COOLING-ONLY PRISM ANALYSIS OF ELEVEN COLLEGE STATION HOMES AND INTERPRETATION OF BUILDING PHYSICAL PARAMETERS

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ABSTRACT

A cooling-only PRISM analysis has been performed on eleven new residences in College Station using electricity billing data over an entire year. This study revealed that, provided one corrects for effects such as vacation periods, erroneous utility meter readings and abnormal occupancy patterns during holiday periods, the PRISM approach can accurately model whole-building electricity use (R^2 in the range of 0.92 to 0.99). The physical interpretation of the building parameters determined by PRISM has also been evaluated against continuous measurements of indoor temperature and air-conditioner electricity consumption made during the summer as part of another study. We find that the PRISM estimates for balance point temperature are within a few degrees of actually "measured" values and seem to be unbiased. The PRISM estimates for base-load consumption, on the other hand, are consistently higher by 50% to 100% of the measured base-loads, and factors which may contribute to this bias have also been briefly discussed.

INTRODUCTION

Many utilities in the U.S. have a growing commitment to energy conservation as an investment strategy (Fels, 1986). Faced with aging power plants, small but steady increase of energy demand and environmentally benign alternatives that are expensive, several utilities have already initiated demand-side management (DSM) programs to reduce the consumption of residential customers (Fels and Keating, 1993). In these programs, utilities often offer incentives to customers on the basis of how much energy they save. As a result, there is an increasing need for a reliable means of scorekeeping, i.e., accurate determination over time of how much energy has been consumed and how much energy has been saved.

The PRInceton Scorekeeping Method (PRISM) (Fels, 1986) is a widely used scorekeeping method which is currently the method of choice for a number of energy conservation programs. Active users of the computer software for PRISM include municipal and state government researchers, national laboratories, private entrepreneurs and utilities (Mills et al., 1987). PRISM uses readily-available data of whole-house consumption based on utility billing data, and average daily outdoor temperature from weather station data (for the period being studied as well as long-term periods for the calculation of degree-days (ASHRAE, 1993), to determine a weather adjusted index of consumption, the Normalized Annual Consumption (NAC), analogous to the miles-per-gallon rating for automobiles. The NAC represents annual energy consumption during a year of average weather conditions. Total energy savings due to the implementation of a certain program is then derived as the difference in the NACs for the periods before and after implementation. Because the NAC is corrected for weather conditions, the energy conservation is not obscured by differences in weather from one year to the next, e.g. an unusually cool summer or an abnormally hot one (Fels, 1986).

The specific goal of this study is to model the whole-house monthly electricity consumption over a period of one year for a small sample of relatively new residences of College Station using PRISM and to determine the validity of outdoor temperature as a predictor for consumption. The extent to which the PRISM estimates for base-load electricity use and house balance point temperature (Mitchell, 1983) are physically consistent will also be assessed since continuous measurements of cooling energy and indoor temperature for many of these residences during the summer season have been gathered in the framework of another project (Reddy et al., 1992).

HOUSE SELECTION AND DESCRIPTION

The following criteria were adopted in an effort to select residences which exemplify the characteristics of newer College Station homes.

(a) The houses should be of recent construction, built during or after 1989.

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Table 1. Characteristics of the sample of houses selected.

House	Conditioned area (ft^2)	Builder	Good Cents?	No. of ACs	Billing Months
1	2201	Borski	Yes	1	12
2	2650	Ranier	Yes	2	8
3	2105	Husfeld	Yes	1	12
4	1397	Lege	Yes	1	12
5	1637	Thomas	Yes	1	12
6	2609	Thomas	Yes	2	12
7	3449	Signature	No	2	12
8	3635	Willems	No	2	12
9	2000	Mariott	No	1	12
10	2447	Lightsey	No	1	12
11	1607	Willems	No	1	12

(b) Some of the homes should have passed the College Station Good Cents requirements (Griffith, 1991).

(c) The sample should include houses of varied sizes, i.e., different heated and/or conditioned square footage.

(d) The sample should, if possible, be representative of the builder distribution for homes built in College Station.

Of a pool of 200 homes which met criteria (a) (60 Good Cents and 140 non-participant homes), eleven homes were selected as the sample for study. The characteristics of these house are given in Table 1. All these houses have gas heating and gas-fired domestic hot water systems. Hence electricity is used solely for lighting, appliances and air-conditioning (AC).

Figure 1 depicts time plots of the monthly electricity use in the eleven houses over a year. As expected, they have an annual cycle due to air-conditioning use, with a minimum around January and a maximum around July. A few outliers (such as October and November use in H9) are also to be noted. These will be discussed later in this paper.

BRIEF DESCRIPTION OF PRISM

Models such as PRISM are based on the steady-state energy balance of a house operated as a one-zone building. In order to make the description pertinent our study, let us consider a space where the required cooling is supplied by electric ACs. Further, let us assume that the building uses gas for water-heating and space heating. The space thermal cooling load Q_c is

$$Q_c = Q_{int} + UA(T_{out} - T_{in}) \qquad (1)$$

where

Q_{int} = heat gains from occupants, equipment, solar, ...

UA = heat loss coefficient of the building including ventilation/infiltration effects,

T_{out} = outdoor dry-bulb temperature, and

T_{in} = indoor dry-bulb temperature.

It is convenient to define the balance point temperature τ (Mitchell, 1983) as

$$\tau = T_{in} - \frac{Q_{int}}{UA} \qquad (2)$$

In words, τ is the outdoor temperature above which cooling is required and below which heating is required. Because heating is provided in all eleven houses by gas, we need only concern ourselves with cooling loads. Combining eqs.(1) and (2), we have

$$E_{cool} = \frac{UA}{COP}(T_{out} - \tau) \quad \text{if } T_{out} > \tau \qquad (3)$$
$$= 0 \quad \text{otherwise}$$

where

COP = coefficient of performance of the AC, and

E_{cool} = electricity consumed by the AC.

Equation (3) can be expressed more compactly as

$$E_{cool} = \frac{UA}{COP}(T_{out} - \tau)^+ \qquad (4)$$

where the + superscript indicates that negative values of the term within the brackets should be set to zero.

The whole-house electricity consumption E is the sum of the base-load and E_{cool}. Thus

$$E = \alpha + \beta(T_{out} - \tau)^{+} \quad (5)$$

where

α = base-load electricity use, and
β = (UA / COP) (6)

If β and τ are constant, the consumption over n days is

$$\sum^{n} E = n\alpha + \beta \sum_{i=1}^{n} (T_{out,i} - \tau)^{+} \quad (7)$$

$$= n\alpha + \beta * CDD(\tau)$$

where CDD = cooling degree-days to the base τ (ASHRAE, 1993).

Note that during an average year (with n=365), $\sum^{n} E = NAC$, as discussed earlier. The expected average daily electric consumption is

$$\overline{E} = \alpha + \beta \frac{CDD(\tau)}{n} \quad (8)$$

Equation (8) is the model used by PRISM. PRISM uses standard statistical techniques (ordinary least squares regression) to calculate α and β for various guessed values of τ, and determine the optimal set of physical parameters that minimizes the sum of squares of the model residuals (Fels, 1986). PRISM also tells its user how much faith to place in its results because standard errors for α, β and τ as well as model coefficient of variation (CV) are estimated (Fels, 1986).

The coefficients α, β and τ have a clear physical interpretation, as discussed above. However, one should always expect the statistical determination of these parameters from billing data to have uncertainty and bias associated with them. Minehart and Meier (1994) used synthetic data to conclude that though NAC is PRISM's most robust parameter, assigning physical significance to α, β and τ may be highly inappropriate especially in locations with mild climates (such as San Francisco, CA), while the significance gets better in harsher climates. The parameter identification seems to suffer from consistent bias. The study found that in mild climates, for example, the balance point temperature is under-estimated, while β tends to be over-estimated.

Though extensions have been proposed to the basic PRISM model, these have yet to find widespread acceptance. Outdoor wet-bulb temperature would also impact E_{cool}, especially in hot and humid locations due to the high latent load contribution. Humidity levels (and solar loads) are correlated with T_{out} to a certain degree, and thus PRISM implicitly accounts for these factors, at least partially. Rabl and Rialhe (1992), from an analysis of data from 50 buildings, found that adding occupancy as an additional parameter in the PRISM model appreciably improves the accuracy of the model. They concluded that interpretation of the individual parameters is, however, suspect due to biases which are far greater than the standard errors indicated by the regression. Finally, attempts at using PRISM for commercial buildings have had mixed success (Eto, 1988) because of the inherent limitations of using degree-day concepts to commercial buildings which operate with multi-zones, have simultaneous heating and cooling, may have night set-back and other effects.

PRISM ANALYSIS OF DATA

PRISM needs four files to complete a run: the meter file, temperature file, and the heating and cooling degree-days file. The first step in a PRISM analysis is assembling the energy data for the houses to be analyzed. The utility billing data for a period of one year (with one exception where only 8 months of data was available) for the eleven houses from September 1991 to August 1992 were collected from College Station Utilities. The data were then formatted in the meter files into columns of dates and corresponding consumption, according to PRISM's requirements.

Next, a daily average temperature for College Station during the entire billing period as well as for the last twelve years was obtained from Avery et al. (1984) and from the LoanSTAR data files (Claridge et al., 1991). Temperatures during the billing period were then collated into the temperature file. Long-term weather data for College Station were used to create the last two files needed for a PRISM run. These files contain the numbers of heating and cooling degree-days for each possible reference temperature τ from -10°F to 120°F over a period of 10 to 12 years.

Generally accepted criteria for "good results" are a CV(NAC) < 8% and a R^2 > 0.7 (Fels and Reynolds, 1991). Table 2 assembles these statistical indices for each of the 11 homes studied. Figure 2 shows the

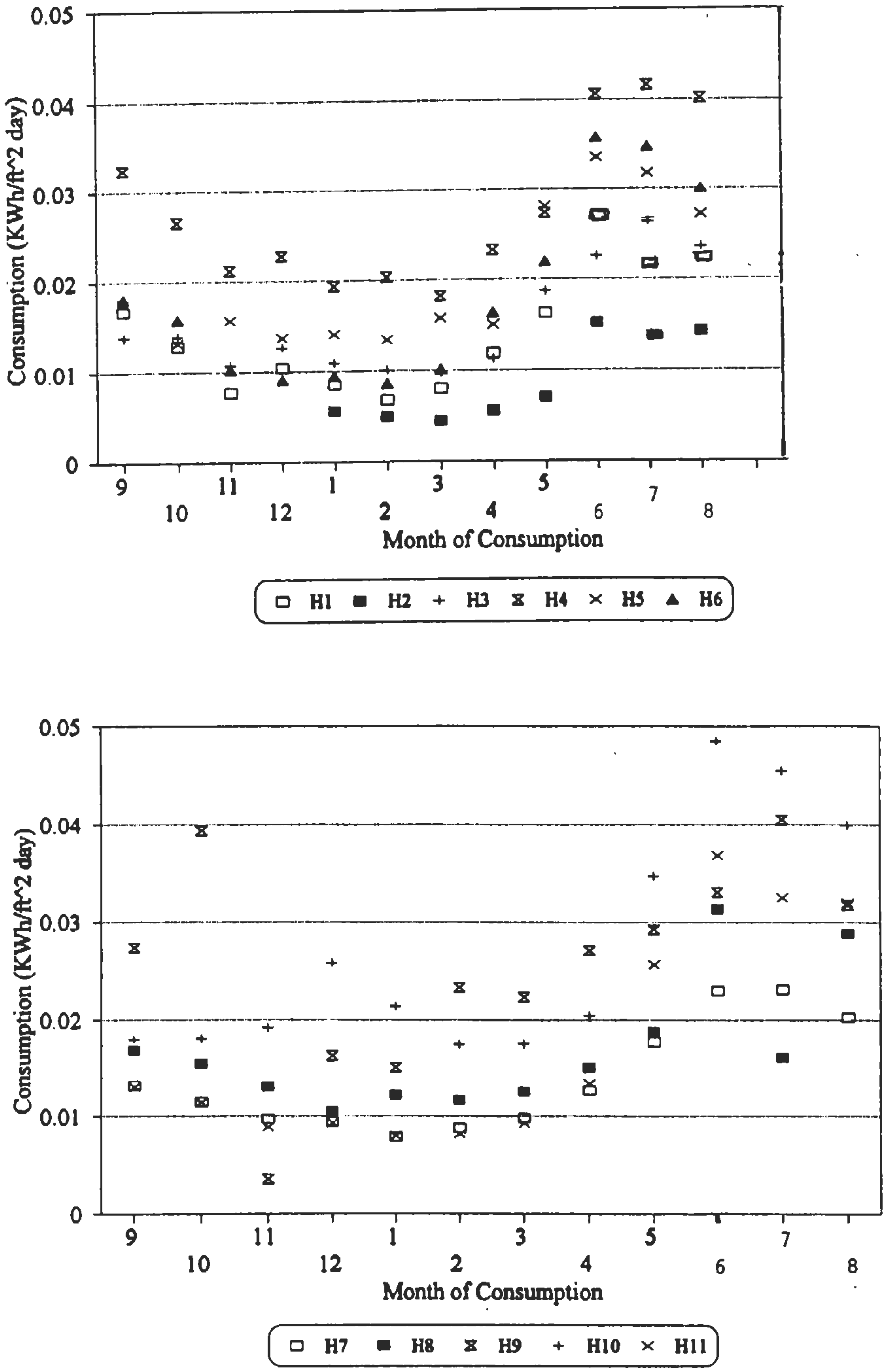

Figure 1. Electricity consumption for houses 1 through 11, normalized for house size and billing dates. Note that month of consumption is when consumption actually occurred as opposed to month when consumption was billed.

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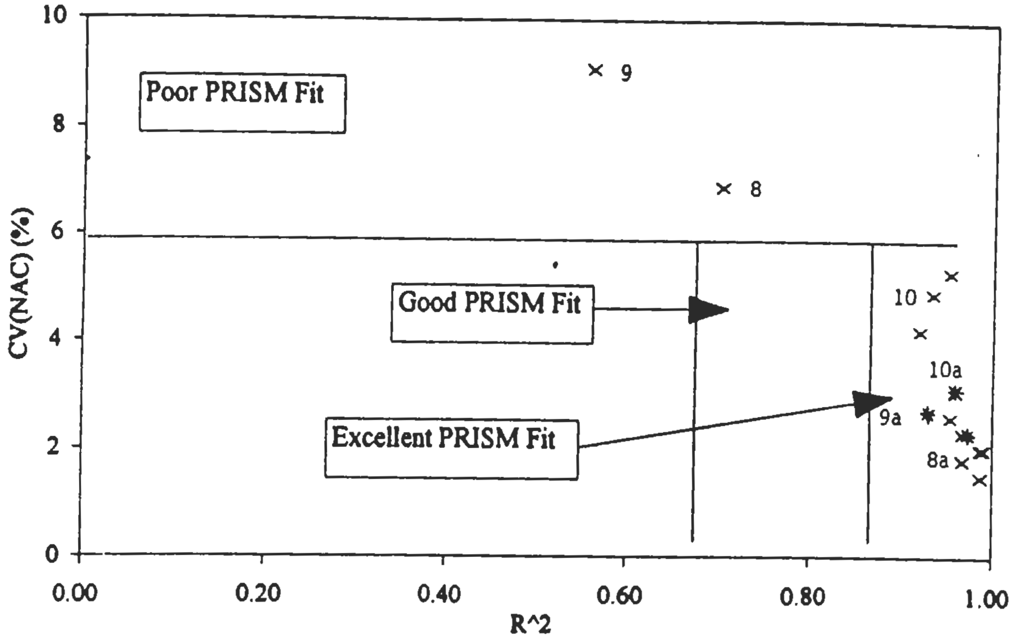

Figure 2: A plot of R-square versus CV(NAC) to show regions of excellent, good, and poor PRISM fit for all eleven houses. Alternate PRISM runs for houses 8, 9, and 10 are shown as astrices.

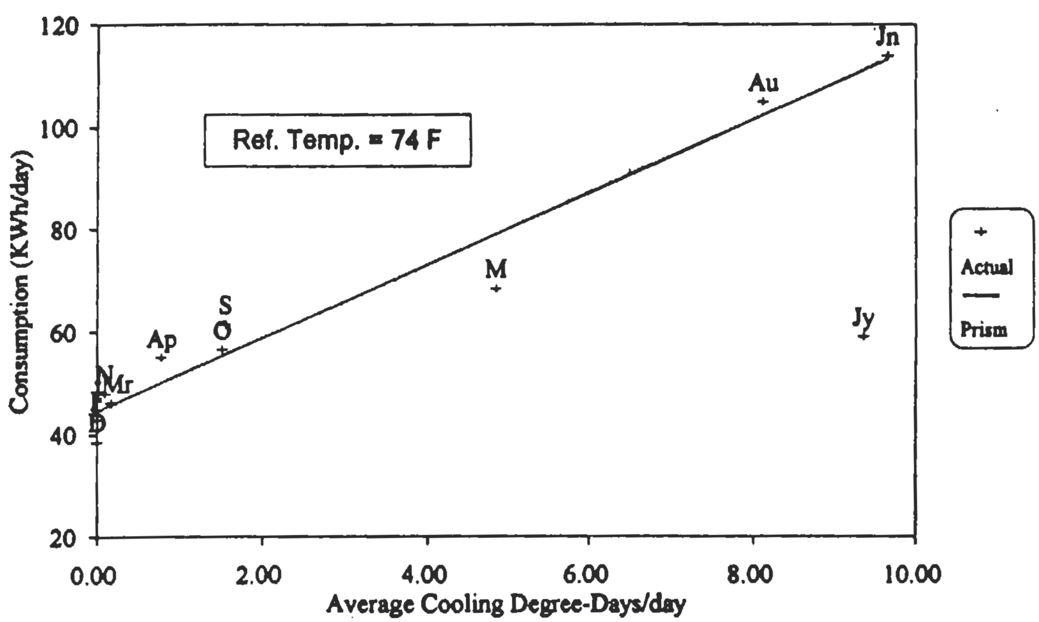

Figure 3: Actual average daily consumption and PRISM cooling curve for house 8a.

regions of excellent, good and poor PRISM fit using raw data from College Station Utilities. Note that we have defined the criteria for good and excellent regions a little differently from the Fels and Reynolds (1991) study. We note that except for a couple of houses (which will be discussed below), all houses fall in the region of excellent PRISM fit. The R^2 values are excellent (in the range of 0.92 to 0.99) with CV(NAC) in the range 1.5 - 5.3%.

Of the eleven homes, house 8 (H8) and H9 did not fall into the region of acceptable PRISM fit. Inquiry as to the reason for the poor fit led to the discovery that the occupants of H8 were on vacation for two-and-half weeks during July 1992. This accounted for the abnormally low consumption for this house in July (see Fig. 3). As a result, omitting the July consumption data from the PRISM run gives much better PRISM fit to the data as is shown by the increase in R^2 and decrease in CV(NAC) for H8 in Table 2 (Run 8a).

For H9, a very high consumption in October followed by a very low November consumption is observed (see Fig. 1). Investigation with College Station Utilities revealed that the October value was not a real reading but an estimation, while the November value was an actual meter reading. Because PRISM (as well as most programs) does not correct for such vagaries in the data, the consumption for both these months were combined into a single two-month period which improved the PRISM fit substantially; R^2 increased from 0.559 to 0.930 (see Table 2).

Similarly, H10 had an abnormally high use in December (see Figs. 1 and 4). This was found to be due to Christmas company. Omitting the December consumption data from the PRISM run gives a better PRISM fit (R^2 increased from 0.934 to 0.960).

Table 2 also shows the physical parameters of all eleven homes obtained by the PRISM analysis. The values of the PRISM coefficients, both unnormalized as well as floor-area normalized, are also shown. Except for one or two houses, the area-normalized base-loads are generally in the range of 8 to 20 kWh/ft^2/day, while the normalized cooling slopes are in the range of 1 to 2 kWh/ft^2/°F/day. The NAC and how much of the total electricity use is likely to be due to cooling are also listed. We note that in the newer residences in College Station, typically 30% to 50% of the total annual electricity use is for cooling.

Table 2. PRISM results for each house.

					Area normalized (10^{-3})					
House	Area	Base load (α)	Cooling slope (β)	Ref. temp.(τ)	Base load (α_n)	Cooling slope (β_n)	NAC	Cooling as % of NAC	CV(NAC) %	R^2
–	ft^2	kWh/d	kWh/°F/d	°F	kWh/ft^2/d	kWh/ft^2/°F/d	kWh/yr	%	–	–
1	2201	18.49	2.60	69.85	8.40	1.18	11722.7	42.4	4.2	0.920
2	2650	13.15	2.73	74.02	4.96	1.03	8063.7	40.4	5.3	0.953
3	2105	23.57	2.98	73.08	10.74	1.36	12604.2	31.7	2.6	0.954
4	1397	28.26	2.36	70.68	20.23	1.69	14474.4	28.7	1.8	0.968
5	1637	22.86	3.39	74.54	13.96	2.07	12124.2	31.1	2.3	0.967
6	2609	23.17	4.53	68.90	8.88	1.73	17947.1	52.8	2.0	0.987
7	3449	29.99	3.22	68.68	8.69	0.93	17831.2	38.6	1.5	0.987
8	3635	42.25	3.33	68.31	11.62	0.91	22793.7	32.3	6.9	0.702
8a	–	44.49	7.11	74.00	12.24	1.96	24752.2	34.3	2.3	0.973
9	2000	30.81	1.84	60.00	15.40	0.92	18809.1	40.2	9.1	0.559
9a	-	27.06	1.33	51.13	13.53	0.67	18765.8	47.3	2.7	0.930
10	2447	49.05	18.03	80.00	20.05	7.37	25618.8	30.1	4.9	0.934
10a	–	44.77	10.09	76.65	18.29	4.12	24614.8	33.6	3.1	0.960
11	1607	12.84	3.47	71.14	7.99	2.16	10512.5	55.4	2.0	0.990

*An "a" after the house number denotes data from an alternate PRISM run.

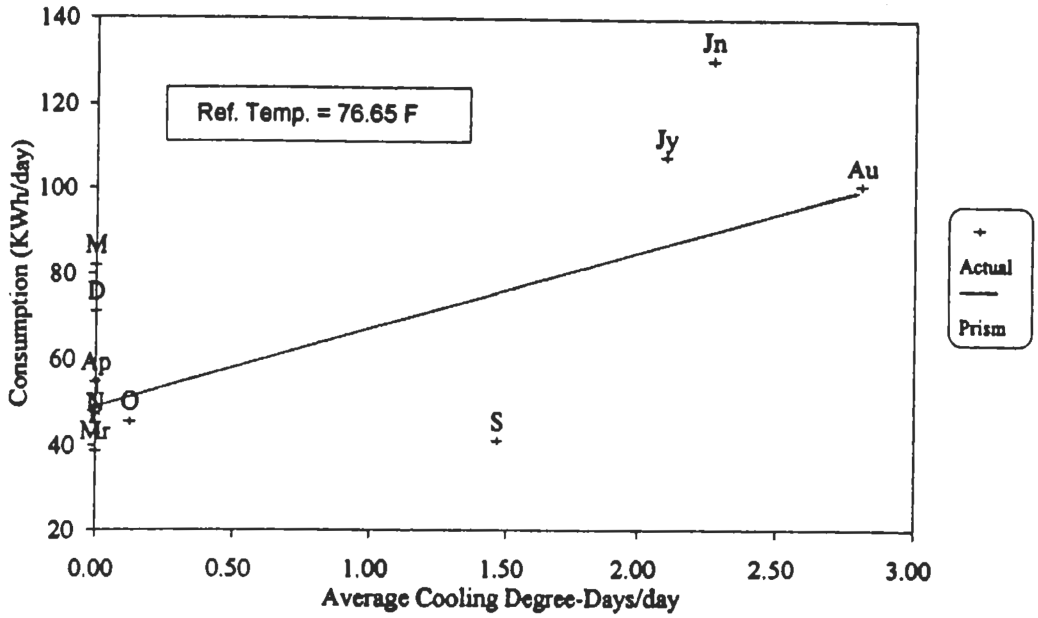

Figure 4: Actual average daily consumption and PRISM cooling curve for house 10.

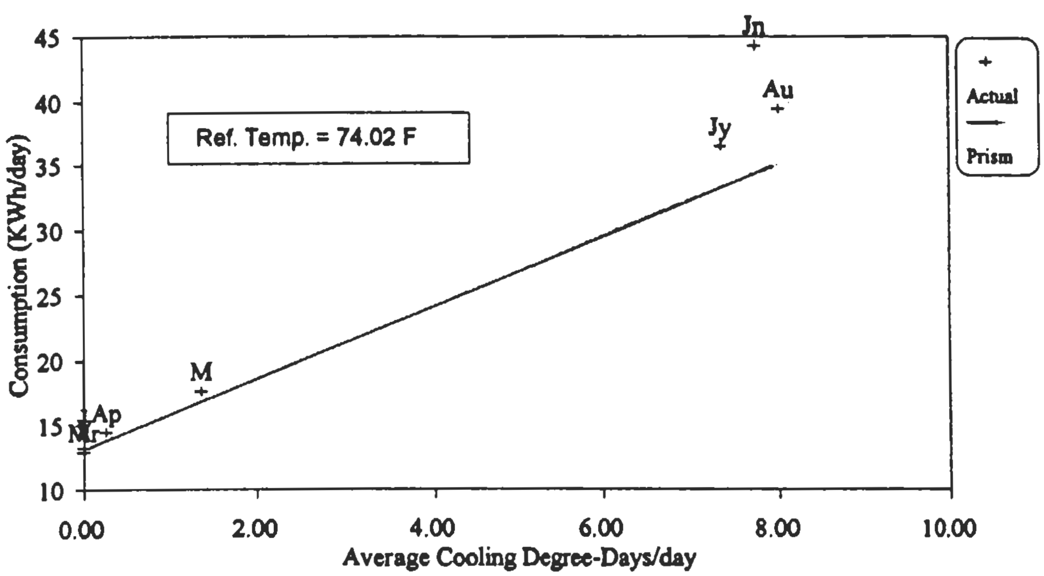

Figure 5: Actual average daily consumption and PRISM cooling curve for house 2.

DISCUSSION OF RESULTS

(a) Balance point temperature

For the most part, the balance point temperatures of the houses, according to PRISM, lie between approximately 68°F and 74°F (see Table 2). H10, with a reference temperature of 76.65°F is still in the reasonable range. For H9, however, τ =51.1°F, which seems unreasonable and a satisfactory explanation could not be found.

(b) Cool-month trends

In general, for the houses studied, consumption decreased from September to November (see Fig. 1). Daily average temperatures of College Station, shown in Table 3, also tend to decrease during this period. In about half of the houses the consumption increased in December and then decreased in January 1992, though from Table 3 we note that January was cooler than December. This behavior may be due to the Christmas holidays in December which affect occupancy patterns.

Table 3. Outdoor dry-bulb monthly average temperatures for College Station

Month	1991-1992 Temp. (°F)	Long-term Temp. (°F)
9	77.8	79
10	73.4	70
11	56.9	59
12	56.2	52
1	50.5	49
2	58.1	53
3	63.9	60
4	68.2	68
5	73.1	75
6	81.8	81
7	84.3	85
8	82.0	84

(c) Warm-month trends

Consumption typically increased from March to June 1992, with the largest increase from May to June. The average daily outdoor temperature behaved in a similar fashion (see Table 3). Although June was not the hottest month, the temperature increase was highest from May to June. Another factor which could explain the sudden increase in electricity use in June is the start of the summer holidays at the end of May which could have affected occupancy patterns.

(d) Short data sets

For H2, all the months with non-zero cooling degree days lie above the expected consumption curve calculated from the PRISM analysis (Fig. 5). This may be due to the fact that this is the only house for which less than one complete year of data was available.

PRISM PARAMETERS VERSUS MEASURED VALUES

Another facet of this study was to determine the extent to which the PRISM building parameter estimates are physically meaningful. For this purpose, the PRISM base load and reference temperature were compared to the values obtained by actual monitoring during the summer of 1992. As part of another study (Reddy et al., 1992), the compressor electricity and whole-house electricity were measured continuously during the summer months for seven of the eleven houses. From these measurements, the energy use attributed to the air-handler of the cooling system (which is not explicitly monitored) can be deduced following a procedure described by Reddy et al., (1992). Because all the houses have water heating and space heating provided by gas, the base-load electricity consumption of the houses can be determined on an hourly basis. The daily base load was taken as the mean value of all the days in the particular month, while the indoor temperature was calculated as the average of the hourly temperatures. In order to evaluate the extent to which hourly indoor temperatures vary during the day, we have also computed the monthly standard deviation of the hourly values for each month. (See Table 4.)

The balance point temperature can be estimated as follows from monitored data. We shall assume that $Q_{int} = E_{int}$ which, if occupant loads and solar loads are neglected, is a good assumption in these houses that use gas for water heating and for space heating. Then from from eqs (2) and (6) we have

$$\tau = T_{in} - \frac{E_{int}}{\beta * COP} \qquad (9)$$

Assuming a typical value of COP = 3 (i.e., Seasonal Energy Efficiency Ratio, or SEER, = 10) for new ACs (O'Neal, 1994), τ can be estimated for each of the houses using measured values of T_{in} and E_{int} and PRISM estimated value of β. These balance point temperatures are also shown in Table 4. We note that, except for H9, the PRISM estimated and "measured" values of τ are within 2°F in all cases and seem to show little or no bias.

Table 4. PRISM and actual values for comparison

House	Measured Average of T_{in} (°F)	Measured Std. Dev. of T_{in} (°F)	Measured Estimated τ from eq.(9) (°F)	PRISM τ (°F)	PRISM α kWh/d	Actual Measured Base load kWh/d	Percent difference
1	70.40	1.69	68.71	69.85	18.49	13.15	40.6
2	77.52	1.43	76.59	74.02	13.15	7.65	71.9
3	76.37	2.60	75.01	73.08	23.57	12.12	94.5
4	74.65	1.31	72.94	70.68	28.26	12.08	133.9
5	73.75	0.54	72.66	74.54	22.86	10.99	108.0
8	74.96	0.77	73.85	74.00	44.49	23.68	87.9
9	71.95	2.91	67.63	51.13	27.06	17.24	56.9

The percent differences between the PRISM and actual daily base loads for the houses, on the other hand, are relatively high ranging from 50 % to more than 100%, and exhibiting a consistent bias. It is difficult to satisfactorily explain this bias, though the fact that our measurements were done only in summer while PRISM estimates a mean annual value, could be a contributing factor. Another factor is our assumption that $Q_{int} = E_{int}$, whereby we neglect solar loads as well as loads due to occupants.

CONCLUSIONS

This study revealed that provided one is careful in correcting for effects such as vacation periods, erroneous utility meter readings and abnormal occupancy patterns during holiday periods, the PRISM approach can be used to accurately model whole-building electricity use in cooling-only residences. Further, the present analysis has shown that the estimates for balance point temperatures provided by the PRISM model are within a few degrees of actually "measured" values and seem to be unbiased. The PRISM estimates for base load consumption on the other hand are consistently high, by about 50 - 100%. Factors which may have caused this bias are also briefly stated.

ACKNOWLEDGMENTS

The cooperation of Phil Teinert of College Station Utilities is acknowledged. The assistance of S. Bhattacharyya and S. Vaidya in the preliminary stages of this study is greatly appreciated. This project has been funded in part by the National Science Foundation, by the Texas Higher Education Coordinating Board under the Energy Research and Applications Program (ERAP) project #222, and by the City of College Station. A critical review by Kelly Kissock is gratefully acknowledged.

NOMENCLATURE

AC	air-conditioner
CDD	cooling degree-days
COP	coefficient of performance of the AC
CV	coefficient of variation
E	whole-house electricity consumption
E_{cool}	electricity consumption of the AC
E_{int}	measured base-load electricity
NAC	normalized annual consumption
n	number of days
Q_c	thermal cooling load
Q_{int}	thermal internal loads
R^2	coefficient of determination
T_{in}	indoor dry-bulb temperature
T_{out}	outdoor dry-bulb temperature
UA	overall building heat loss coefficient
α	base-load electricity use
β	building loss defined by eq.(6)
τ	balance point temperature of the house

REFERENCES

ASHRAE, 1993. Fundamentals, *American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc.*, Atlanta, GA.

Avery, M., Bryan, J. and Griffiths, J.F., 1984. Office of the State Climatologist, Texas A&M University, College Station, TX.

Claridge, D., Haberl, J., Turner, W. O'Neal, D., Heffington, W., Tombari, C. and Jaeger, S., 1991. "Improving Energy Conservation Retrofits with Measured Savings", *ASHRAE Journal*, October.

Eto, J. H., 1988. "On using Degree-Days to Account for the Effects of Weather on Annual Energy Use in Office Buildings", *Energy and Buildings*, Vol. 12, pp. 113-127.

Fels, M., 1986. "PRISM: An Introduction", *Energy and Buildings*, Vol. 9, Nos. 1 & 2, pp. 1-9.

Fels, M. and Reynolds, C., 1991. "Towards Standardizing the Measurements of Whole-Building Energy Savings in DSM Programs", Proceedings 1991 Energy Program Evaluation Conference, pp. 75-85, Chicago, Argonne National Lab.

Fels, M. F. and Keating, K. M., 1993. "Measurement of Energy Savings from Demand-Side Management Programs in US Electric Utilities, *Annual Review of Energy and the Environment*, Vol. 18, pp. 57-88.

Griffith, L., 1991. "Preliminary Measurements of the Influence of Air-Conditioner Sizing on Utility Peak Loads", TEES Technical Report Series, National Science Foundation Undergraduate Summer Research Program, Oct.

Mills, E., Fels, M. and Reynolds, C., 1987. "PRISM: A Tool for Tracking Retrofit Savings", *Energy Auditor and Retrofitter*, Nov./Dec., pp.30-33.

Minehart, D. L. and Meier, A. K, 1994. "Using Synthetic Data to Explore the Usefulness of PRISM's Parameters at Inferring Causes of Changes in Normalized Annual Consumption", *Energy*, Vol. 19, no. 2, pp. 135-148.

Mitchell, J. W., 1983. Energy Engineering, John Wiley and Sons, New York.

O'Neal, D., 1994. Personal communication.

Rabl. A, and Rialhe, A., 1992. "Energy Signature Models for Commercial Buildings: Test with Measured Data and Interpretation", *Energy and Buildings*, Vol. 19, pp. 143-154.

Reddy, T. A., Vaidya, S., Griffith, L., Bhattacharyya, S. and Claridge, D. E., 1992. "A Field Study on Residential Air-Conditioner Peak Loads during Summer in College Station, Texas", Energy Systems Laboratory Report ESL-TR-92/08-04, Texas A&M University, College Station, TX.