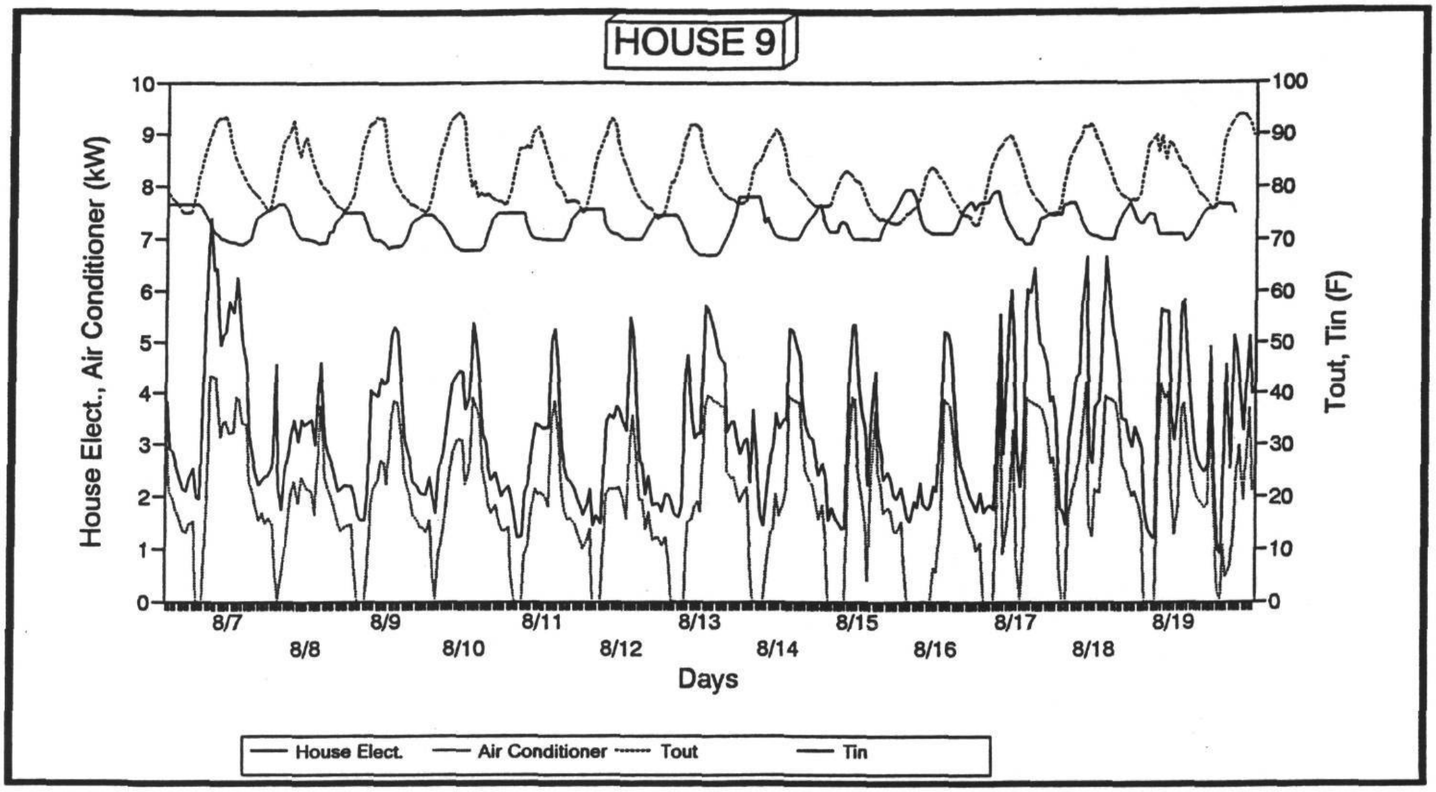


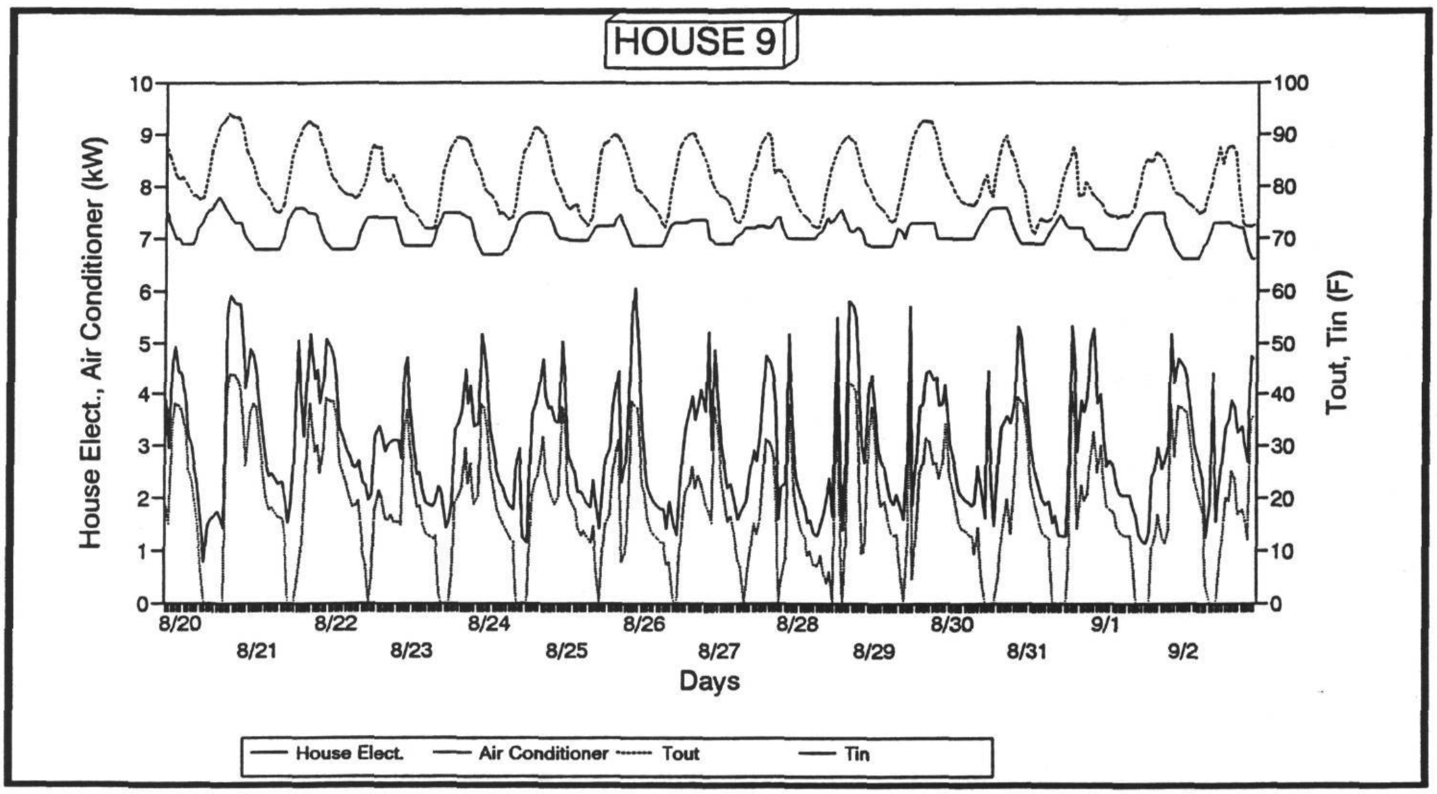
Air conditioner and whole house electricity use in kW are shown for August 2 - September 1, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.



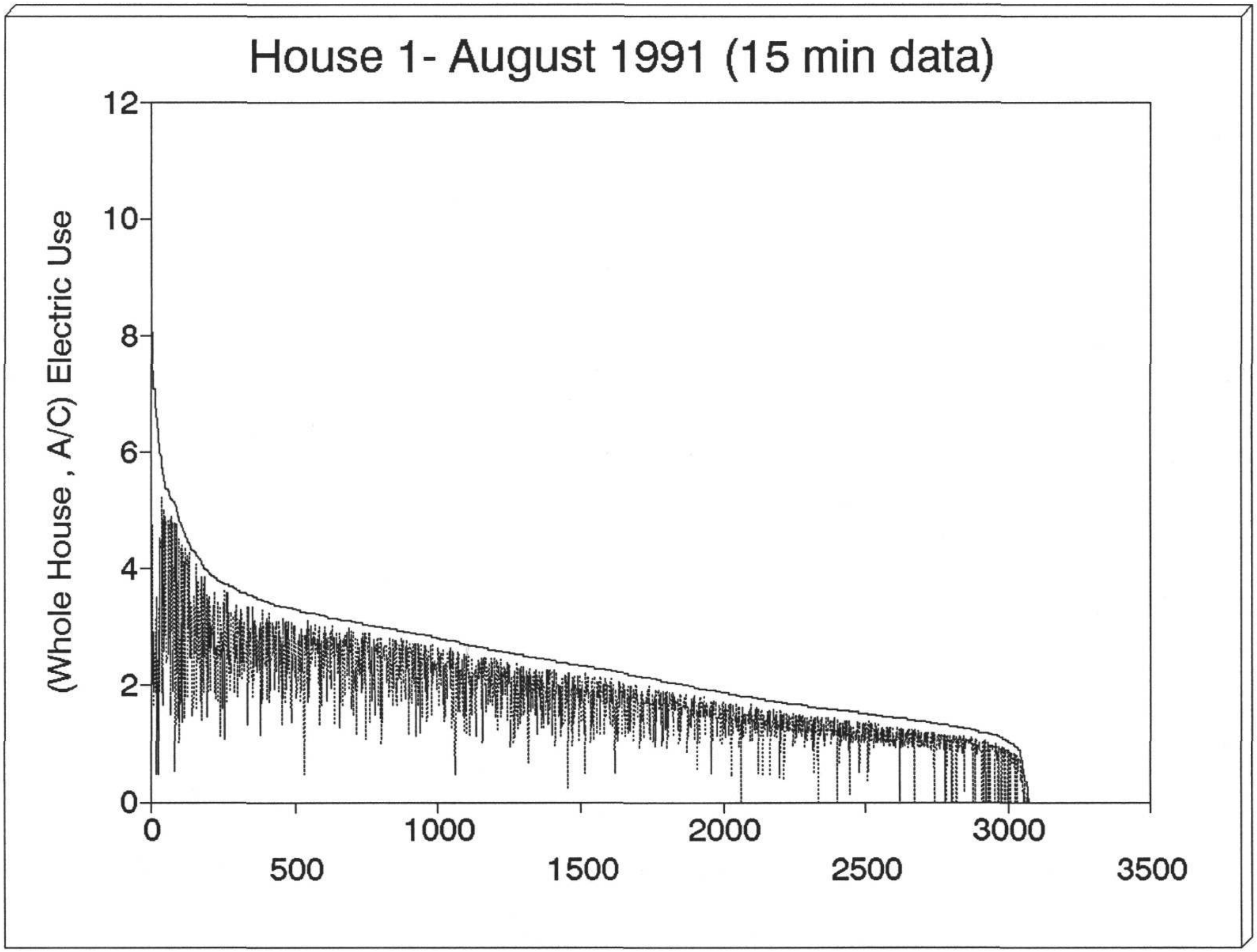


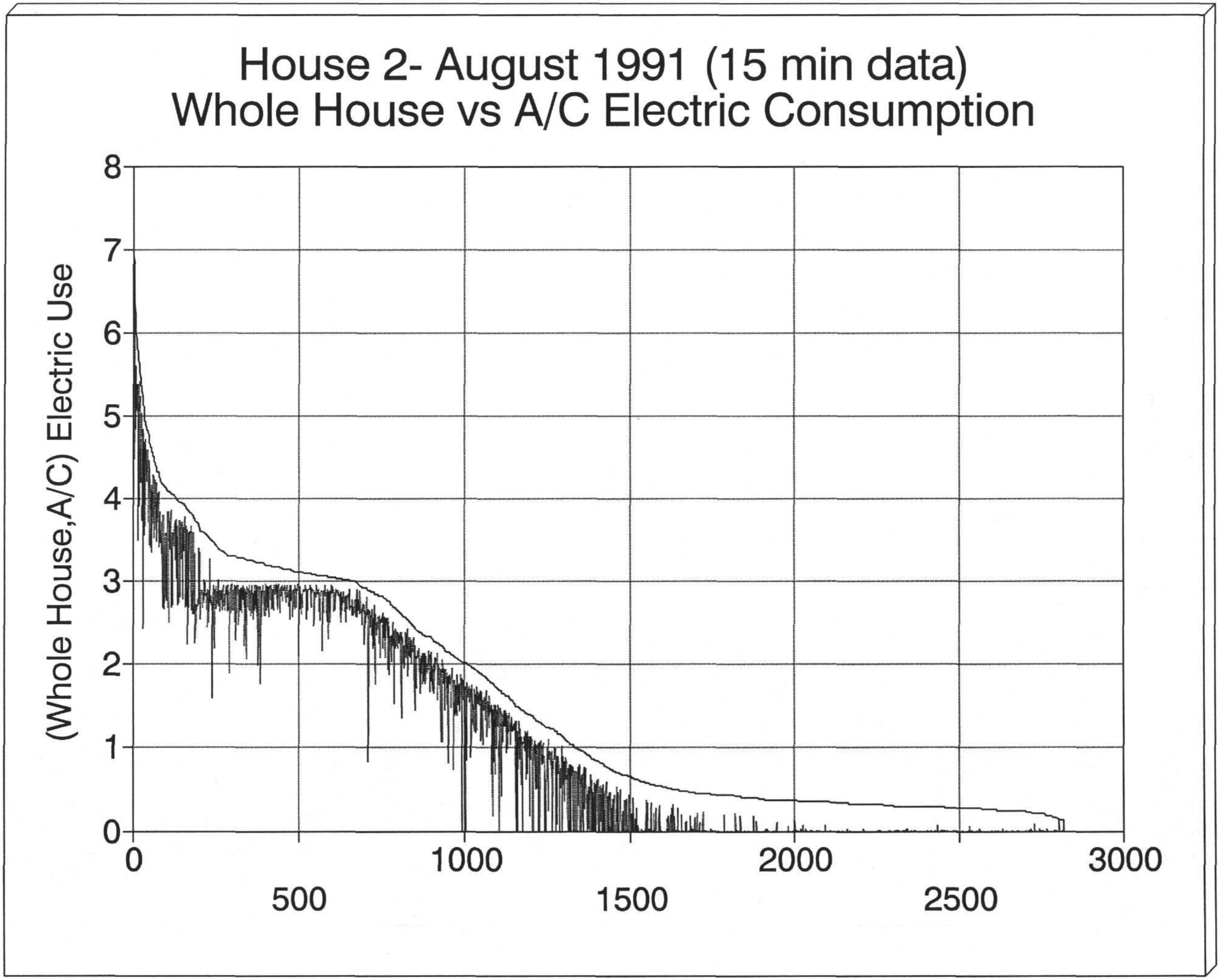
Air conditioner and whole house electricity use in kW are shown for August 13 - September 2, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.

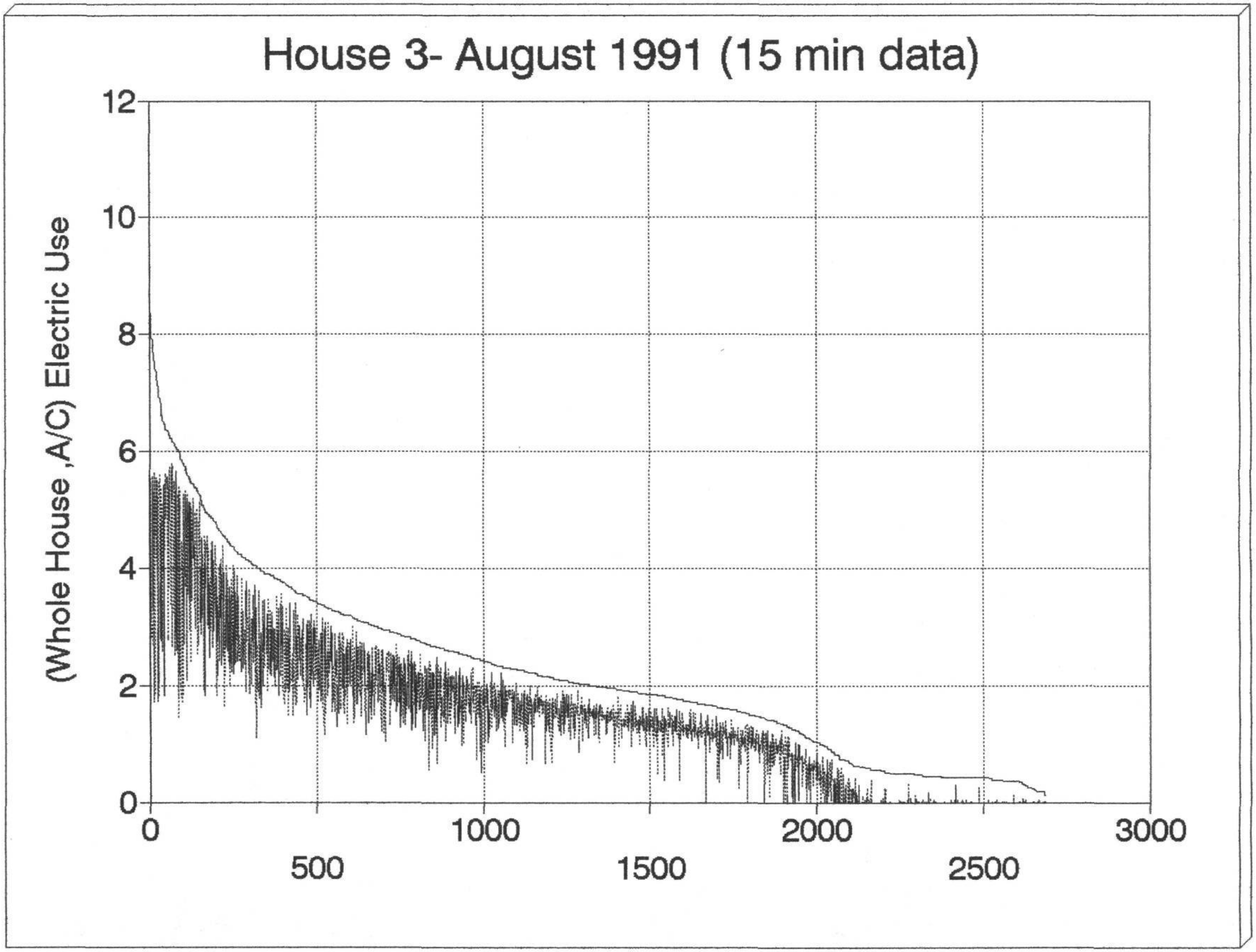


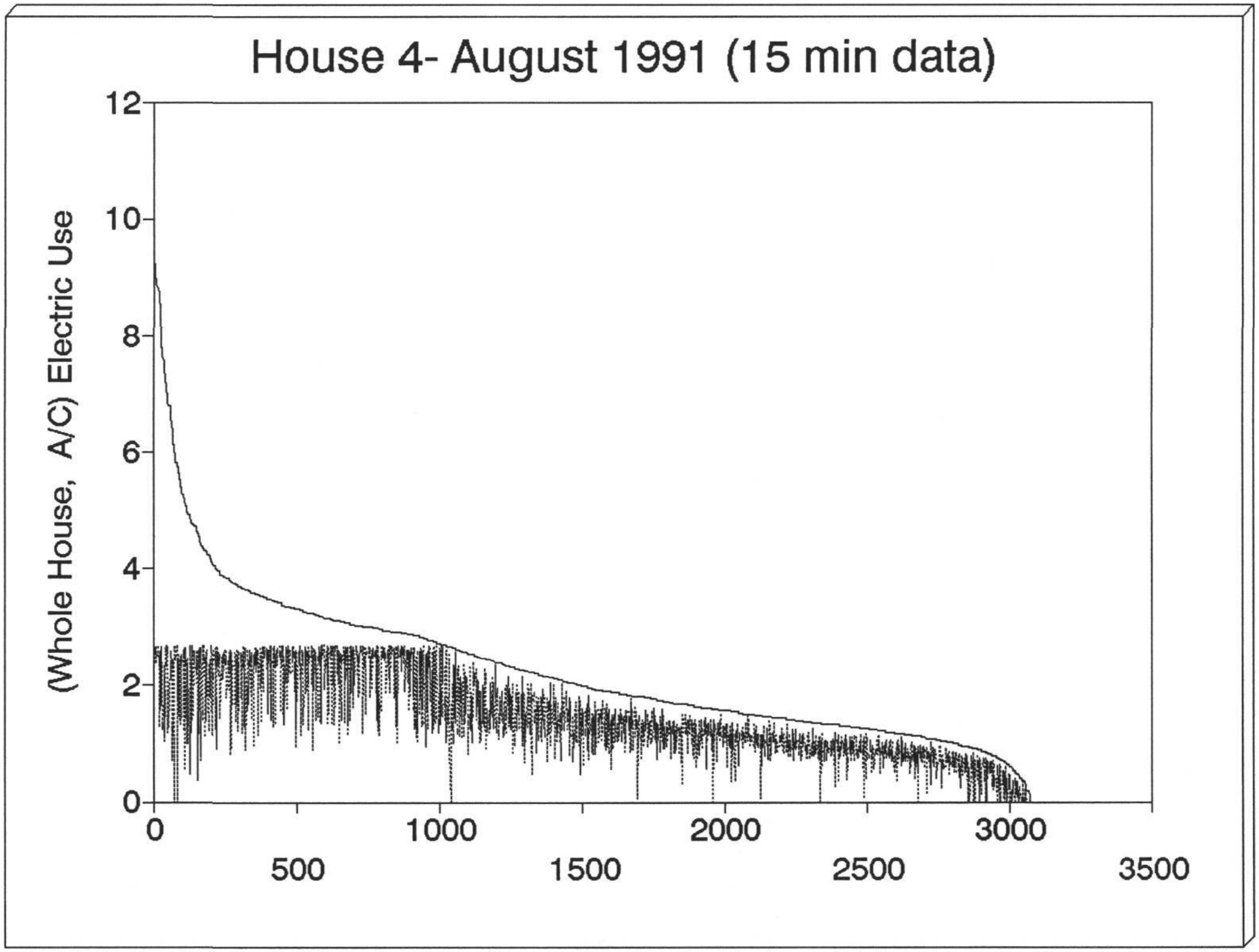


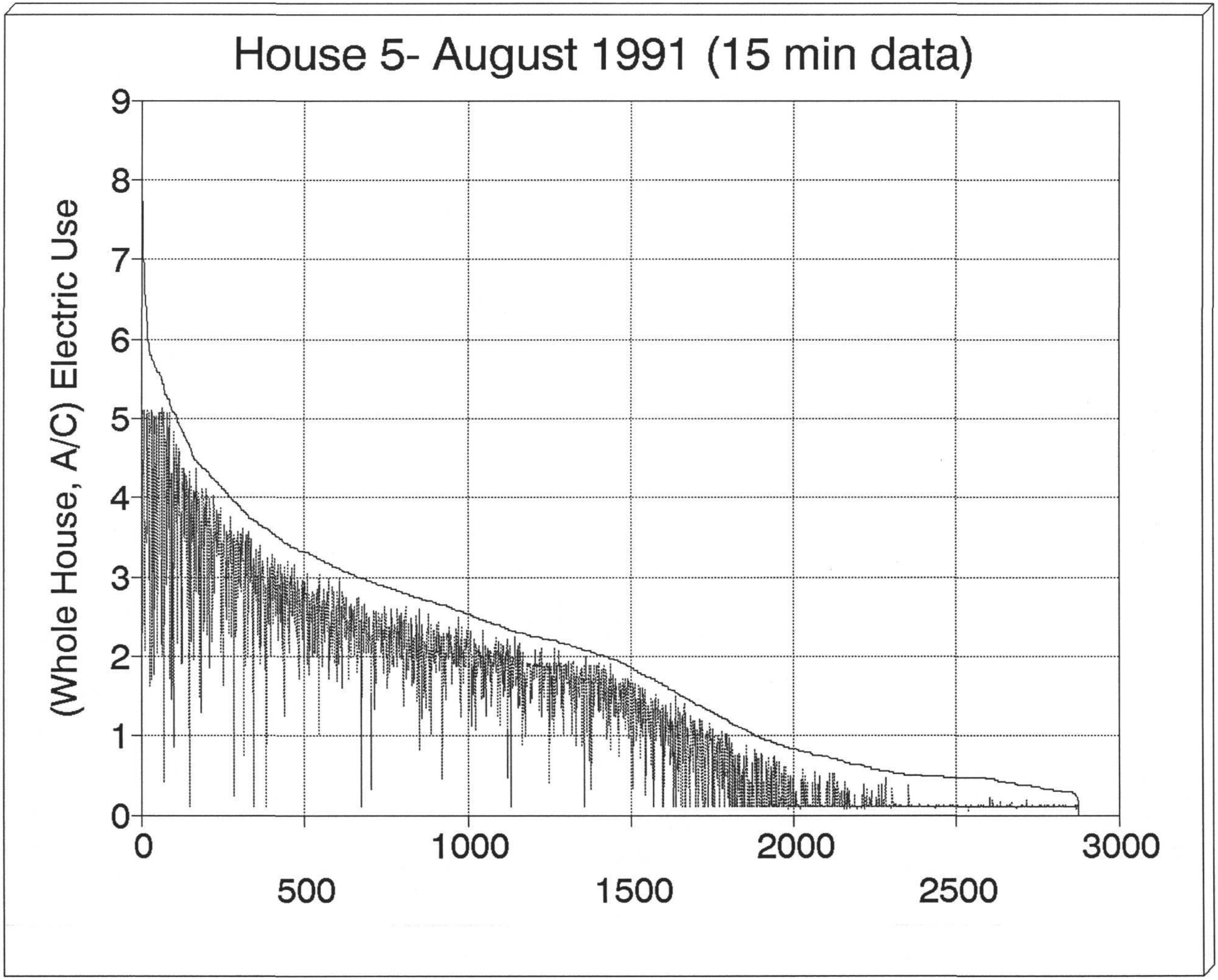
Air conditioner and whole house electricity use in kW are shown for August 7 - September 2, 1991 in the bottom traces. Indoor and outdoor temperatures are shown in the top data lines.

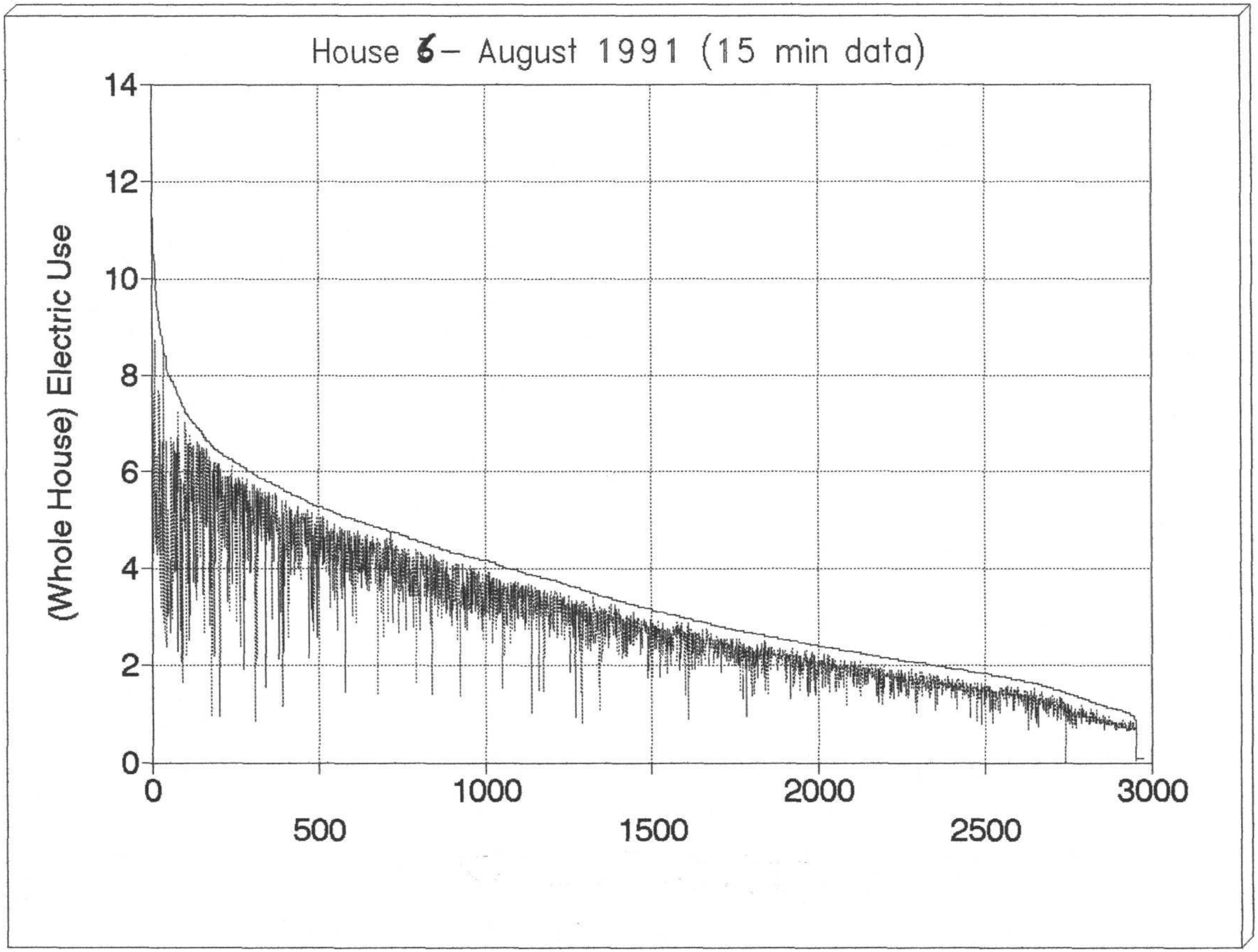

House 1- August 1991 (15 min data)
(Whole House , A/C) Electric Use
12
10
8
6
4
2
0
0
500
1000
1500
2000
2500
3000
3500

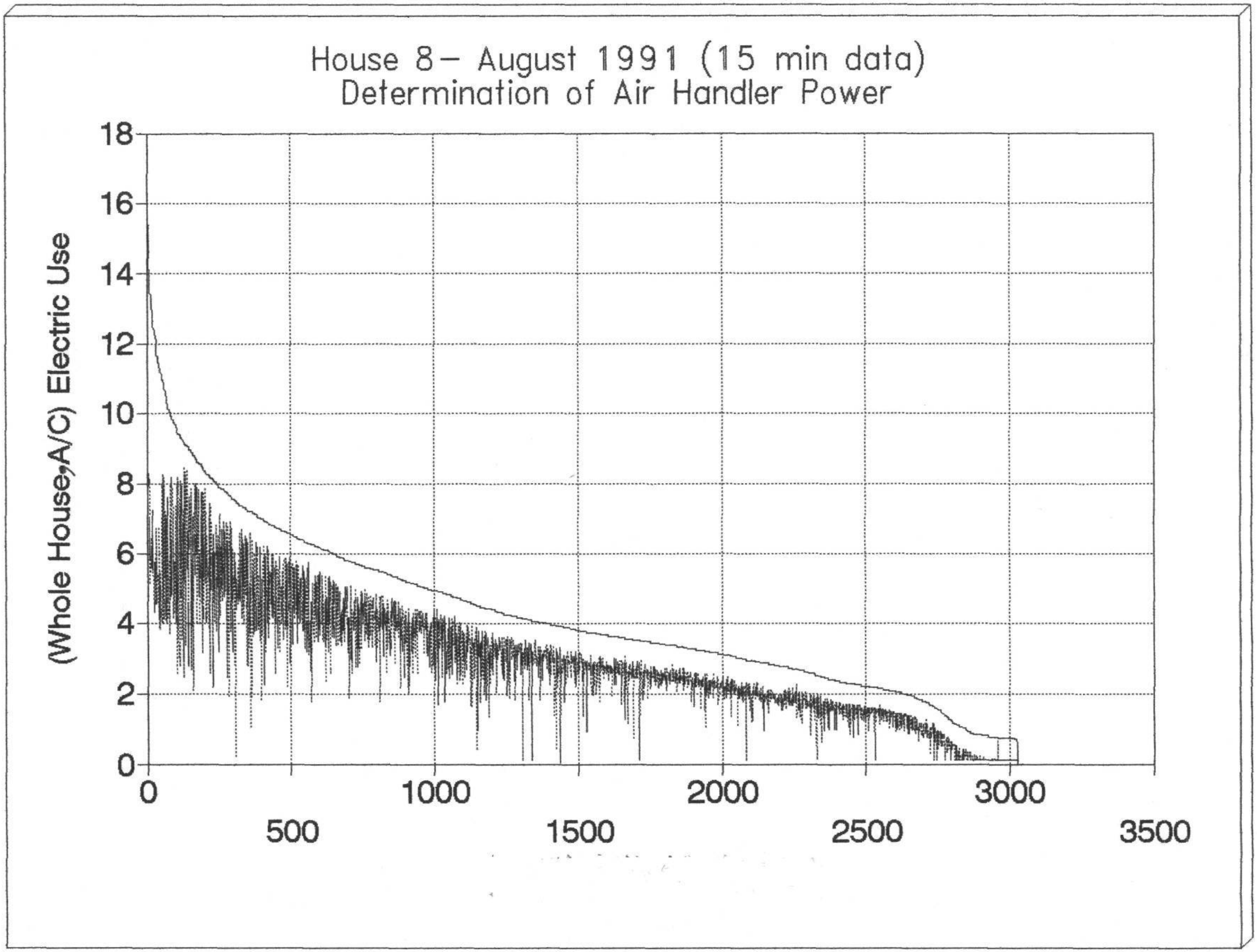

House 2- August 1991 (15 min data)
Whole House vs A/C Electric Consumption
(Whole House,A/C) Electric Use
0
1
2
3
4
5
6
7
8
0
500
1000
1500
2000
2500
3000

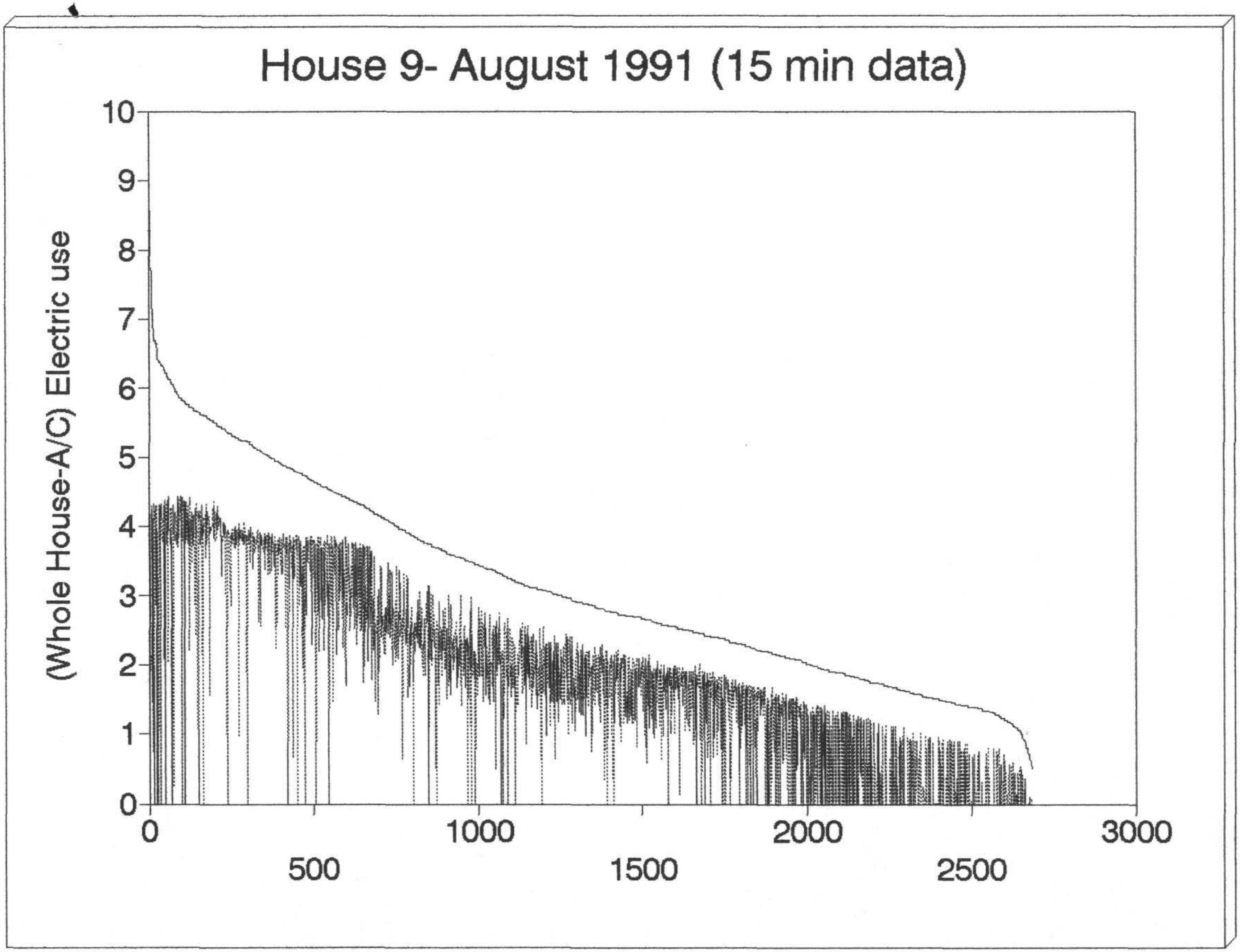

House 3- August 1991 (15 min data)
(Whole House ,A/C) Electric Use
0
2
4
6
8
10
12
0
500
1000
1500
2000
2500
3000


House 4- August 1991 (15 min data)
(Whole House, A/C) Electric Use
0
2
4
6
8
10
12
0
500
1000
1500
2000
2500
3000
3500

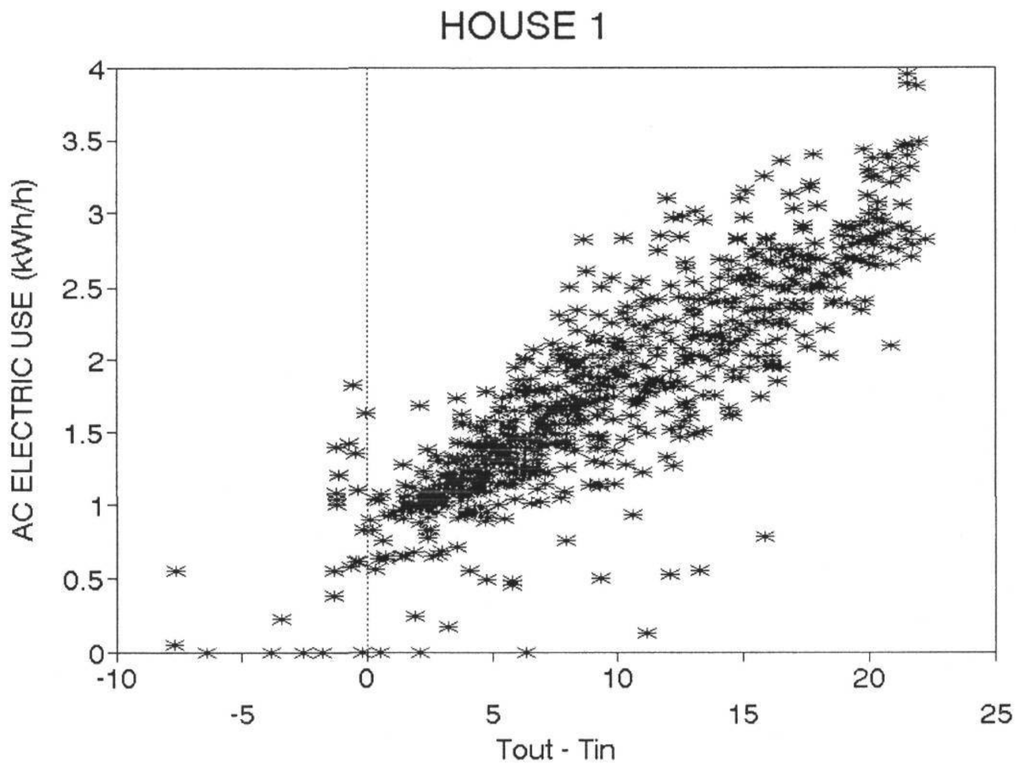

House 5- August 1991 (15 min data)
(Whole House, A/C) Electric Use
0
1
2
3
4
5
6
7
8
9
0
500
1000
1500
2000
2500
3000

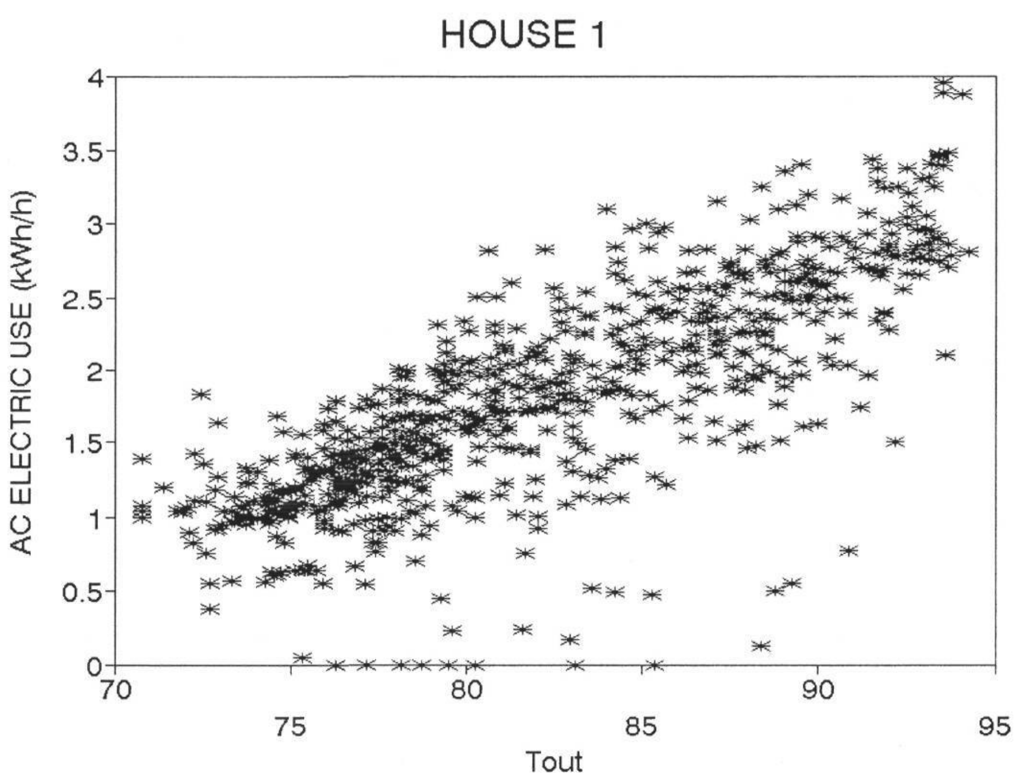

House 6– August 1991 (15 min data)
(Whole House) Electric Use
0
2
4
6
8
10
12
14
0
500
1000
1500
2000
2500
3000

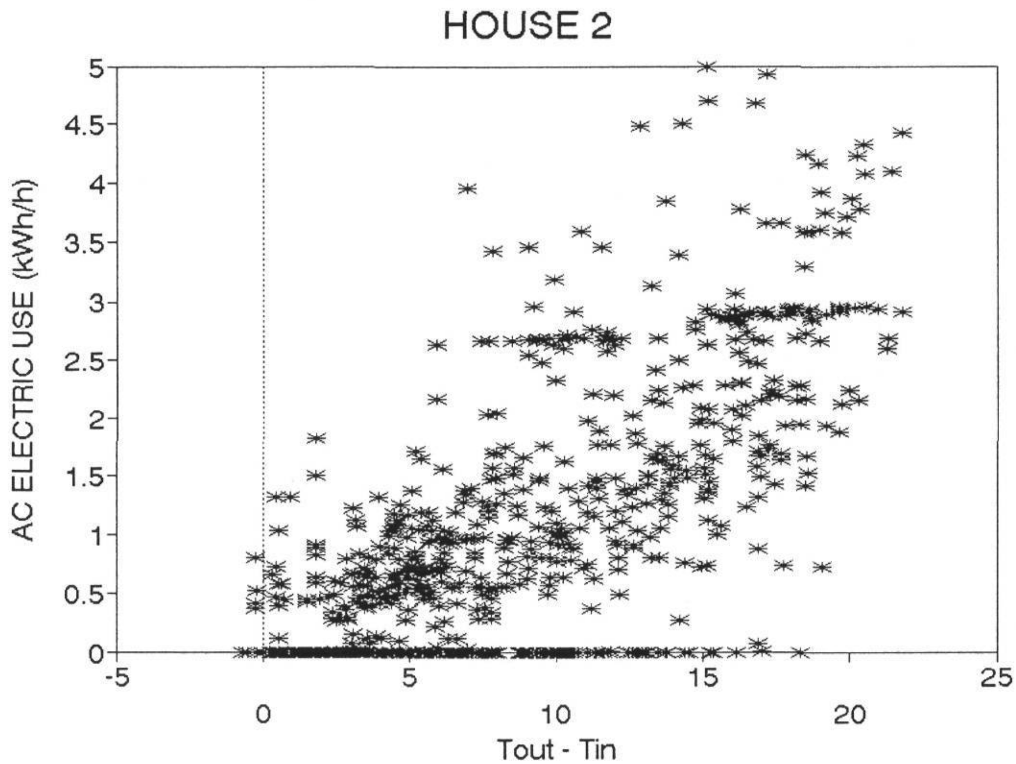

House 8– August 1991 (15 min data)
Determination of Air Handler Power
(Whole House,A/C) Electric Use
0
2
4
6
8
10
12
14
16
18
0
500
1000
1500
2000
2500
3000
3500

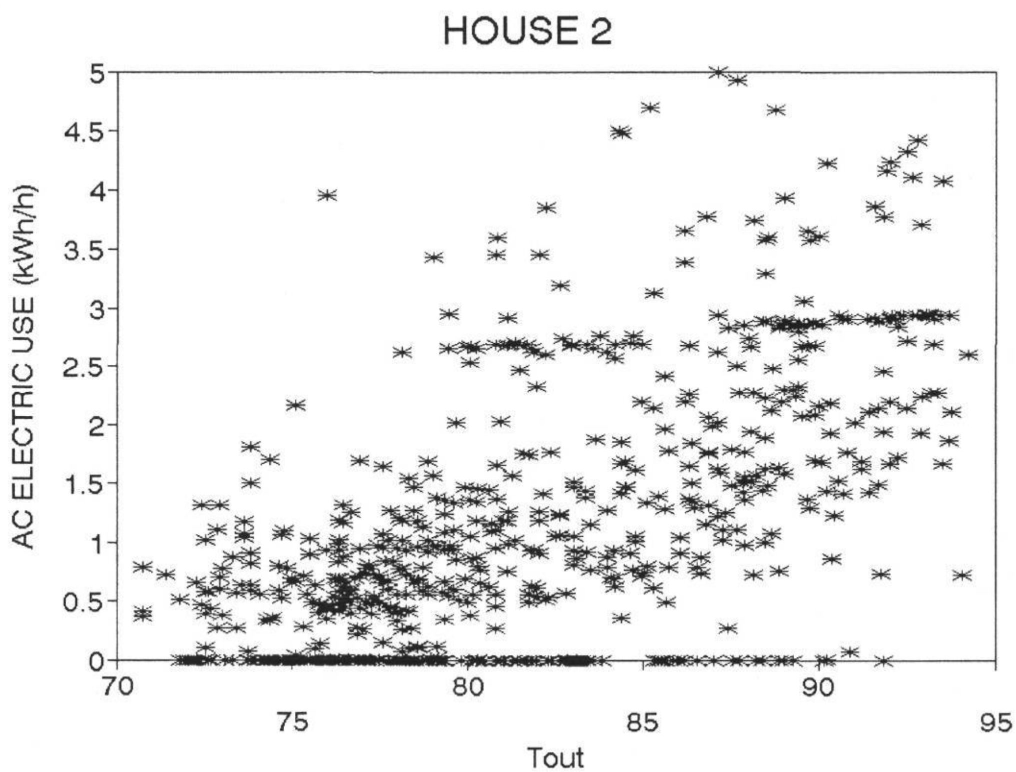


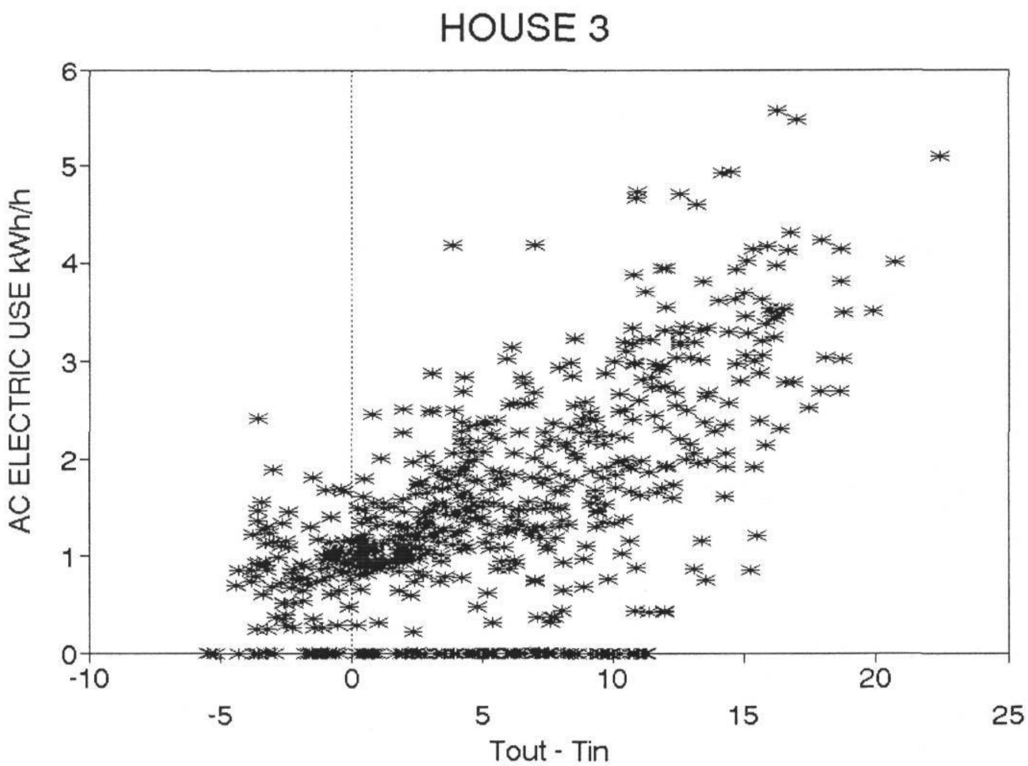
House 9- August 1991 (15 min data)
(Whole House-A/C) Electric use
0
1
2
3
4
5
6
7
8
9
10
0
500
1000
1500
2000
2500
3000

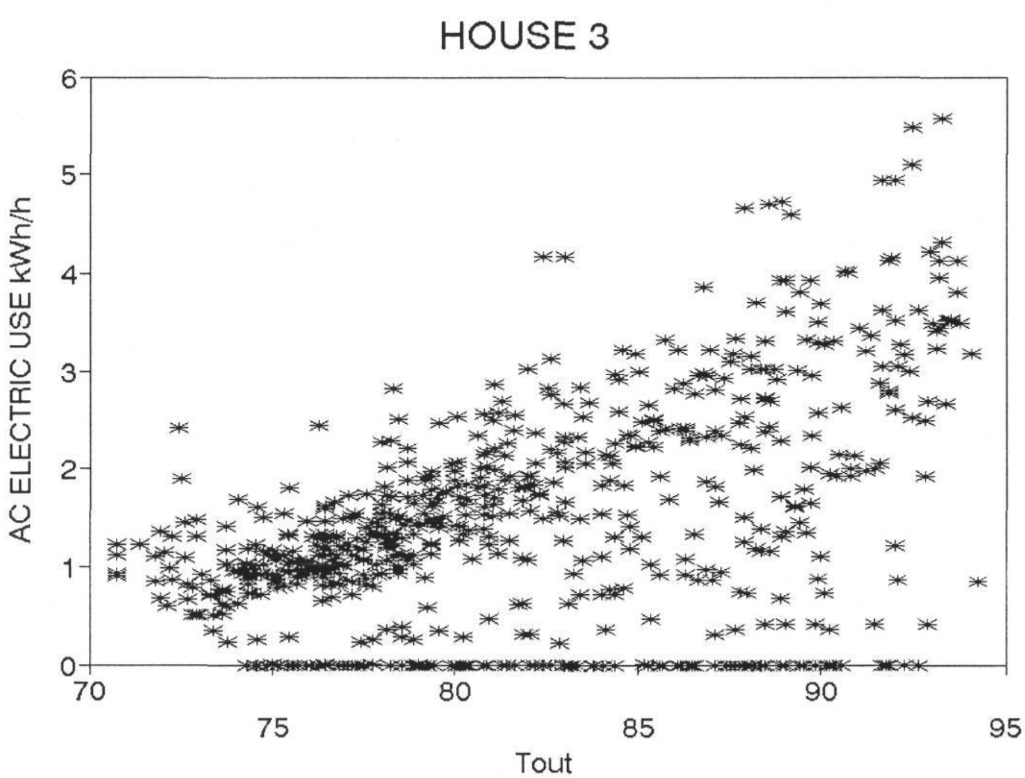

HOUSE 1
AC ELECTRIC USE (kWh/h)
0
0.5
1
1.5
2
2.5
3
3.5
4
-10
-5
0
5
10
15
20
25
Tout - Tin

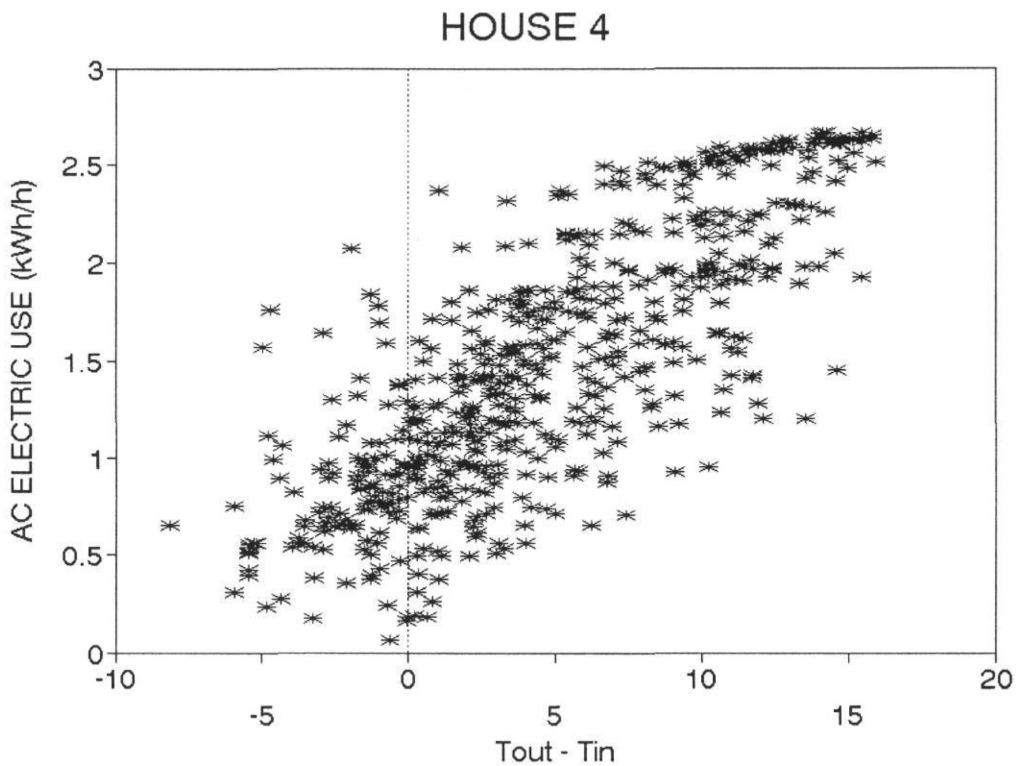

HOUSE 1
AC ELECTRIC USE (kWh/h)
0
0.5
1
1.5
2
2.5
3
3.5
4
70
75
80
85
90
95
Tout

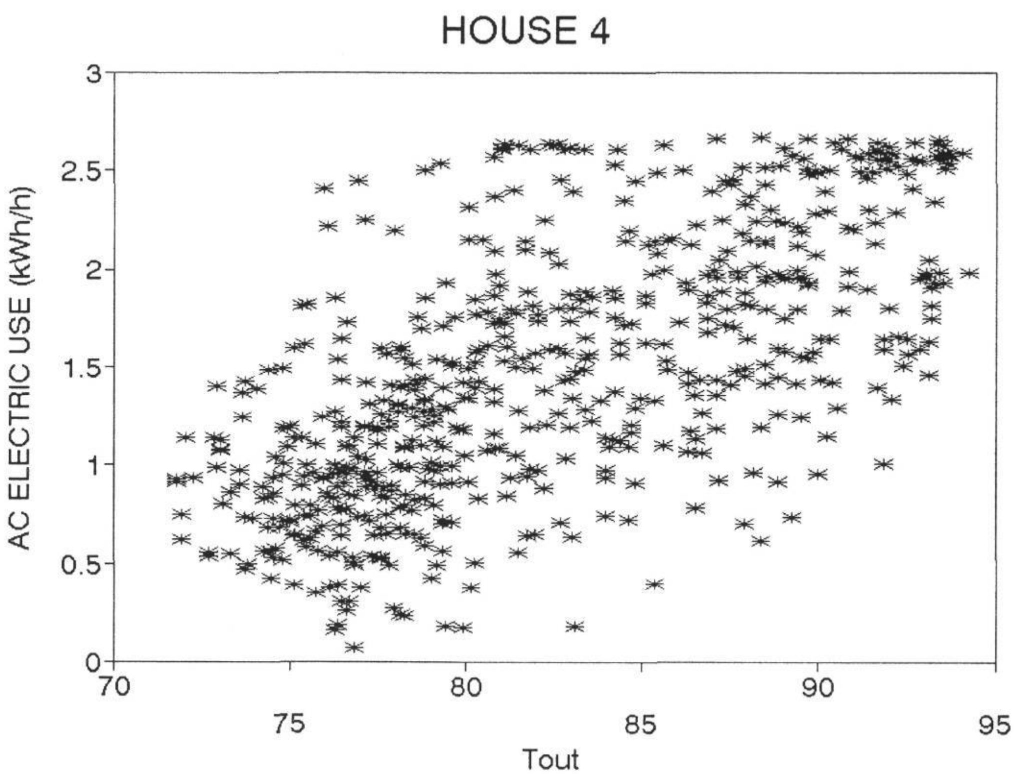

HOUSE 2
AC ELECTRIC USE (kWh/h)
Tout - Tin
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
-5
0
5
10
15
20
25

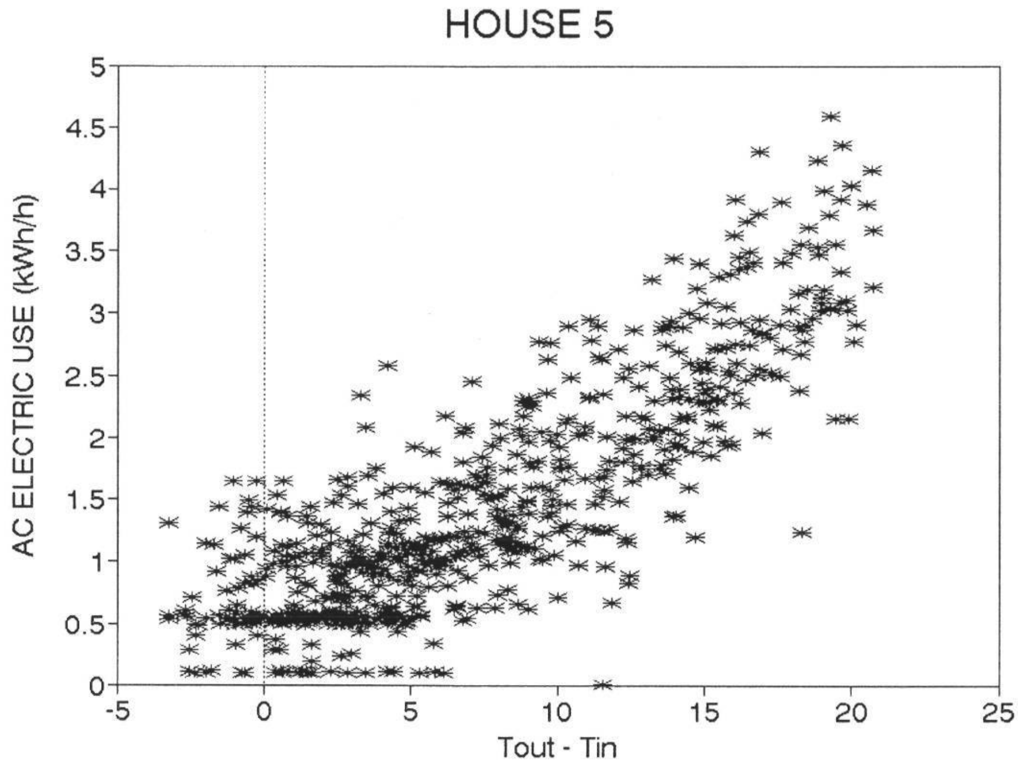

HOUSE 2
AC ELECTRIC USE (kWh/h)
Tout
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
70
75
80
85
90
95

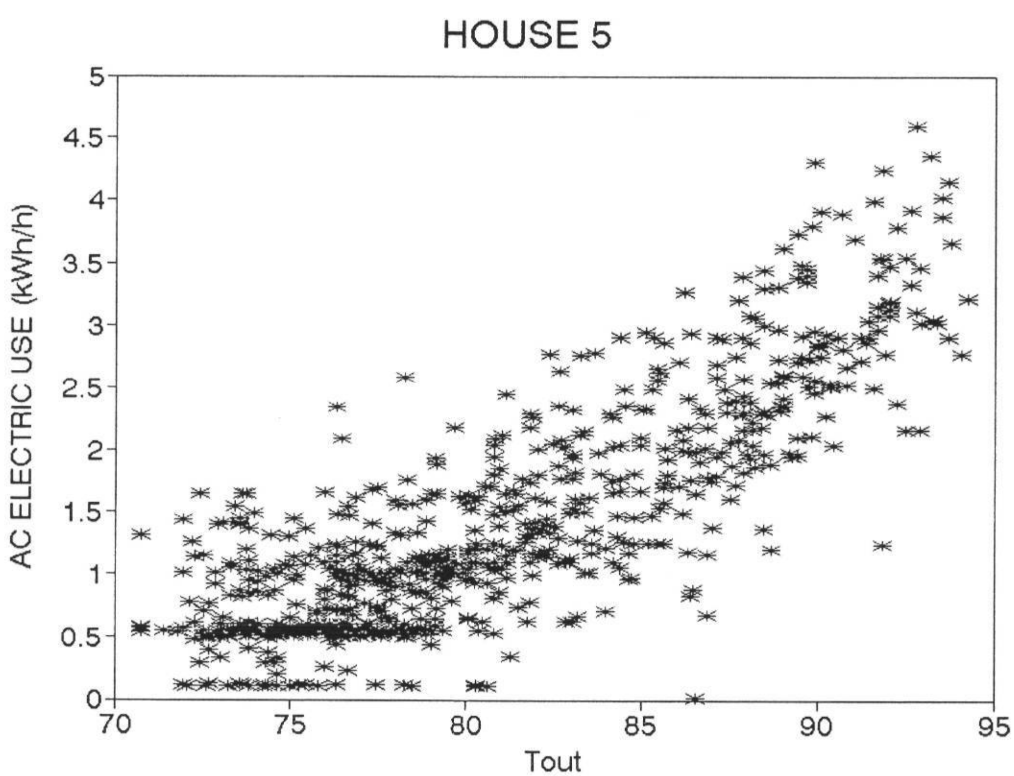

HOUSE 3
AC ELECTRIC USE kWh/h
Tout - Tin
6
5
4
3
2
1
0
-10
-5
0
5
10
15
20
25


HOUSE 3
AC ELECTRIC USE kWh/h
Tout
6
5
4
3
2
1
0
70
75
80
85
90
95

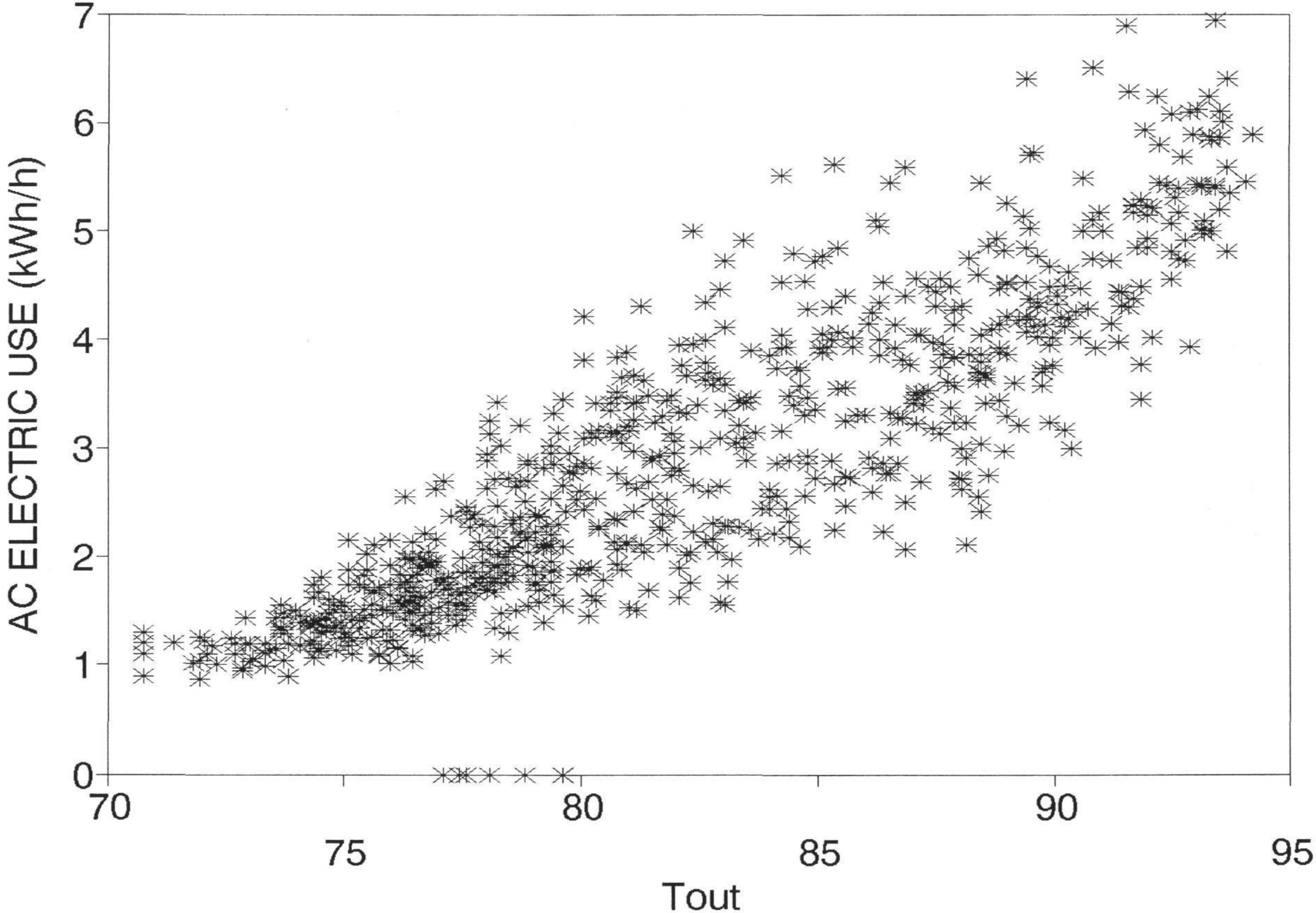

HOUSE 4
AC ELECTRIC USE (kWh/h)
3
2.5
2
1.5
1
0.5
0
-10
0
10
20
-5
5
15
Tout - Tin

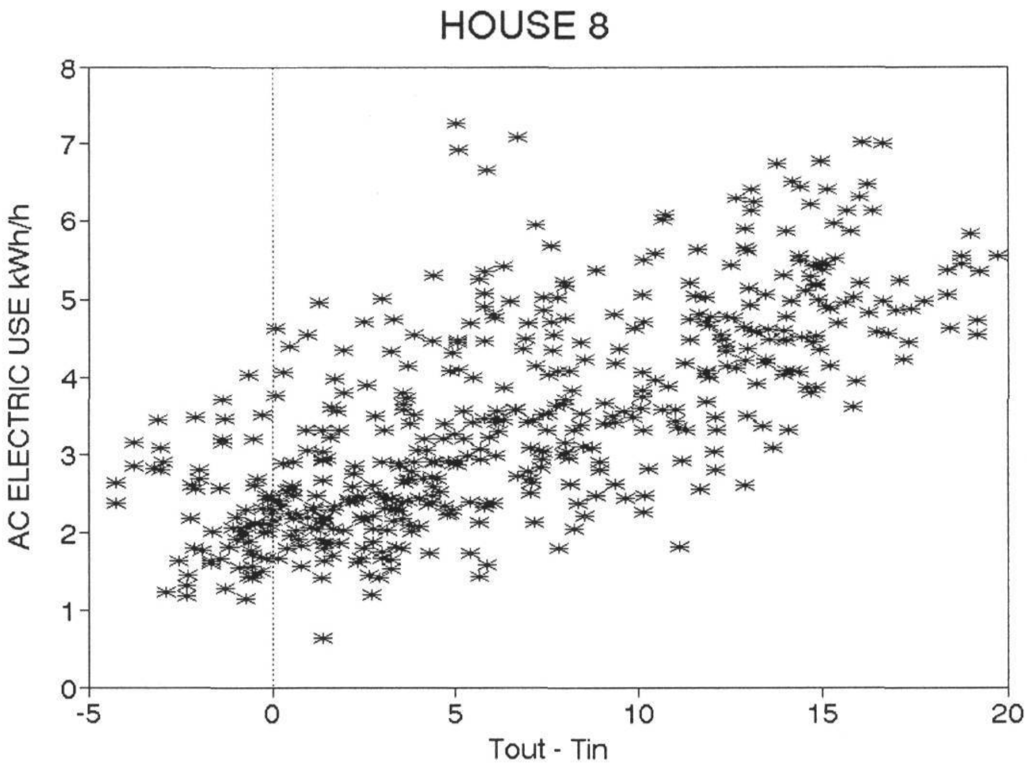

HOUSE 4
AC ELECTRIC USE (kWh/h)
3
2.5
2
1.5
1
0.5
0
70
80
90
75
85
95
Tout

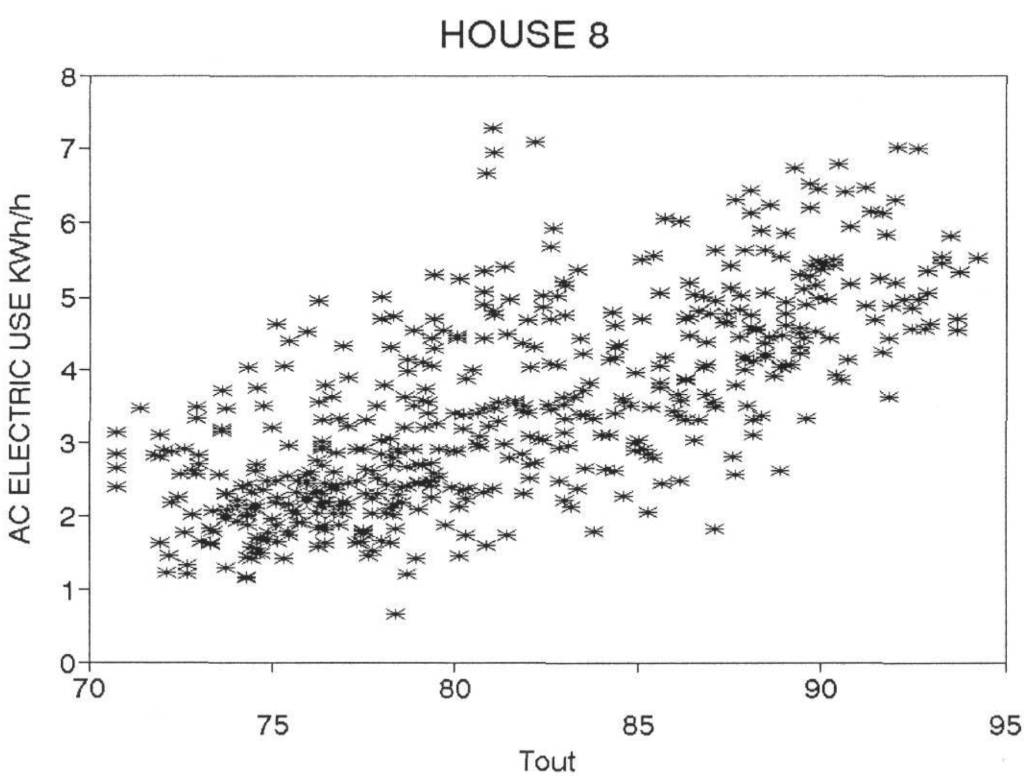

HOUSE 5
AC ELECTRIC USE (kWh/h)
Tout - Tin
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
-5
0
5
10
15
20
25

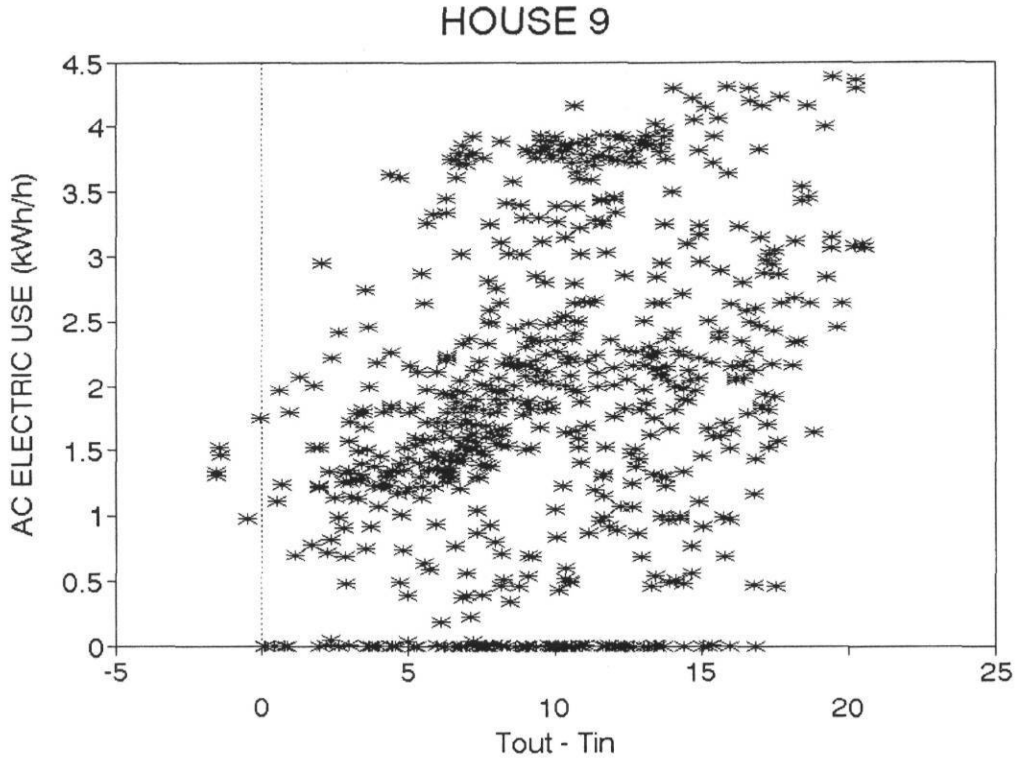

HOUSE 5
AC ELECTRIC USE (kWh/h)
Tout
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
70
75
80
85
90
95

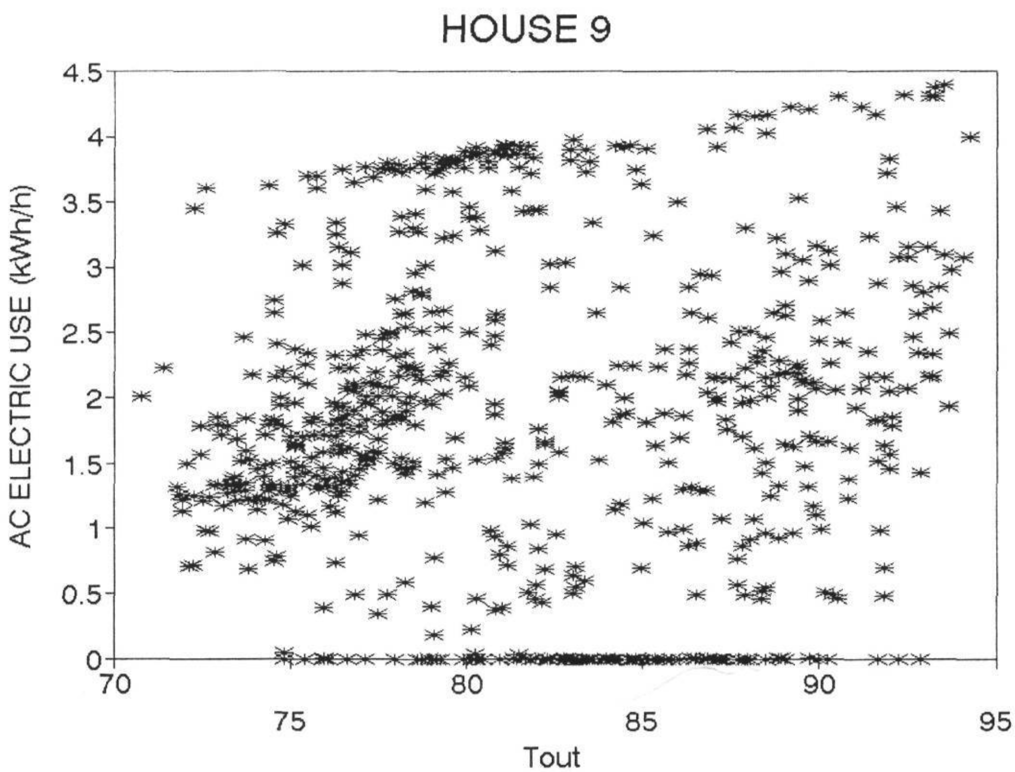
HOUSE 6

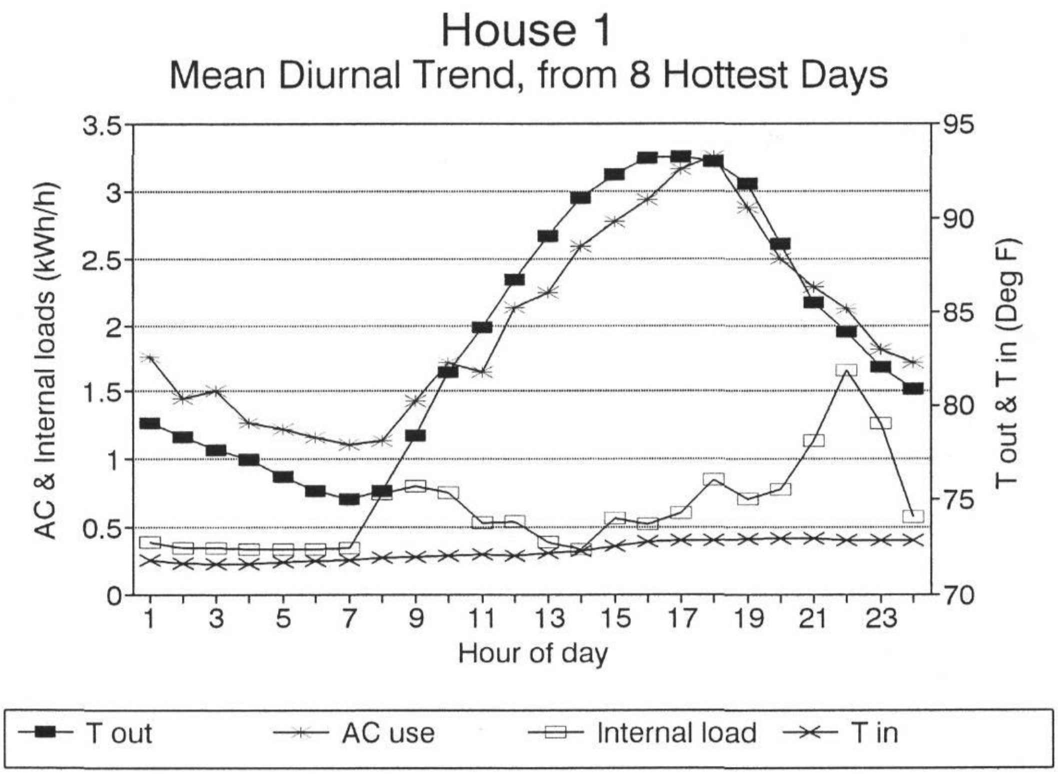


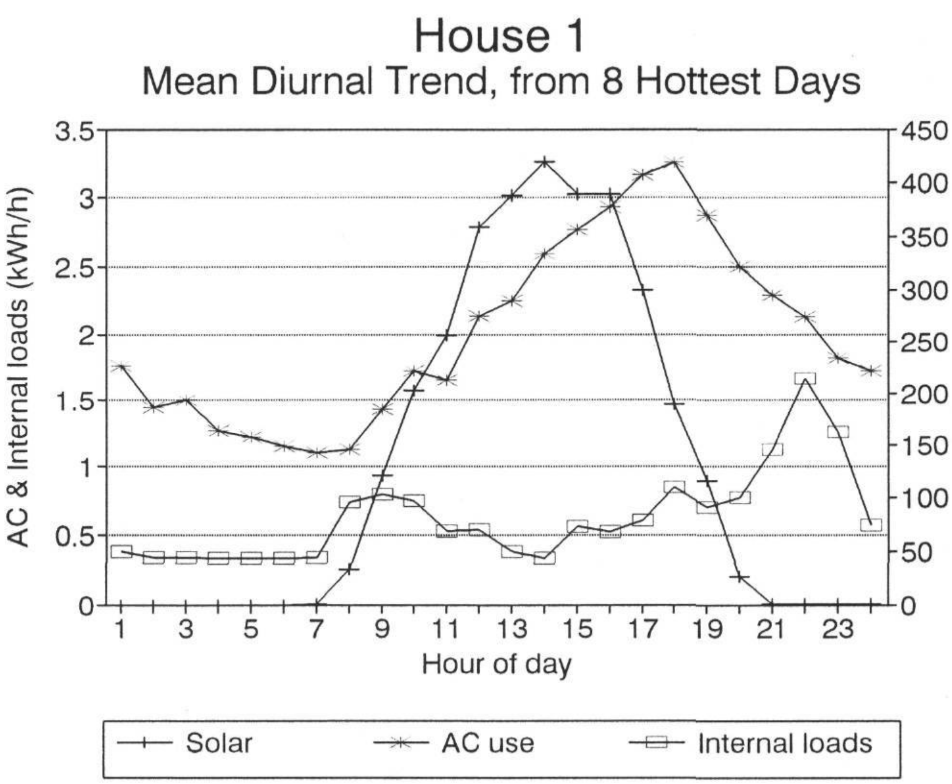

HOUSE 8
AC ELECTRIC USE kWh/h
0
1
2
3
4
5
6
7
8
-5
0
5
10
15
20
Tout - Tin


HOUSE 8
AC ELECTRIC USE KWh/h
0
1
2
3
4
5
6
7
8
70
75
80
85
90
95
Tout

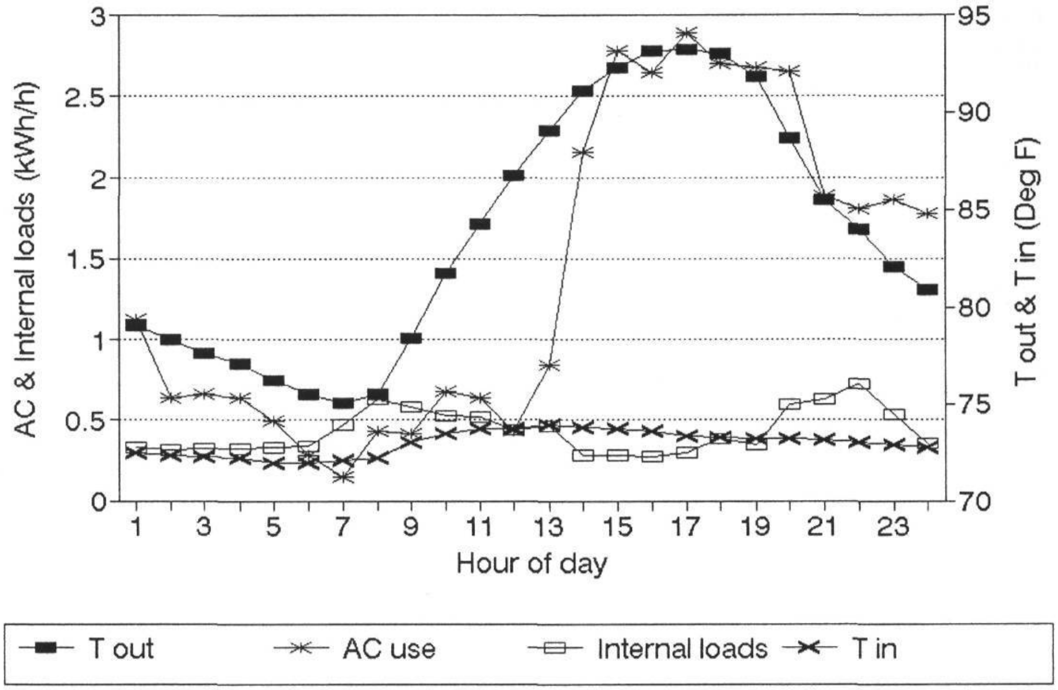

HOUSE 9
AC ELECTRIC USE (kWh/h)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-5
0
5
10
15
20
25
Tout - Tin


HOUSE 9
AC ELECTRIC USE (kWh/h)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
70
75
80
85
90
95
Tout

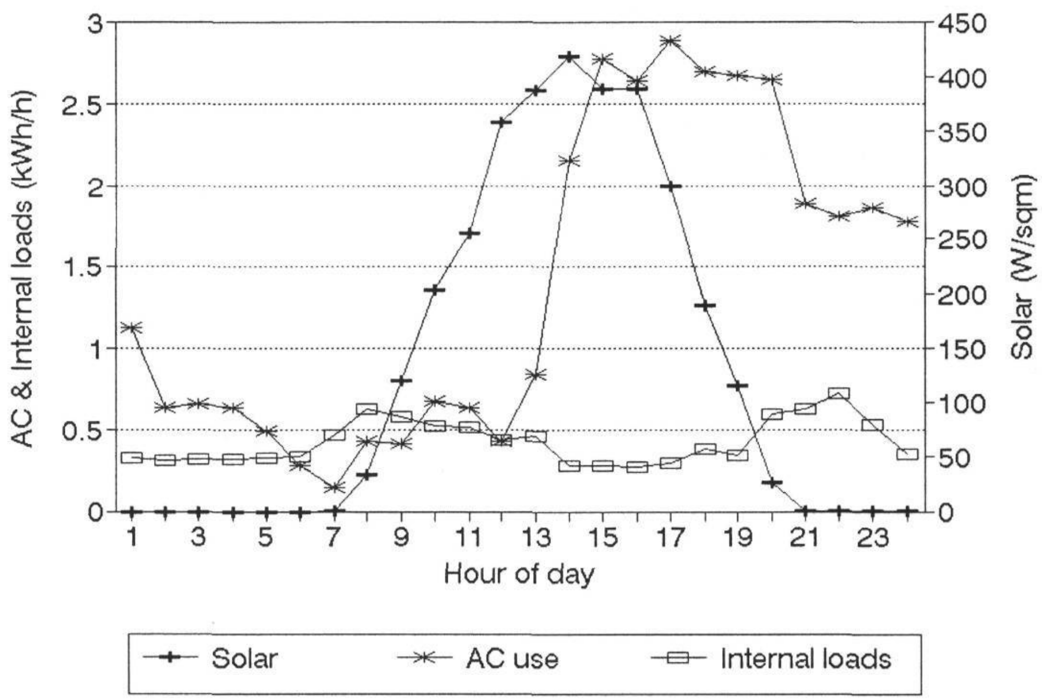

House 1
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
T out & T in (Deg F)
Hour of day
T out
AC use
Internal load
T in

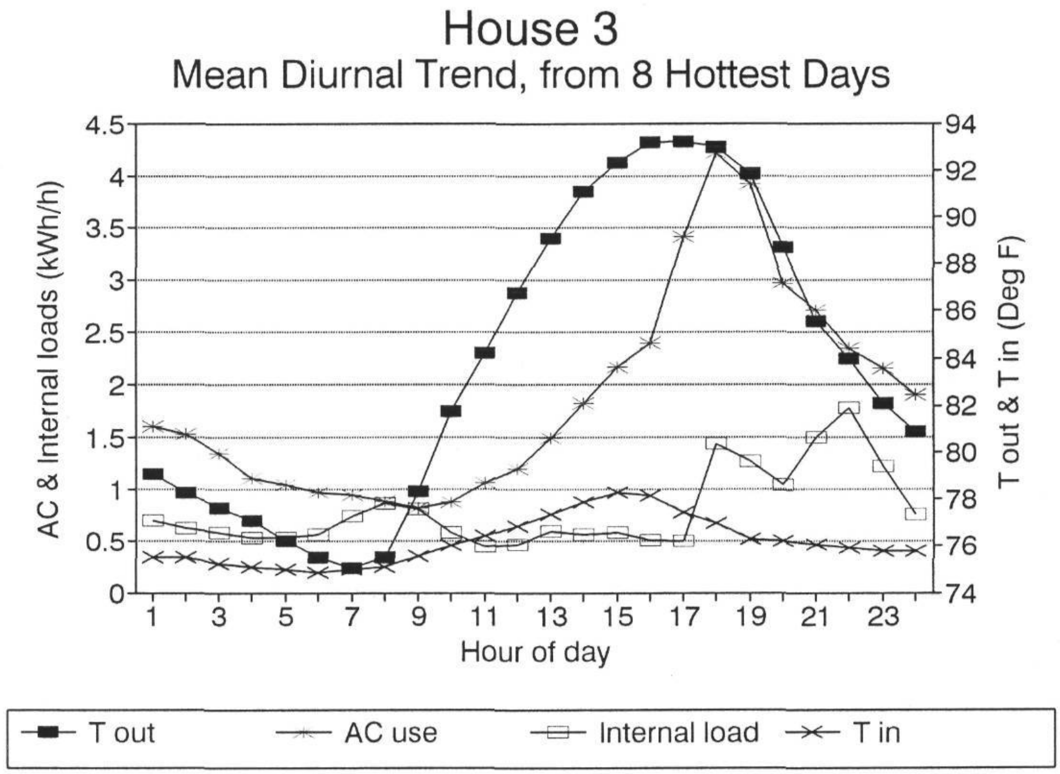

House 1
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
Solar (W/sqm)
Hour of day
Solar
AC use
Internal loads

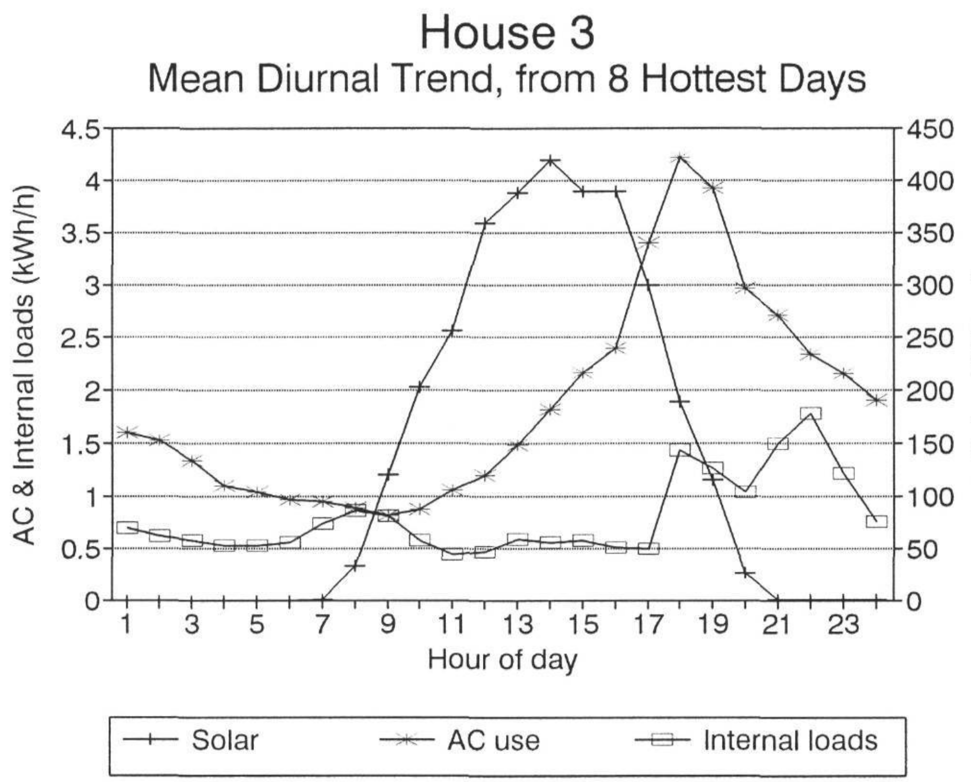
House 2
Mean Diurnal Trend, from 8 Hottest Days

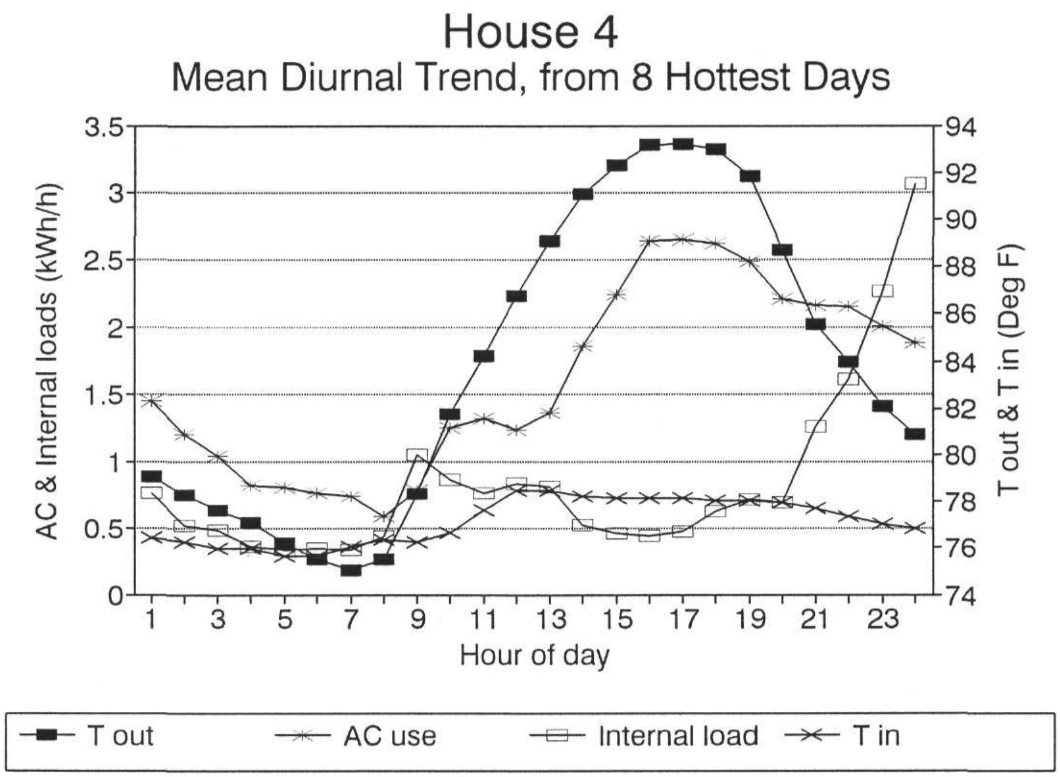


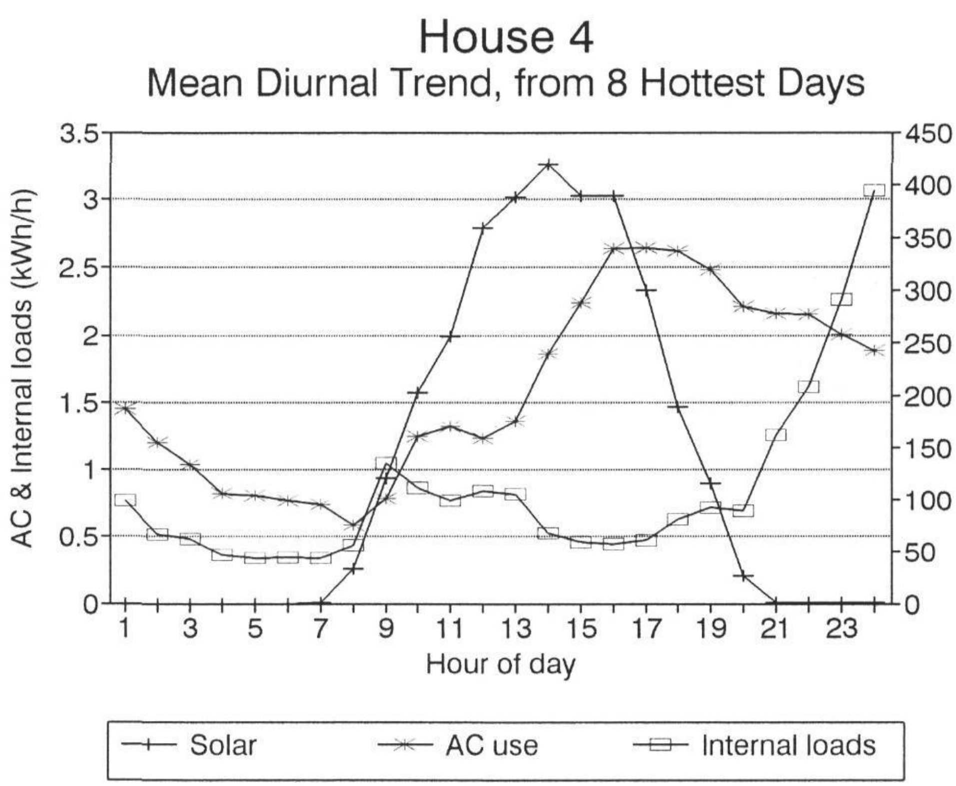
House 2
Mean Diurnal Trend, from 8 Hottest Days

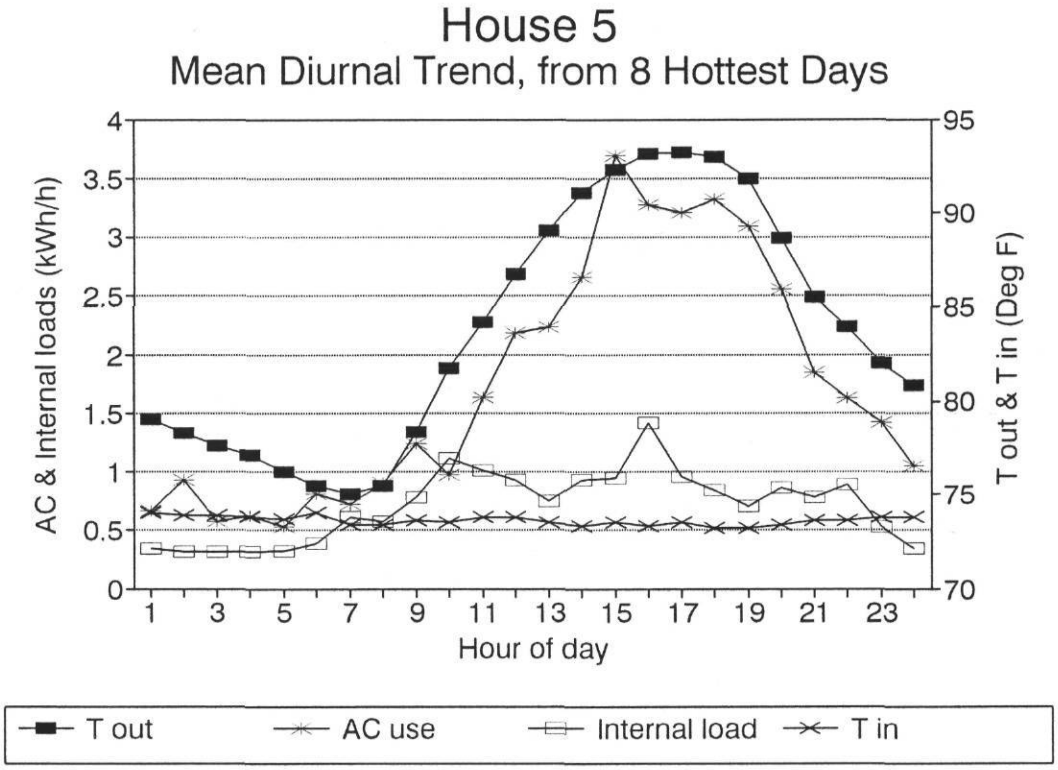


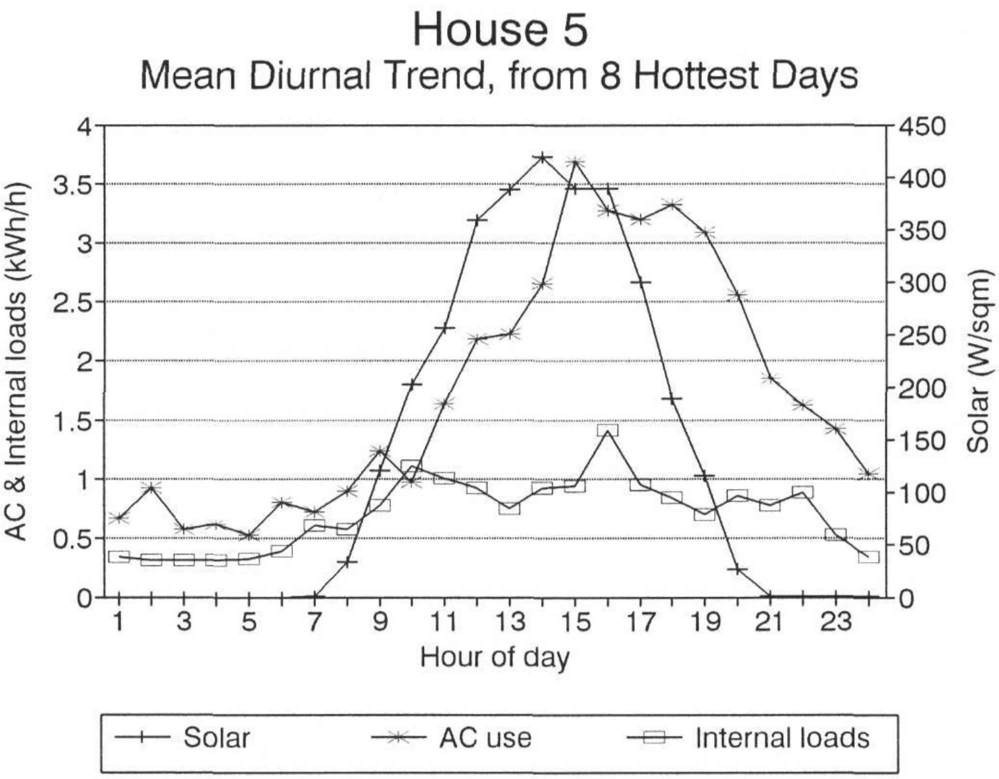

House 3
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
T out & T in (Deg F)
Hour of day
T out
AC use
Internal load
T in

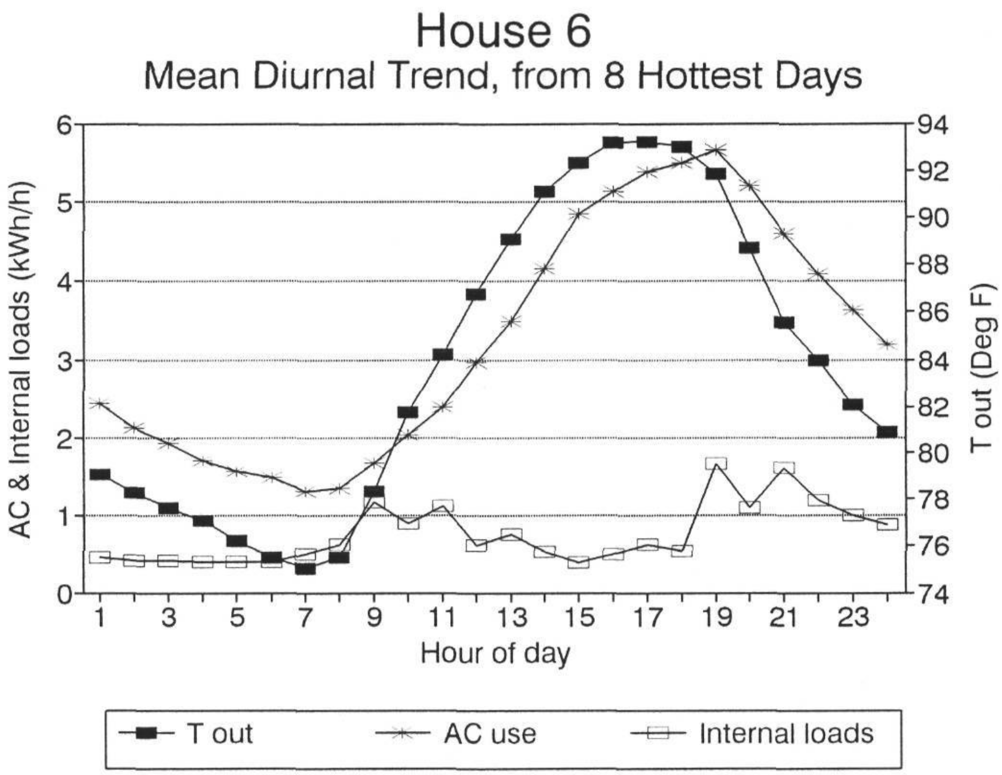

House 3
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
Solar (W/sqm)
Hour of day
Solar
AC use
Internal loads

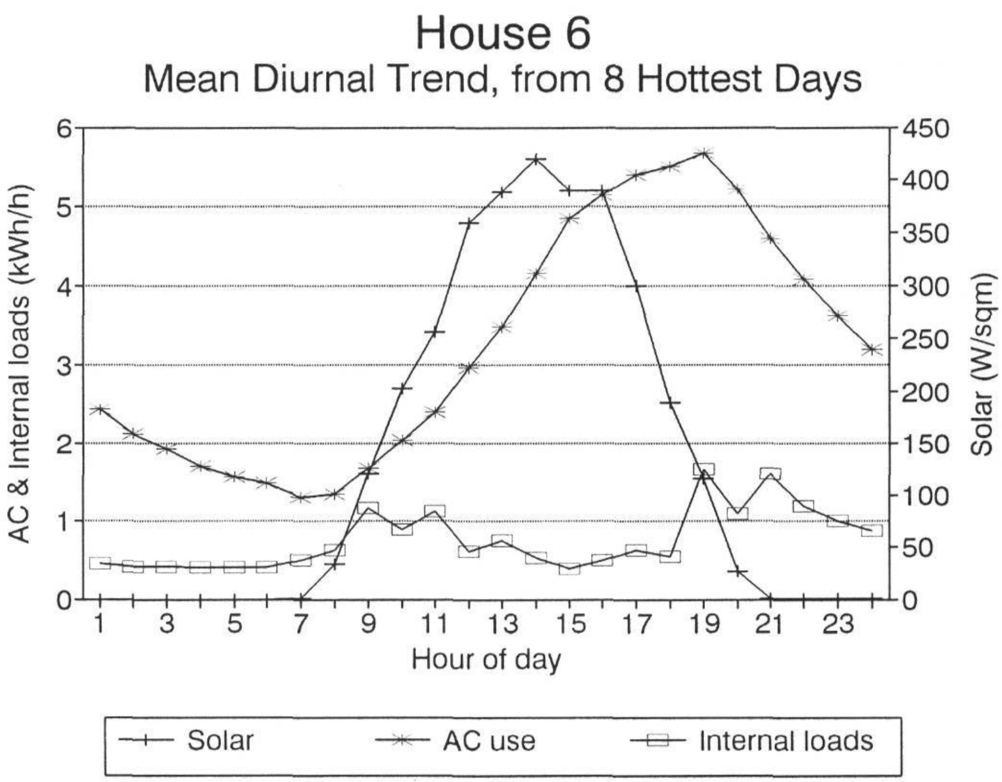

House 4
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
T out & T in (Deg F)
Hour of day
T out
AC use
Internal load
T in

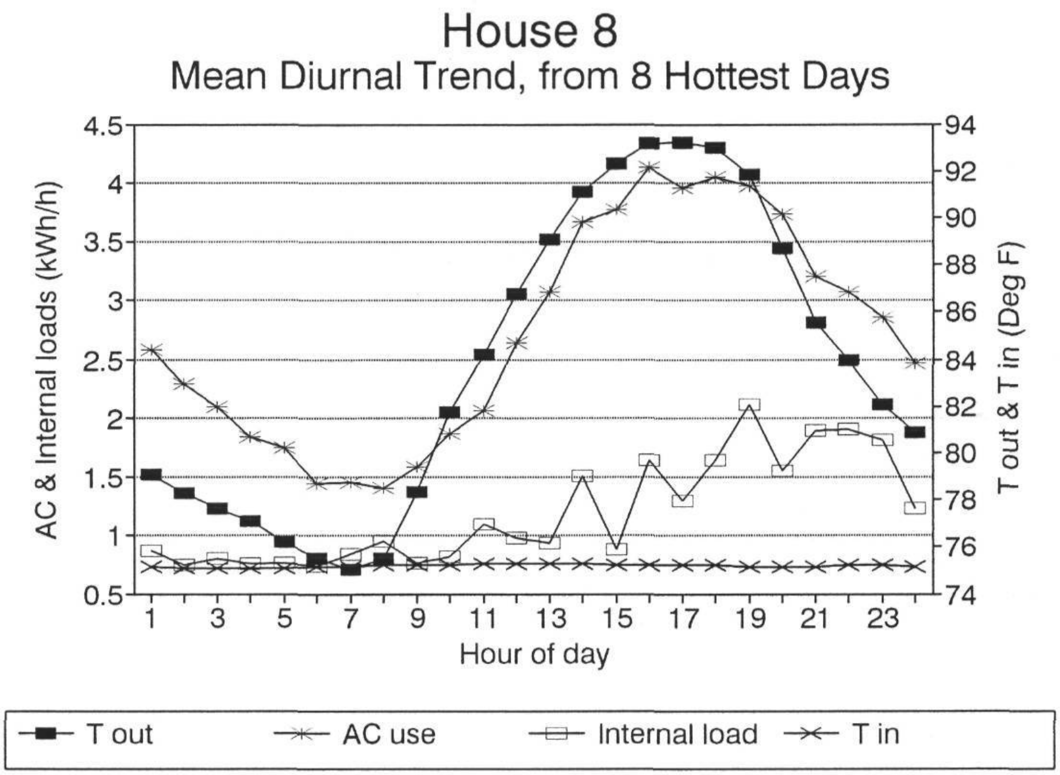

House 4
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
Solar (W/sqm)
Hour of day
Solar
AC use
Internal loads

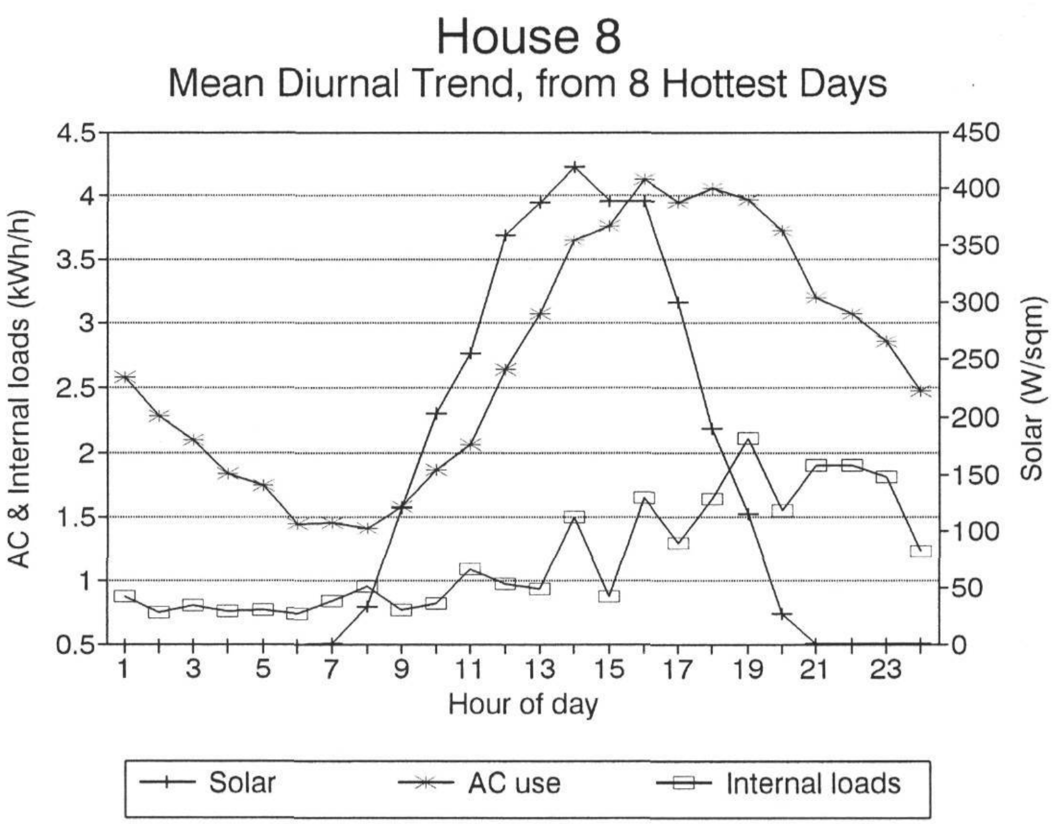

House 5
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
T out & T in (Deg F)
Hour of day
T out
AC use
Internal load
T in

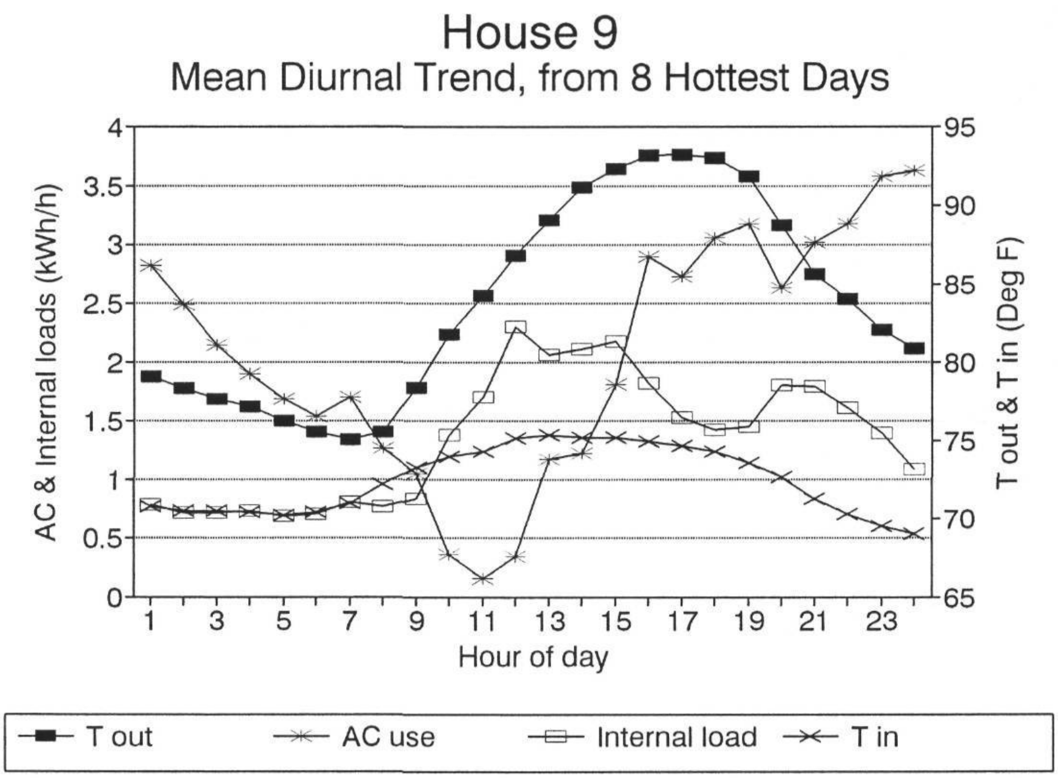

House 5
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
Solar (W/sqm)
Hour of day
Solar
AC use
Internal loads

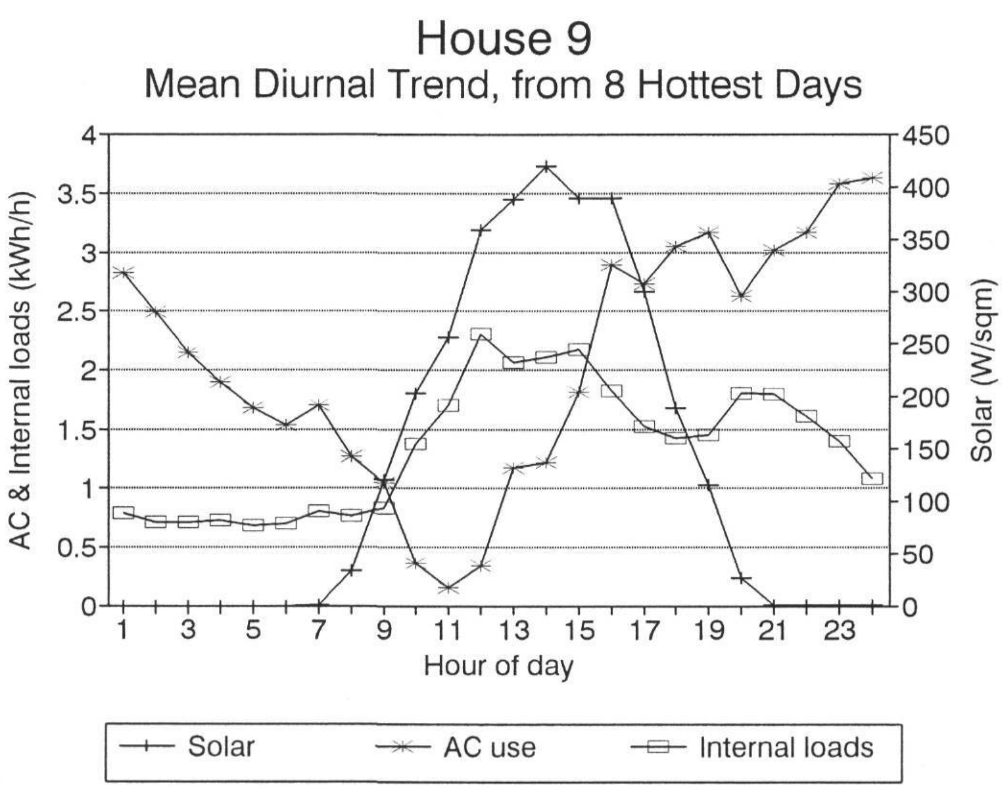

House 6
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
T out (Deg F)
Hour of day
T out
AC use
Internal loads


House 6
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
Solar (W/sqm)
Hour of day
Solar
AC use
Internal loads


House 8
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
T out & T in (Deg F)
Hour of day
T out
AC use
Internal load
T in


House 8
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
Solar (W/sqm)
Hour of day
Solar
AC use
Internal loads


House 9
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
T out & T in (Deg F)
Hour of day
0
0.5
1
1.5
2
2.5
3
3.5
4
65
70
75
80
85
90
95
1
3
5
7
9
11
13
15
17
19
21
23
T out
AC use
Internal load
T in


House 9
Mean Diurnal Trend, from 8 Hottest Days
AC & Internal loads (kWh/h)
Solar (W/sqm)
Hour of day
0
0.5
1
1.5
2
2.5
3
3.5
4
0
50
100
150
200
250
300
350
400
450
1
3
5
7
9
11
13
15
17
19
21
23
Solar
AC use
Internal loads