STEADY STATE MODELS FOR ANALYSIS OF COMMERCIAL BUILDING ENERGY DATA

Ari Rabl, Les Norford and Joe Spadaro
Center for Energy and Environmental Studies
Princeton University

ABSTRACT

This paper examines the suitability of steady state methods for the analysis of energy consumption data of commercial buildings. Steady state methods have the appeal of simplicity, and often a more detailed and accurate transient analysis is prevented by lack of data. A steady state analysis can yield information on the following points: weather correction, variation of energy consumption with thermostat setpoint (i.e. cost of comfort), the ratio of heat loss coefficient and heating efficiency. A recently developed procedure, called PRISM, has been very successful when applied to residential buildings. By contrast to residential buildings, the energy consumption of commercial buildings is dominated by equipment rather than the building shell; hence weather correction may be relatively unimportant. Furthermore, the baseload may vary independently of the weather and the variation can be large compared to the heating load; in such a case PRISM can give misleading results. Another important difference between the two building types lies in the ventilation system. Most commercial buildings use forced ventilation by central fans, and the heat loss coefficient changes sharply (by as much as a factor of two) as the ventilation rate is changed between occupied and unoccupied periods. This feature affects the interpretation of the heat loss coefficient that can be extracted by a steady state analysis. In fact, the determination of the heat loss coefficient may be impossible without data on supply rates of fresh air. These features are illustrated with data for several individual office buildings as well as an aggregate of buildings. The relation between thermostat setpoints and space conditioning cost is derived.

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1. INTRODUCTION

There are many methods and models for the analysis of energy use in buildings. No single one is universally the best. Rather, the choice depends on what one wants to calculate and what data are available. This paper provides an overview of various models and examines the suitability of steady state models for the analysis of existing commercial buildings.

Table I summarizes the most important methods. Steady state methods are listed in part a), transient methods in part b). The table is arranged to distinguish the goals of different methods, as emphasized by Subbarao [1985]. The designer of a building is concerned with the forward problem: he has the description of the building and he wants to calculate its peak and average loads. By contrast, once a building has been in use the energy consumption is known, from utility bills if not from an energy management system. At that point some relevant questions are:

1. How does the consumption compare with design predictions (and in case of discrepancies, are they due to added equipment loads, longer operating hours, anomalous weather, to unintended thermostat settings, to malfunctioning systems, or to other causes)?

2. How would the consumption change if thermostat settings or ventilation rates are changed (in other words: what is the cost of comfort)?

3. How much could be saved by retrofits of building shell or equipment?

4. If such retrofits are implemented, can one verify that the savings are due to the retrofit and not to such causes as changes in the weather?

5. How can one optimize the control of the HVAC equipment?

6. How does consumption compare with similar buildings?

Here one is faced with the inverse problem: given performance data for a building, how much can one learn about its physical characteristics? One could try to go back to the blueprints of the building and repeat the analysis performed at the design stage. But there are several problems. The process requires much labor, assuming that the original blueprints or a computer program modeling the building can be found at all. There is the possibility of errors or misinterpretations [Diamond et al 1985]. And the builder may not have followed all the original specifications. The energy consumption, on the other hand, is measured with great care by the utility companies, and monthly data are part of the bill. For additional data with finer time resolution one can read the utility meter(s) for a few days, or sub and spot meter.

For the inverse problem the number of adjustable parameters in a model should be small enough to permit meaningful determination by statistical fitting procedures [Hammarsten 1986]. Thermal networks [Sonderegger 1977], lagged variables [Subbarao 1985], modal analysis [Bacot 1985; Sicard et al. 1985], and Fourier analysis [Shurcliff 1984; Subbarao 1984] meet this requirement. Such simulation programs as BLAST and DOE2.1 do not. One could try to calibrate the computer program by comparing its output with measured data and adjusting some of the input as necessary. However, this so-called calibrated computer program approach lacks a systematic procedure for deciding which of the innumerable input parameters should be adjusted by how much.

The present paper investigates the suitability of steady state methods for the inverse problem. Steady state methods can provide information about:

1. Sensitivity of energy consumption to weather,

2. Cost of comfort (only approximate, if night setback),

3. Heat loss coefficient and/or efficiency of heating equipment.

Transient models are necessary to analyze warmup and cooldown effects for accurate evaluation of changes in thermostat setpoints, for optimal control of HVAC equipment startup, and for calculation of hourly peak loads. But transient models need input data with short time resolution (hourly being typical). In many commercial buildings the air exchange rate can vary sharply between occupied and unoccupied periods, and a transient analysis is not meaningful without air exchange data. If data for a transient analysis are not available, one is limited to steady state methods.

For residential buildings a successful steady state model has been developed in recent years [Fels 1984]. Called PRISM (for PRInceton Scorekeeping Method), it is an excellent method for weather correction of energy data in buildings where the base level is relatively constant. The heating-only version of this model characterizes a building in terms of three parameters: the base level, the heating slope (ratio of heat loss coefficient and efficiency of heating equipment) and reference temperature (value of ambient temperature below which heating is required). The model can be extended to include cooling.

An examination of the differences between residential and commercial buildings points out reasons why the application of PRISM to commercial buildings may be problematic. We illustrate this with several examples. There does not seem to be a single general procedure. One has to approach each building with caution, gathering as much information as practical and plotting it in several ways to find out what is going on. A plot of energy use versus time of year is a good starting point; it shows at a glance whether ambient temperature is a significant factor. If it is not, then weather correction is not important. But even in that case one may be able to extract information about the heat loss coefficient and/or the heating efficiency by examining the overall energy balance during the coldest days of the year.

2. THE THEORY OF STEADY STATE MODELS

Zero Heat Capacity

In steady state the thermal energy balance of a building is written as

$$Q_h + Q_{gain} = L\,(T_{int} - T_{amb}) \tag{2.1}$$

where

Q_h (Q_c) = rate of thermal input by heating (cooling) equipment;

Q_{gain} = rate of heat gain from solar radiation, occupants, lights, equipment, etc.;

L = heat loss coefficient of building, including supply of fresh air and infiltration;

T_{int} = interior temperature;

T_{amb} = ambient air temperature.

The steady state equation is exact if the heat capacity of the building is zero or if the temperatures are constant.

The total energy consumption of the building is

$$Q_h/\eta_h + \alpha \tag{2.2}$$

where

α = base level, i.e. non heating/cooling consumption;

η_h (η_c) = efficiency of heating (cooling) equipment.

The relation between Q_{gain} and α depends on the building. Quite generally one can write

$$Q_{gain} = f\,\alpha + Q_{free} \tag{2.3}$$

where

Q_{free} = free heat from solar radiation and occupants;

f = fraction of α that contributes heat to the building.

For lights f is close to unity, but f can be quite small for domestic hot water if most of its heat goes down the drain. Some commercial buildings have significant categories for which f is zero, for example computer rooms with dedicated chillers, and exterior lights.

Fig.2.1 shows how the total energy consumption of a building with zero heat capacity varies with ambient temperature if one assumes constant values for efficiency of heating and cooling equipment, heat loss coefficient, base level consumption and Q_{gain}. Also assumed is thermostatic control to keep the interior temperature between the lower and upper limits $T_{int,min}$ and $T_{int,max}$ (heating and cooling thermostat setpoints).

Heating becomes necessary whenever T_{amb} drops below the heating reference temperature τ_h, given by

$$\tau_h = T_{int,min} - Q_{gain}/L. \tag{2.4}$$

Below this temperature the energy use decreases linearly with T_{amb}, and the slope of this portion of the curve is

$$\beta_h = - L/\eta_h. \tag{2.5}$$

Between τ_h and τ_{c1} neither heating nor cooling are required, and the energy use is constant at the base level α.

If the heat loss coefficient L is constant, then cooling becomes necessary when T_{amb} rises above the reference temperature for cooling τ_{c1}

$$\tau_{c1} = T_{int,max} - Q_{gain}/L. \tag{2.6}$$

The energy increases linearly with slope

$$\beta_c = L/\eta_c. \tag{2.7}$$

However, in most buildings there is an additional feature which is presented schematically by the kink in the cooling portion of Fig.2.1. Since τ_{c1} is less than $T_{int,max}$, the building can be kept comfortable if one simply brings in enough ambient air. In houses one opens the windows. In commercial buildings with sealed windows there is something that has the same effect: when T_{amb} is between τ_{c1} and τ_{c2} the air dampers of the central ventilation system are adjusted automatically to increase the intake of outside air. This is called economizer cycle (because it saves energy compared to the old way of running the air conditioner below τ_{c2}) and it is employed in almost all new office buildings. The economizer cycle requires extra fan power relative to that needed in the absence of a cooling load. Ideally, the controls will use the fans and the cooling equipment in a way that minimizes energy consumption and smoothly varies energy use with outdoor temperature. An abrupt change, such as is depicted for a house where windows can be opened, indicates for a commercial building that a more energy-efficient strategy was switched off (outdoor airflow prematurely returned to its minimum value) or cooling equipment was turned on when T_{amb} was already above τ_{c1}.

Open windows or economizer increase the air flow and hence the heat loss coefficient. To find the upper limit τ_{c2} of T_{amb} beyond which the air conditioner must be used, let L_{max} denote the largest value of L that can be achieved (with central ventilation it is well defined, with open windows it depends on wind velocity). τ_{c2} is obtained by replacing L by L_{max} in Equation 2.6

$$\tau_{c2} = T_{int,max} - Q_{gain}/L_{max}. \tag{2.8}$$

The temperature interval over which open windows/economizer can be used is

$$\Delta T_{econ} = \tau_{c2} - \tau_{c1} = Q_{gain} (1/L - 1/L_{max}). \tag{2.9}$$

The difference between τ_h and $T_{int,min}$ depends on base level and on heat loss coefficient, and several degrees C are typical for American houses. Compared to houses, commercial buildings have lower surface-to-volume ratios and larger internal heat gains due to lights, office equipment and occupants. The difference between τ_h and $T_{int,min}$ can be on the order of 10 C. In fact, some large office buildings require cooling even in winter. The difference $\Delta T_{econ} = \tau_{c1} - \tau_{c2}$ can be almost as large as the difference between τ_h and $T_{int,min}$, since L_{max} can be several times as large as L, both in residential and in commercial buildings.

Effect of Heat Capacity

Since buildings have a finite heat capacity, this simple picture is not quite true, especially if a thermostat setback for night time or unoccupied periods allows the interior temperature to fluctuate. However, a steady state analysis can be acceptable if one considers averages over appropriate time periods. Since the variations of ambient and of interior temperature, as well as solar radiation, follow a roughly periodic pattern of day/night cycles, it is natural to reinterpret Fig.2.1 in terms of daily averages. The heat capacity term becomes small if the interior temperature is the same at the beginning and at the end of the averaging period. In that case Fig.2.1 continues to be correct for all days when ambient stays either entirely below τ_h or entirely above τ_{c2}. Heat capacity affects only the transition region where the sharp corners may become rounded.

Solar Effects

For Fig.2.1 we have assumed that the heat gain Q_{gain} is constant, even though the solar contribution to this term is quite variable. The effect of solar radiation on Fig.2.1 depends on the design of the building and on the time scale over which one averages. Day-to-day variations are large, and may cause appreciable scatter about the trend line in Fig.2.1. But when one considers monthly averages, the solar radiation is approximately correlated with average ambient temperature; hence the pattern of Fig.2.1 persists although the interpretation of the slope parameters β_h and β_c is affected by the solar contribution. Perhaps a better approach might be a plot versus degree days that are based on sol-air temperature [ASHRAE 1981; Erbs et al. 1984] rather than air temperature, a suggestion made by Jeff Gordon [personal communication 1985]. Similarly for cooling data one could replace ambient temperature by the temperature-humidity index, together with a correction for sol-air temperature. These alternatives have not yet been tested.

Aggregates of Buildings

Fig.2.2a shows what happens when one combines the energy consumption of two buildings with different reference temperatures. In the transition region between the two reference temperatures only one building requires heat. Below the lower reference temperature the slope for the total consumption is equal to the sum of the individual slopes. For an aggregate of many buildings the transition region consists of many small straight segments, as shown in Fig.2.2b. In practice they may not be distinguishable in the data.

3. WEATHER CORRECTION WITH PRISM

The PRISM model for heating data is directly based on Equations 2.1 to 2.5. As input for PRISM one needs only data that are readily available: energy consumption for several periods of the year (obtainable from monthly bills) as well as daily average ambient temperatures for the same time periods (available from the nearest weather station). The parameters of the model are base level α, heating parameter β_h, and heating reference temperature τ_h; they are determined by a least squares fit to the equation

$$Q_i = \alpha + \beta_h H_i(\tau_h) \tag{3.1}$$

where

Q_i = daily average consumption during the i'th period;

$H_i(\tau)$ = average number of degree days per day relative to reference temperature τ_h during the same period.

$$H_i(\tau_h) = \sum_{j=1}^{N_i} (T_{amb,ij} - \tau_h)_+ / N_i \tag{3.2}$$

the + subscript under the parenthesis indicating that only positive terms are included in the sum over the N_i days in period i.

The normalized, i.e. weather corrected, annual energy consumption NAC is then given by

$$NAC = 365 \text{ days} * \alpha + \beta_h H_o(\tau_h) \tag{3.3}$$

where

$H_o(\tau_h)$ = average number, over a long period, of annual heating degree days relative to the reference temperature τ_h.

The slope β_h is the heat loss per day and per unit inside-outside temperature difference, divided by the efficiency η_h of the heating equipment. The reference temperature τ_h is a 24 hour average and includes the effect of thermostat setback.

The reader may wonder whether the parameters can be determined directly from a graph of Q_i versus average T_{amb}. That would be simpler than Equation 3.1 because it could be plotted without first finding $H_i(\tau_h)$. However, in general the daily average temperature is different from the average degree days per day whenever the period is not equal to 1 day and the temperature crosses the value τ_h during the period. Therefore a plot versus $H_i(\tau_h)$ is equivalent to one versus average T_{amb} during period i only if the length of each period is equal to 1 day or if $T_{amb} < \tau_h$ for all days.

Recently PRISM has been extended to houses with air conditioning by adding an analogous term for cooling [Fels et al. 1985]

$$NAC = 365 \text{ days} * \alpha + \beta_h H_o(\tau_h) + \beta_c C_o(\tau_c) \tag{3.4}$$

where

$C_o(\tau_c)$ = number of cooling degree days above τ_c.

However, in cold climates the cooling parameters cannot be as well determined as those for heating because the temperature differences are smaller and the cooling season is shorter. When Equation 3.4 was applied to residential data the use of air conditioning was found to be quite erratic and the correlation with cooling degree days was relatively poor in a large fraction of the houses, although in many houses the fit was excellent [Fels et al. 1985].

Equation 3.4 is based on the the dashed line in Fig.2.1, i.e. no use of open windows or economizer. Open windows represent a further complication; if their use were as regular as implied by the solid line in Fig.2.1, then Equation 3.4 would be replaced by

$$NAC = 365\ \alpha + \beta_h\ H(\tau_h) + \beta_c\ [C(\tau_{c2}) + (\tau_{c2} - \tau_{c1})\ N(\tau_{c2})] \qquad (3.5)$$

where

$N(\tau_{c2})$ = number of days above τ_{c2}.

Now the number of parameters is so large that in many cases their determination from monthly data may not be possible, to say nothing about the fact that an economizer will often deviate from the open-window idealization.

A potential problem in interpreting a fit like PRISM lies in the possibility of correlations between different variables; for example, PRISM may compensate a high base level with a low reference temperature for heating or a low heat loss coefficient. One might wonder if it would not be better to avoid the transition regions in Fig.2.1 and to carry out separate fits for each straight line portion. However, at least as far as the normalized annual consumption is concerned, a single fit has been shown to yield the best estimate [Fels 1984].

For weather correction PRISM is reliable whenever the energy consumption is closely correlated with ambient temperature and can be approximated by the pattern in Fig.2.1. The normalized annual consumption NAC can be determined within a standard deviation of 3 to 4%. By contrast, the individual parameters are less well determined, with standard deviations on the order of five to ten percent for α, β_h and $H(\tau_h)$, and their interpretation requires much stronger assumptions. For example, PRISM can determine the NAC of houses with electric heat pumps, even though the efficiency of a heat pump varies with ambient temperature and the sloping portion of Fig.2.1 curves upward. PRISM simply draws the best straight line, compensating for the curvature by lowering the reference temperature [Fels et al. 1985].

PRISM has worked very well when applied to the heating energy consumption in residential buildings, of both the single and multifamily variety [Fels et al. 1985; Hirst et al. 1984; Dunsworth et al. 1984; DeCicco et al. 1985]. Even slight seasonal variations of the base level (due to the effect of water main temperature on water heating load) can be accommodated [Fels et al. 1985].

4. DIFFERENCES BETWEEN RESIDENTIAL AND COMMERCIAL BUILDINGS

To determine the extent to which PRISM may be suitable for commercial buildings, let us examine the differences between commercial and residential buildings in the light of the above assumptions.

Baseload

Weather correction is less important for commercial buildings than for residences, because the baseload component tends to be relatively large. The baseload in office buildings and retail stores is due mostly to lights, office equipment and fans. With traditional design and control technologies such loads are likely to be quite constant throughout the year. In the future the baseload consumption may become more variable as more sophisticated controls for lighting and HVAC equipment are introduced. Furthermore, in some buildings energy use varies strongly with workload. If the baseload shows large variations that are not correlated with ambient temperature (as may be determined with submeters), then PRISM may give misleading results.

Occupancy Schedule

Weekend energy use in most commercial buildings is greatly reduced. On Mondays the consumption may be abnormally high while the building is brought back to comfortable conditions. Ideally one should carry out separate PRISM fits for different days according to the occupancy schedule, but that is possible only if daily data are available. With monthly data the results may be skewed by nonuniform distribution of degree days over weekdays and weekends.

Ventilation system

Commercial buildings have controlled air intake during occupied periods and are subject to infiltration during unoccupied periods. The effective heat loss coefficient L can easily change by a factor of two between occupied and unoccupied periods, by contrast to houses where L does not change abruptly. PRISM fits daily averages, and it assumes that L is constant. For commercial buildings PRISM fits may be skewed by diurnal variations of L and of temperature difference.

Solar Radiation

Compared to houses solar effects may be more important because office buildings tend to have larger window/wall area ratios.

Simultaneous Heating and Cooling

Because of their large baseload commercial buildings tend to have a large cooling load. Simultaneous heating and cooling is very common and affects the interpretation of the PRISM parameters. For instance, part of what appears to be baseload may actually be simultaneous heating and cooling.

5. DATA FOR SOME COMMERCIAL BUILDINGS

Individual Buildings

We begin with data from three local office buildings, all-electric three-story structures of medium size (50,000 to 80,000 ft^2). Fig.5.1 shows monthly energy consumption and ambient temperature for 1984. Buildings #2 and #3 correlate neither with heating nor with cooling degree days. All three buildings use more energy in February than in January, even though February was warmer. The peaks occur at different times: in September for #2 and in February for #1 and #3, definitely not the hottest or coldest months. The only feature common to all three buildings is the smallness of the seasonal variation.

As another example we present data for two all-electric office buildings that have been instrumented with about 100 data channels [Norford et al. 1985]. For the North building the pattern has been so erratic that a PRISM fit of its monthly consumption data is meaningless, with a correlation coefficient $R^2 < 0.1$. For the South Building, on the other hand, the monthly consumption correlates quite well with heating and cooling degree days, as shown in Fig.5.2. Ambient is represented by the heating and cooling degree days corresponding to the reference temperatures of the PRISM fit. In addition to the actual consumption, the consumption calculated by PRISM is also indicated. Note that one outlier, March 1985, has been removed from the data set because the occupant load was abnormally large during that month. The agreement (using PRISM heating-cooling model) is excellent, with R^2 of 0.98.

Taking a closer look, we plot daily consumption versus daily average temperature for the South building in Fig.5.3. Different operating conditions, deduced from submetered HVAC equipment, provide some explanation for the large scatter. Weekend consumption is roughly half the weekday value, except for days when the building was conditioned around the clock either because of overtime work or to prevent uncomfortable conditions Monday morning.

The cutoff temperatures for heating and cooling are approximately 14 and 18 C, respectively. Between these temperatures there is a plateau corresponding to a baseload of about 3,800 kWh/day. At 18 C there seems to be a kink, corresponding to increased ventilation rate in the economizer mode. PRISM does not account for the mode of economizer/open windows, and fits instead a single straight line through the cooling portion. Hence it is not surprising that the baseload (3,445 +- 434 kWh/day) and the cooling reference temperature (15.6 +- 6.1 C) of the monthly PRISM fit differ from the daily pattern.

The weekday heating data in Fig.5.3 are separated according to the number of hours per day that the building has been conditioned. In spring, fall and summer this has typically been 12 hours. In colder weather the heating system controls turn on the heat pumps and fans earlier in the morning to bring the building to comfort conditions by the time the occupants arrive. For much of the winter the building was conditioned continuously. This condition was manually set by the building operator, who overrode the control system due to lack-of-heat complaints, inadequate performance of the controls and problems with the heat distribution system. While the continuous operation was probably not necessary for a major part of the winter, it shows that building energy consumption increases with length of operating period as well as decreasing ambient temperature.

In cold weather, i.e. with minimum supply of outdoor air, the heat loss coefficient of this building is in the range of 25 to 30 kW/C occupied and 15 to 20 kW/C unoccupied. The COP of the South building heat pump is about 3.0 to 3.5. Under 24 hour operation the heating slope of Fig.5.3 should therefore be around 27.5 kW/C * 24 hr/3.25 = 203 kWh/C day. This agrees with the slope of 208 kWh/C day obtained by a PRISM fit to the heating portion of Fig.5.3, shown by the dashed line. However, for a given operating period, the slope is only about half as large. For the 24 hour points we have data which indicate that the air flow increased with ambient temperature; this can explain the small slope of the 24 hour points. The use of more than minimal outdoor air at 0 C, way below the balance temperature, is an example of simultaneous heating and cooling. The slope of the 12 hour points should correspond to a heat loss coefficient half way between the daytime and the night time values, or roughly 166 kWh/C day. The slope of the 12 hour heating points is somewhat smaller, but again this is probably due to changes in air flow.

As a final data set we quote results for five buildings on the Princeton campus in which submetered data have been recorded for both steam and electricity. Four of these five buildings have energy plots similar to the Astrophysics Building in Fig.5.4a. Here the steam use for heating increases with (T_{int} - T_{amb}) in approximately linear fashion. For the fifth, the Music Building in Fig.5.4b, the plot has a strange feature: if one draws a trend line through the steam data, the y-intercept is much too high, implying that heating would be needed even when ambient is warmer than the interior. Such a pattern could appear if the air exchange rate is increased (economizer or open windows) as T_{amb} goes up, in order to avoid overheating portions of the building (a form of simultaneous heating and cooling). Another possibility, a large consumer of process steam, can be ruled out since this is the music building. More plausible is a malfunctioning of the steam traps in the building, allowing steam to return to the central boiler plant without giving up all of its latent heat in the building.

In selecting these examples we have not looked for perversity. Rather, the nine buildings that we have mentioned happen to be the ones for which data were most readily available. From our sample, it is clear that occasional sucess may be expected, but in general one must be circumspect when applying a simple approach such as PRISM to commercial buildings.

<u>Data for Aggregate of Buildings on University Campus</u>

Fuel data for a university central boiler plant provide an interesting example for the application of PRISM to an aggregate of commercial and residential buildings. Steam is used for space heating, for process heat (cafeterias, laboratories), and for air conditioning. The only other energy input to the buildings is electricity, which shows little seasonal variation.

The daily fuel consumption for weekdays is plotted versus T_{amb} in

Fig.5.5. To reduce the number of individual points and clarify the trends we show averages for each 1 F bin of ambient temperature. The general trend is the same as for residential buildings: both in the heating and in the cooling season the consumption increases linearly with temperature, and in between there seems to be a plateau corresponding to the baseload. PRISM gives reasonable fits with R^2 between 0.75 and 0.8 for the (unaveraged) daily data. However, when one separates the days by time of year (not shown here) one finds significant variations that may be due to the academic calendar or to campus growth. There seems to be an economizer kink in the cooling portion, around 72 F. This value is consistent with the relatively high interior temperatures (74 to 78 F) maintained on the Princeton campus in summer.

The results of several PRISM fits are summarized in Table II. The fits of the top portion of the table are based on Equation 3.3 and account for heating only. The remaining fits include heating and cooling, as per Equation 3.4. Separate fits are shown for weekends and weekdays, as well as for all days combined. Differences in the individual parameters for the separate time periods do not look significant, but the 3% difference in normalized annual consumption is statistically significant.

The base level accounts for approximately 80% of the annual total and weather correction is not as important as for residential buildings. In fact, there may be systematic variations of the base level that are not weather-related. If one separates the data of Fig.5.5 according to month one finds that the base level seems to be appreciably larger (around 1,500 MBTU/day) in May 1985 than in September 1984 (around 1,200 MBTU/day). Variations due to the academic calendar are likely. Change due to growth could also contribute.

6. ALTERNATIVE DETERMINATION OF HEAT LOSS COEFFICIENT

In some cases the heat loss coefficient can be determined directly from short term data for steady state conditions during cold weather. If one knows the total heat input Q to the building and the temperature difference $T_{int} - T_{amb}$, then the heat loss coefficient is

$$L = Q/(T_{int} - T_{amb}). \tag{6.1}$$

In practice the quantities on the right hand side may not be known. Whether Q equals the measured energy consumption depends on the building (heating system, domestic hot water consumption, etc.). For electric resistance heating the case is simple because one can assume 100 % efficiency. For other heating types one needs either measurements (which may be difficult) or assumptions (which may be uncertain) about the efficiency of the heating system.

Lacking data for T_{int}, let's guess a value of 21 C for occupied periods. For unoccupied periods a guess for T_{int} is more difficult. Typical average nighttime values in cold weather might be between 12 and 18 C, including the effect of cooldown time. If there is thermostat setback, data must be averaged over at least one full cycle. One might guess a 24 hour average value of (21 C + 15 C)/2 = 18 C, with an uncertainty of +- (2 C + 3 C)/2 = +- 2.5 C. With ambient at -7 C the relative error in $(T_{int} - T_{amb})$ is an acceptable 10%.

For an illustration let us return to the data in Fig.5.4a. Both the steam and the electricity constitute a direct thermal input to the building, with 100% efficiency. T_{int} was measured, hence Q is plotted against (T_{int} - T_{amb}). Following Equation 6.1 we draw a straight line from the origin to the average of the points for the coldest weather. The slope is 1.8 W/m^2 C. Lacking air exchange data, we do not know the actual heat loss coefficient at any time; the slope in Fig.5.4a is merely an approximate average. The uncertainty in Q, reflected by the scatter of the data points, is larger than the error we would have made had we guessed the interior temperature. A least squares fit through the data would intercept the y-axis at a value somewhat below zero, consistent with positive heat gains from occupants and solar radiation. The advantage of using winter data is the relative smallness of the solar radiation term.

7. THERMOSTAT SETPOINTS AND COST OF COMFORT

For buildings that are kept at constant temperature 24 hours a day it is easy to calculate how much the energy consumption changes if the thermostat setpoint is changed by δT: simply shift the reference temperature by δT in Equation 3.3 or 3.4. It is more relevant to ask how the consumption changes if only the setpoint for occupied periods is changed, assuming that the unoccupied setpoint is already at the lowest (in winter) or highest (in summer) acceptable value. Strictly speaking this requires a transient model. A reasonable estimate can be obtained even from steady state results. Suppose the thermostat for heating during occupied periods is raised by δT. Since PRISM determines the reference temperature τ_h we need to know how the latter is affected by δT. In the absence of thermal mass that would be simple

$$\delta\tau_{h,mass=0} = \delta T * \text{occupied time/total time.} \tag{7.1}$$

If the mass were infinite, the building would not cool down at all and the result is again simple

$$\delta\tau_{h,mass=\infty} = \delta T. \tag{7.2}$$

The real answer must lie somewhere in between, as indicated by the temperature patterns in Fig.7.1. One can narrow the uncertainty by adding the cooldown time of the building to the daily occupied time in Equation 7.1. The cooldown time is the time it takes T_{int} to drop from the daytime to the night time setpoint; it depends not only on the building but on temperatures. Typical values for light office buildings are on the order of a few hours.

The Princeton campus buildings are typically conditioned 16 hours a day. Adding a three hour cooldown period [see data in Rabl, 1984], this implies

$$\delta\tau_{h,campus} \simeq \delta T * (16+3)/24 \simeq 0.8\ \delta T. \tag{7.3}$$

The range between upper and lower bounds is relatively narrow because the unoccupied period is short.

The upper and lower bounds of Equations 7.1 and 7.2 hold also for the cooling season, but Equation 7.3 is less reliable. In summer the temperature difference $T_{int} - T_{amb}$ is small (and can change sign at night) and hence the unoccupied T_{int} does not change as fast as in winter. Also the setpoint during the unoccupied period is so high that the buildings receive no or almost no cooling at that time. The difference between the cooldown rate in winter and the warmup rate in summer is illustrated schematically in Fig.7.1. It suggests that the effective change in the summer reference temperature for cooling may be close to the upper limit

$$\delta\tau_{c,campus} \approx \delta T. \tag{7.4}$$

Combining Equations 7.3 and 7.4 with the basic equation of PRISM, Equation 3.3 or 3.4, we find that the annual heating energy increases by

$$\delta Q_h = \beta_h \; [H(\tau_h + 0.8\;\delta T) - H(\tau_h)] \tag{7.5}$$

if the daytime heating setpoint of the thermostat is raised by δT. Similarly the annual cooling energy decreases by

$$\delta Q_c = \beta_c \; [C(\tau_c + \delta T) - C(\tau_c)] \tag{7.6}$$

if the daytime cooling setpoint of the thermostat is raised by δT.

For the Princeton campus the most appropriate fit is probably the h + c PRISM fit for weekdays in Table II. The reference temperatures for weekdays are τ_h = 61.0 F and τ_c = 72.0 F. If the heating thermostat setpoint is raised by 1 F during occupied periods Mon-Fri, annual heating fuel increases by

$$\delta Q_h = 44.9 \text{ MBTU/F } [(4017 + 0.8 * 216) - 4017] \text{ Fday} * 5/7 \tag{7.7}$$

$$= 5{,}542 \text{ MBTU per year } (10.5 \text{ MJ/y m}^2 \text{ per } 0.56 \text{ C}).$$

At a fuel cost of 5 $/MBTU this implies an incremental cost of approximately $ 28,000 per year. Similarly the annual cooling energy decreases by

$$\delta Q_c = 31.4 \text{ MBTU/F } [564 - 477] \text{ Fday} * 5/7 \tag{7.8}$$

$$= 1{,}951 \text{ MBTU per year } (3.7 \text{ MJ/y m}^2 \text{ per } 0.56 \text{ C})$$

if the cooling setpoint of the thermostat is lowered by 1 F during occupied periods. This costs approximately $ 10,000 extra per year.

8. CONCLUSIONS

We have addressed the question of how much one can learn about a building if one has daily or monthly whole-building energy consumption data, without any information about supply rates of fresh air. Our examples show that a steady state analysis can be successful not only for residential but even for commercial buildings and for aggregates of commercial buildings. However, one must be very careful with the interpretation of the results. The PRISM model for weather correction of consumption data can give misleading results if the base level varies independently of ambient temperature. In commercial buildings the energy consumption is dominated by equipment rather than the building shell; hence weather correction is not as important as in the residential sector. The connection between heating slope parameter and building heat loss coefficient may be washed out because of large day/night variation in air exchange rates. The behavior of the cooling load is more complicated than the heating load because of the use of open windows or economizer. While this feature can be discerned in daily data (especially if one averages over temperature bins to smooth out irregularities), it may not be possible to account for it if one has only monthly data. We have also shown how one can estimate cost of comfort, i.e. the energy cost of changing the thermostat setpoints of a building.

In analyzing commercial building energy consumption data, one approach is to accept a PRISM fit for weather normalization, with the understanding that the fit is based on a specific set of operating procedures. Another approach is to use PRISM with daily data, as a diagnostic tool. In this mode it is probably most instructive to start with a graphical display of the data, with appropriate labels for individual points.

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Table I. Methods for thermal analysis of buildings.

A * under the "forward" and "inverse" columns indicates applicability to forward problem (calculating energy performance from building characteristics) and inverse problem (determining characteristics of building from energy consumption data). The references refer either to the original work or to a good recent summary.

a) steady state methods

	forward	inverse	comments
degree day method [ASHRAE 1985]	*		Based on Eq.2.1 with fixed T_{ref} = 18.3 C. Can be quite wrong if T_{ref} is different (e.g. in commercial or superinsulated buildings).
variable base degree day method [ASHRAE 1985]	*		Eq.2.1 with variable T_{ref}. Good first approx. for annual consumption; not for peak loads.
bin method [ASHRAE 1985]	*		For constant heat loss coefficient and efficiencies equivalent to variable base DD method, with slightly different input format. Separate calculation possible for nights and weekends if separate T_{amb} data avail. Can accommodate temperature dependent properties.
PRISM [Fels 1984]		*	Needs data for energy use (several periods/year) and for daily average T_{amb}. Best for weather correction and evaluation of retrofits.
ASHRAE TC 4.7 [Knebel, 1983]	*		modified bin method, with cooling load factors etc. to account for some transient effects and determine peak loads.

b) transient methods

	forward	inverse	comments
thermal network (with equivalent thermal parameters) [Sonderegger 1977]	*	*	Hour-by-hour calculation to find peak and annual loads. In inverse direction, data fit to hourly data for T_{int}, T_{amb} and energy. Risk of misleading results if network not well chosen.
response factor series [Stephenson and Mitalas 1967]	*		In forward direction, tabulated results [ASHRAE] for building components, useful for finding peak loads.
lagged variables [Subbarao 1985]		*	In inverse direction, modified series with lagged variables, is good for data fit, but lacks clear physical interpretation.
Fourier [Shurcliff 1984]	*	*	Calculates response to sinusoidal (constant plus diurnal) input. Can be combined with calculation in time domain.
BEVA (Fourier + lagged variable series) [Subbarao 1985]	*	*	Provides clear interpretation for lagged variable series; Peak and annual loads are calculated in time domain.
modal analysis [Bacot 1985]	*	*	Diagonalization of the differential equations for the building; approximation by a small number of modes.
computer simulation (e.g. DOE 2.1, BLAST)	*		Very detailed. Potentially the most accurate method. Also models HVAC equipment. Requires specialized expertise and much labor for coding the input.

Table II. PRISM fit to daily fuel data for central boiler of Princeton campus. Standard deviations are shown in (). h = heating only, Equation 3.3; h + c = heating plus cooling, Equation 3.4.

data set	baseload (per day) α [10^3MBTU]	heating slope β_h [MBTU/Fday]	heating T_{ref} τ_h [F]	cooling slope β_c [MBTU/Fday]	cooling T_{ref} τ_c [F]	consumption (per year) NAC [10^3MBTU]	correlation coefficient R^2
Sep - May h only	1.50 (0.04)	45.4 (2.1)	60.9 (1.4)			730.9 (8.1)	0.77
Jul - Jun all days h only	1.58 (0.02)	45.7 (2.1)	59.0 (1.2)			742.7 (6.5)	0.76
Jul - Jun weekdays h only	1.61 (0.03)	45.6 (2.6)	58.8 (1.4)			750.5 (7.9)	0.75
Jul - Jun weekends h only	1.52 (0.04)	46.5 (3.8)	59.0 (2.1)			723.5 (11.4)	0.79
Jul - Jun all days h + c	1.51 (0.03)	45.0 (1.9)	61.0 (1.2)	35.4 (16.0)	73.0 (4.0)	746.6 (6.4)	0.77
Jul - Jun weekdays h + c	1.53 (0.06)	44.9 (2.3)	61.0 (1.7)	31.4 (14.9)	72.0 (6.0)	753.6 (7.8)	0.76
Jul - Jun weekends h + c	1.49 (0.05)	47.7 (3.8)	59.0 (2.1)	32.0 (27.1)	74.0 (6.0)	726.8 (11.5)	0.79

for conversion to SI units:

1 MBTU = 1.055 GJ

1 MBTU/Fday = 1.899 GJ/Cday

x F = (x - 32)/1.8 C

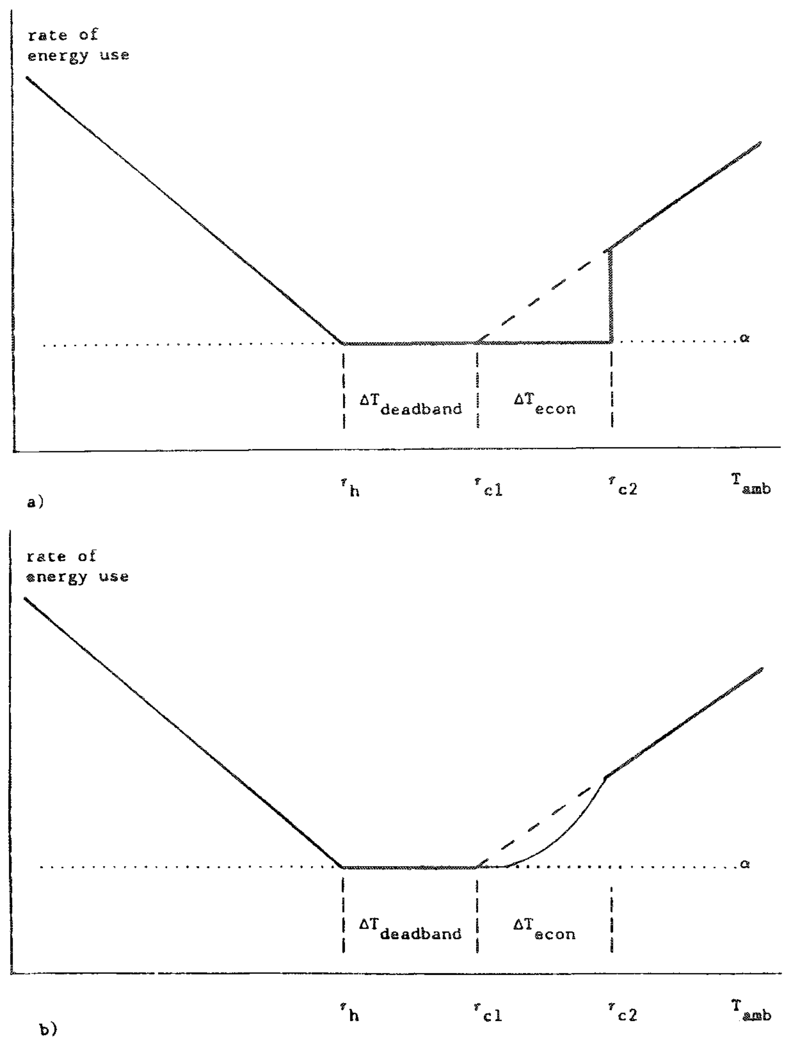


Fig.2.1. Schematic plot of energy (solid line) versus ambient temperature, if baseload α = constant and if open windows (a) or economizer (b) are used in mild weather. $\Delta T_{deadband}$ = difference between thermostat settings for heating and for cooling, τ_{c1} = threshold for cooling without, τ_{c2} with open windows or economizer.

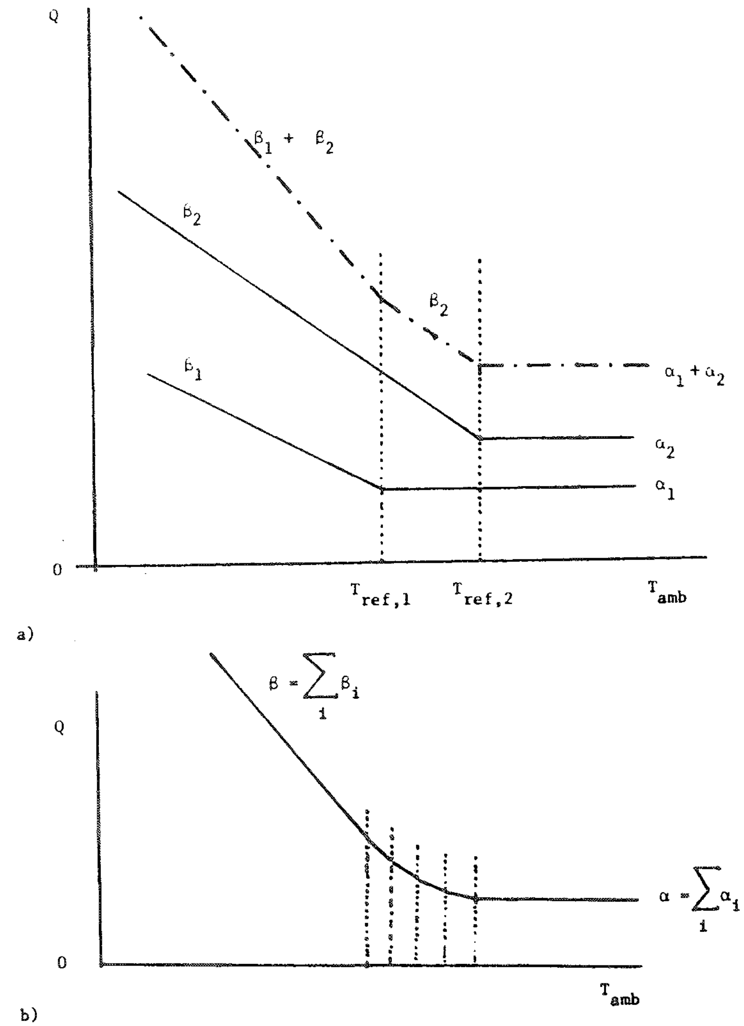


Fig.2.2. Energy consumption as function of T_{amb} for an aggregate of buildings. (a) Two buildings. (b) Many buildings.

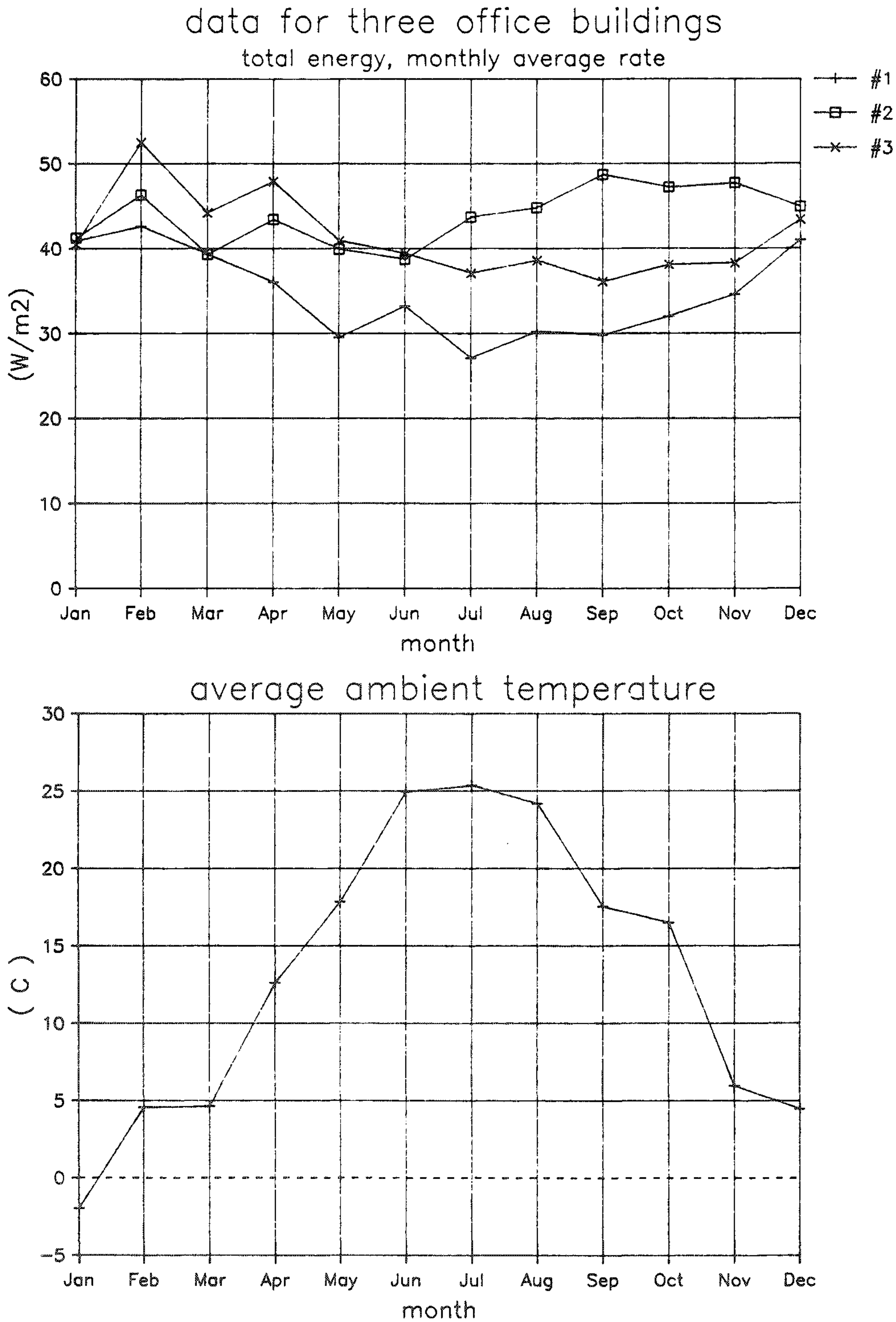


Fig.5.1. Total energy use for three all-electric office buildings in Princeton, built in late the seventies. Plots shows monthly averages for 1984, with corresponding average ambient temperature.

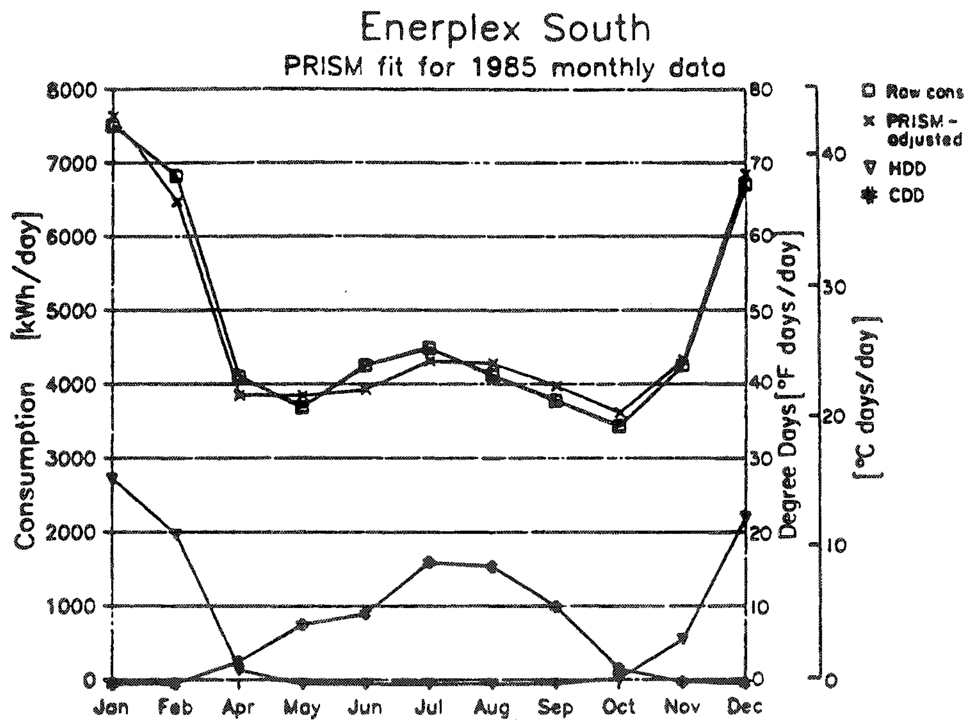


Fig.5.2. PRISM fit to monthly consumption data for Enerplex South Building (all-electric). March has been omitted because of abnormalities in occupant sector. Top curves (left scale) show actual energy and PRISM fit; bottom curves (right scale) show heating and cooling degree days for reference temperatures of PRISM fit.

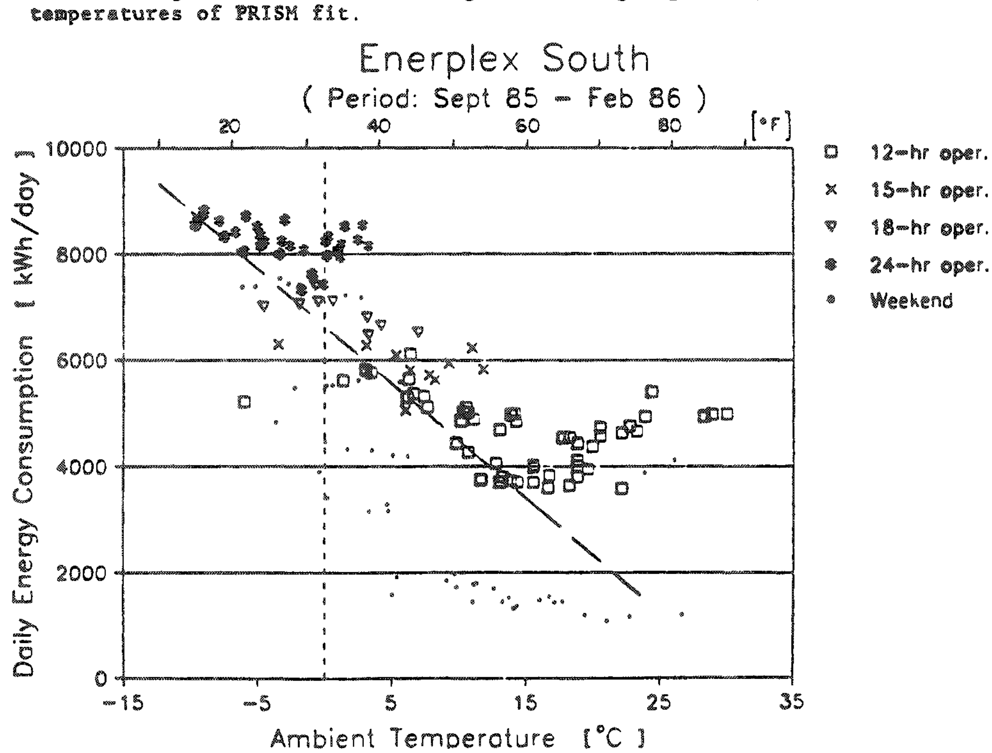


Fig.5.3. Daily average energy use for Enerplex South Building, plotted versus daily average T_{amb}.

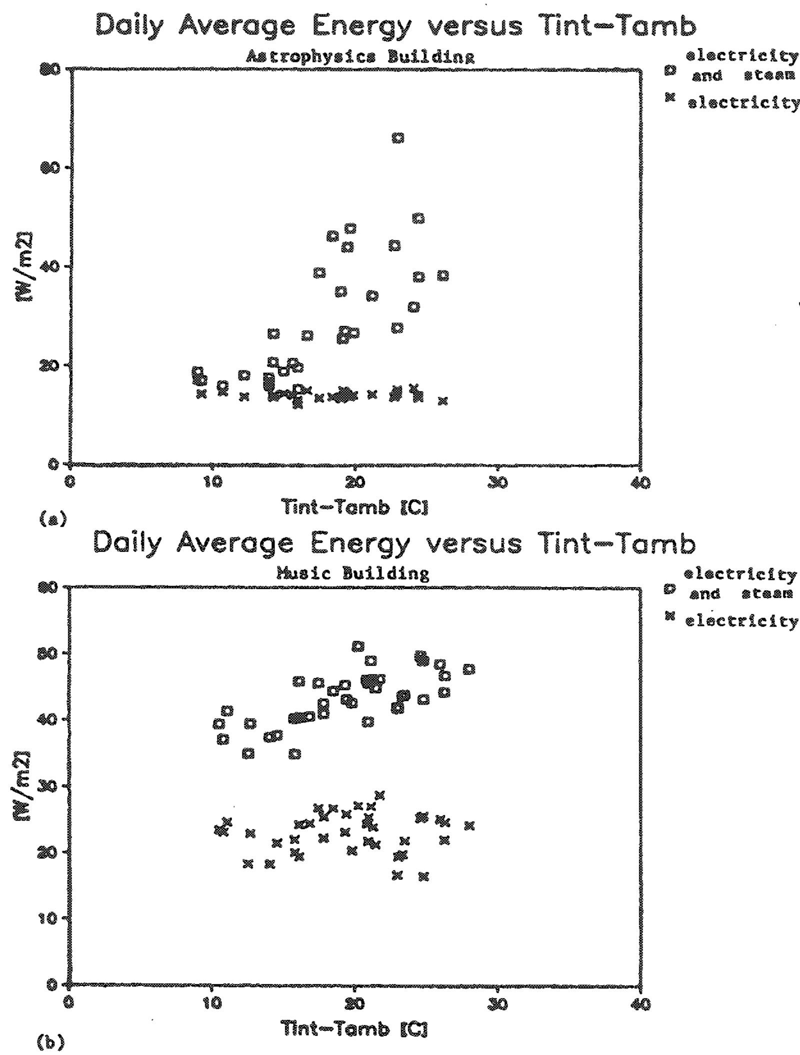


Fig.5.4. Daily average steam and electricity consumption in two buildings on Princeton campus for Jan. and Feb. 1984, plotted versus (T_{int} - T_{amb}). For each day two points are shown: electricity (= cross) and steam + electricity (=square).
(a) Astrophysics Building. (b) Music Building.

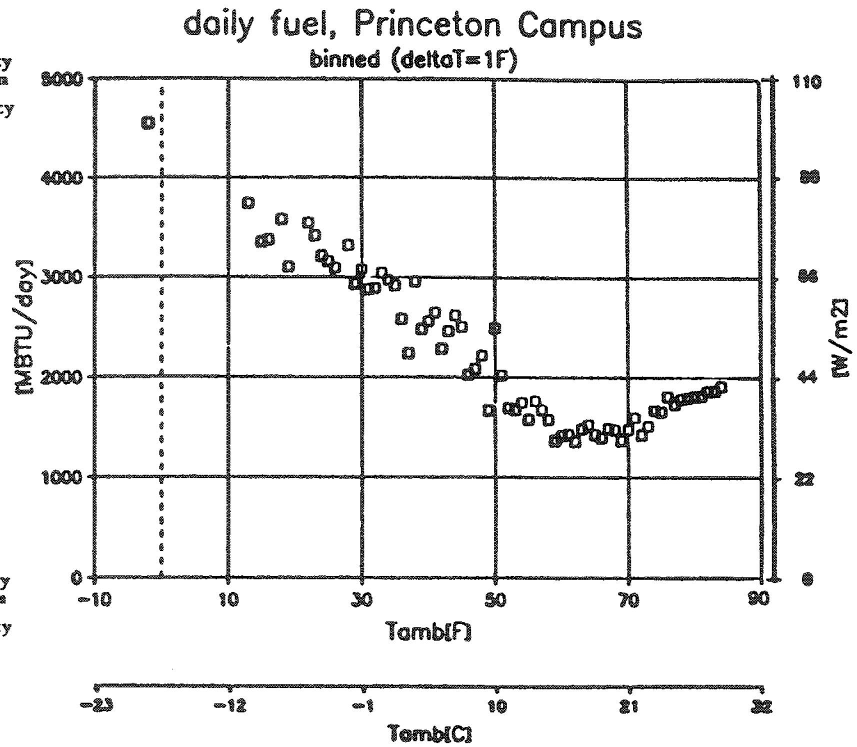
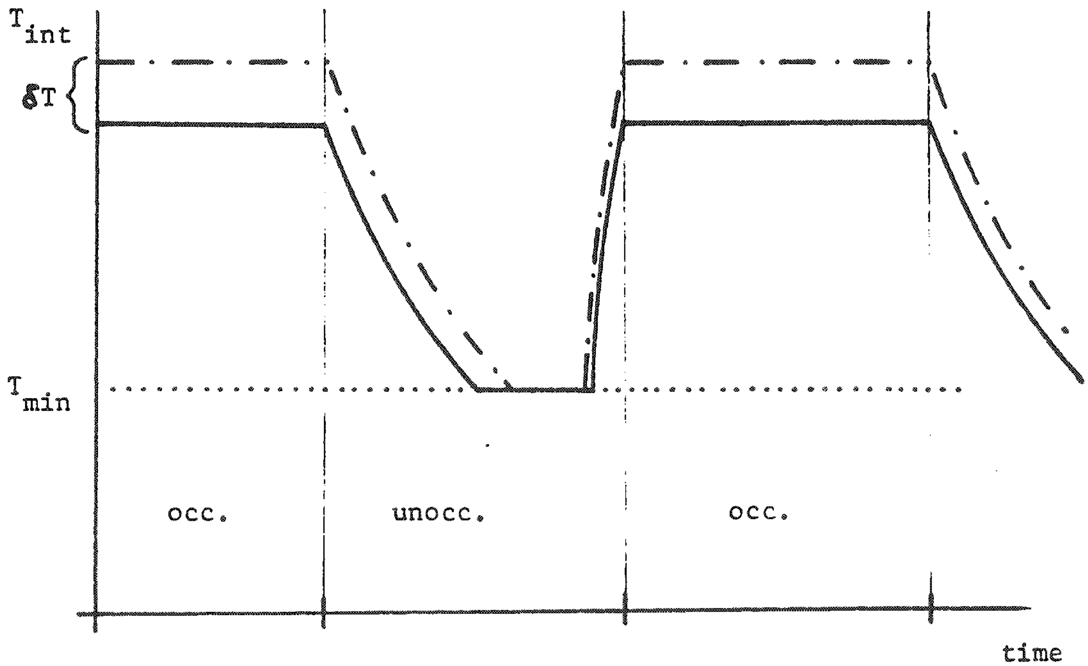
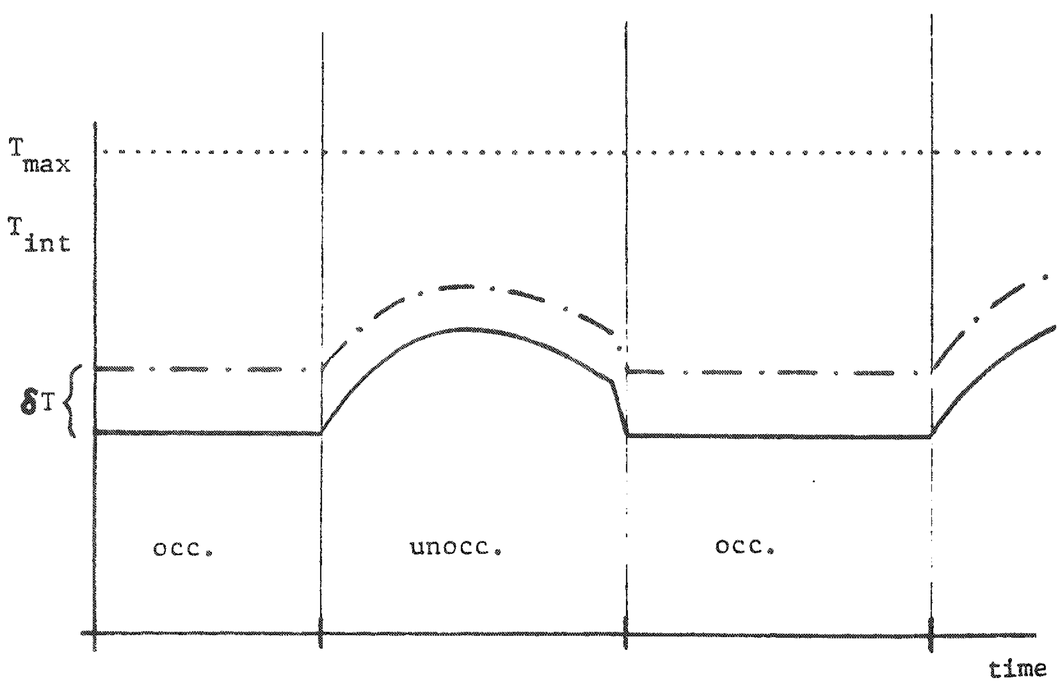


Fig.5.5. Daily fuel consumption versus T_{amb} for Princeton campus, August 1984 - July 1985. averaged within each 1 F interval of T_{amb}. Total building area is 6,000,000 ft2.



a) heating.



b) cooling

Fig.7.1. Typical warmup and cooldown patterns of interior temperature in (a) winter, (b) summer.