THERMAL CHARACTERIZATION BASED ON HIGH TIME RESOLUTION END-USE METERED DATA

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High time resolution electrical end-use data, along with supporting weather and characteristics information, is becoming available from several major metering projects. We have developed a general approach to characterization of residential thermal performance based on such data. Our approach provides:

- Estimates of total annual heating loads under standardized conditions,
- Estimates of the impact of wood heat, temperature control strategy, and other occupant-controlled factors on heating load, and
- Detailed insight into the factors that control heating requirements on a daily basis in single residences or groups of homes.

We begin by deriving a non-parametric relationship between space heating requirements and inside-outside temperature difference from data aggregated to the daily level. The statistical method used is resistant to outliers. Data that is contaminated by wood heat use, or is not reflective of normal occupancy patterns are excluded prior to the fitting process. The resulting model can be used with a reference set of temperature data to derive a standardized measure of annual space heating load. Simple adjustments can be used to permit comparison of homes operated using different control strategies. Because no linear model is imposed, the method can be used for data which does not display an approximate linear relationship between heating load and temperature.

Through analysis of the residuals from the model, we investigate the role of factors other than temperature in determining space heating requirements. Although fitting a multivariate model to the data is conceivable, we find that greater insight can be gained by considering these various factors singly or taken in pairwise combination.

In this paper we present our approach, and illustrate it with examples drawn from the Bonneville Power Administration's End-Use Load and Consumer Assessment Program (ELCAP).

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INTRODUCTION

One of the longstanding problems in building science has been determination of thermal integrity from empirical data. The impact of weatherization programs, for instance, is often assessed in this way, the recent Hood River Project being perhaps the most ambitious example [Hirst, 1987]. Typical practice involves calculating linear fits to plots of billing data versus monthly average temperature. The parameters of the fit are then interpreted in terms of such thermal characteristics as conductive heat loss coefficient (UA), or used directly to compare structures. Very substantial effort has been invested in determining the "best" method for generating these linear fits; much publicized techniques include the Princeton Scorekeeping Method (PRISM) [Fels, 1984] developed at Princeton, and the methods employed in the Building Energy Use Compilation and Analysis projects (BECA) [Goldman, 1985], developed at Lawrence Berkeley Laboratory.

In recent years data sets that provide substantially greater detail than is available in typical electrical billing records have been created, both in terms of temporal resolution and in disaggregation of individual energy end-uses. For instance, the ongoing End-use Load and Consumer Assessment Project (ELCAP) [Schuster, 1985] has, as of April, 1988, resulted in the accumulation of approximately 12,000 building-months of hourly end-use load data. The Hood River project included generation of an extensive end-use data set, and a number of utilities have implemented or are planning end-use metering projects.

Not surprisingly, initial attempts at analysis of detailed data have tended to rely on the traditional approaches. However, the availability of more detailed data sets challenges us to develop techniques that provide more insight than is offered by the linear fitting approaches. It is clearly desirable to develop analytic methods that not only provide accurate characterizations of thermal integrity, but also support explanation or understanding of the results. That is, we wish to know not only how a single structure or group of structures perform on average, but also what factors have influenced that performance. In response to this challenge, we have developed a general approach to thermal analysis that offers significant advantages in dealing with detailed end-use data. Our method provides several useful measures of thermal performance that permit comparison of structures that are

- located in different climates and
- operated with different control strategies.

In addition the method supports quantitative analysis of the role that various factors have in determining performance for single structures or groups of structures. These factors include:

- temperature control strategy,
- the availability of ancillary heat sources (such as wood stoves),
- internal gains,
- meteorological variables such as solar effect, and
- behavior-related variables.

This paper provides an overview of our approach, illustrated with a variety of examples drawn from ELCAP analyses. In order to provide a comprehensive discussion it is necessary to cover a fairly broad range of material. As a result, the level of technical detail included is modest; more detailed discussions of several of the topics treated here may be found in the referenced ELCAP project reports.

BASIC THERMAL ANALYSIS: OVERVIEW AND ILLUSTRATIVE EXAMPLES

In this section we describe our thermal analysis method as it is applied to residences. The method assumes the availability of end-use data at daily or finer time resolution. Application to data at lower time resolution, or to total load data, is possible, but the ability to explore the determinants of energy consumption will be reduced.

Our standard thermal analysis procedure leads to a number of distinct products, as follows:

- Classification (or "daytyping") of each day in the data set on the basis of several criteria, including at a minimum presence or absence of wood stove use, whether or not the structure was occupied, and presence or absence of a thermostat setback.

- An empirical, non-parametric curve representing the observed relationship between daily average inside-outside temperature difference (or outside air temperature, alone) and daily space heating loads,

- One or more estimates of annual space heating energy consumption (AEC) referred to sets of standard weather data and standard operating conditions,

- Parameters of a linear fit to a selected portion of the data, interpretable as effective UA and balance point, and

- The set of residuals of the space heating load data from the empirical temperature-space heating load curve, and estimates of the relationship of those residuals to various explanatory variables.

In the following paragraphs, the techniques used for obtaining each of these products are described, and illustrated with one or more example applications.

Classification by Day Type

Our first step in analysis of the end-use load data is to classify each day (midnight to midnight) on the basis of several factors, including at a minimum wood stove use, occupant temperature control strategy, and whether the structure was occupied or vacant. These classifications have three main uses. First, they are used to determine the frequency with which a particular condition occurs, for instance permitting comparison of the frequency of wood stove use or setback behavior for different groups of residential consumers. Second, they are used to select data that reflect some set of standard operating conditions for further analysis. For example, we estimate the empirical relationship between space heating loads and temperature from data selected to avoid both wood use and periods of vacancy. Finally, through examination of the residuals from the space heat-temperature relationship for days falling into different classes, the impact of different behaviors and control strategies on space heating load can be estimated; this last use is the subject of the residual analysis section to follow.

We have been able to develop automated techniques for daytyping. In working with the ELCAP data set, or other data sets that provide time resolution at the daily level or better, periods in which a residence is effectively vacant can be identified with high reliability from hot water and other appliance load data. Wood stoves are monitored directly in ELCAP and some other studies, so that daytyping on the basis of wood use is straightforward. To date, we have used a simple binary classification (either wood was burned or it was not), but more elaborate classification on the basis of level of wood use is certainly possible. Finally, simple pattern matching techniques can be used to determine the presence of single or multiple setbacks from internal temperature data.

An example of the direct application of daytyping information is given in Figure 1 (taken from LeBaron, 1987). This figure shows the number of days that wood burning equipment was used to supplement the permanent space heating equipment in 68 residences equipped with wood stoves over the 1985-86 heating season. Substantial use of wood to supplement the space heating requirements even in the milder months is apparent; the intensity of wood use varies with the season much as space heating loads vary. The use of the wood stove daytyping information to estimate electrical space heat displacement is discussed in the section on residual analysis.

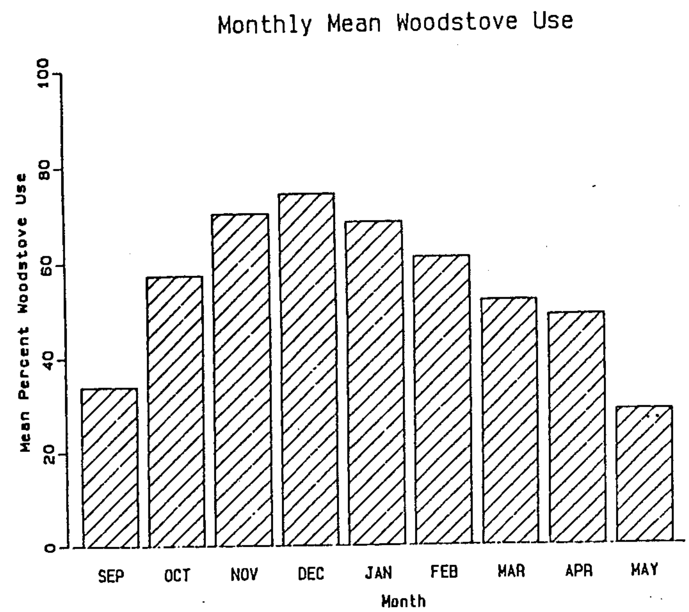


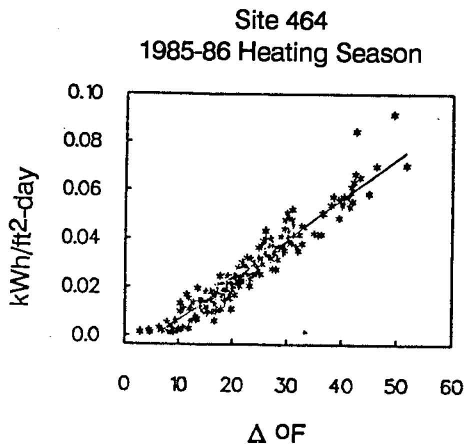
Figure 1. Average monthly woodstove use for 1985-86 for 68 ELCAP homes.

This histogram shows percentage of wood burning days for each month in the heating season averaged across 68 homes. These data along with hourly wood stove usage curves (not shown), indicate that wood stove usage is heaviest at times of high system load, both on a seasonal and a daily basis. Predicting woodstove usage remains one of the problematic forecasting areas for Northwest utilities.

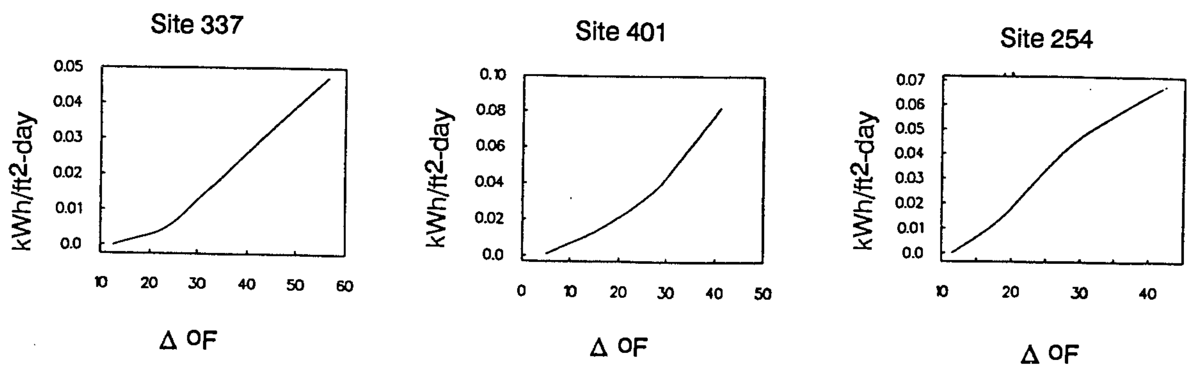
As a final note, preliminary work has suggested that the daytyping approach can be usefully extended to cover additional occupant behaviors. For instance, "laundry days," "dining out" days, "solar days," etc. can be identified from the end-use and meteorological data. Such classifications can be used to investigate the role of different behaviors or climatic conditions in determining energy consumption, or in estimating their effect on demand side conservation strategies.

Empirical Relationship Between Space Heating Loads and Temperature

The key step in our thermal analysis method is computation of a flexible, non-parametric fit to a plot of daily space heating data against either outside temperature or, more frequently, inside-outside temperature difference (Figure 2a). In this fit, extended vacancy periods are not included, and days affected by wood stove use are excluded. The procedure that we use to compute the fit is a locally weighted piecewise regression technique that is resistant to outliers, the so-called "lowess" procedure [Cleveland, 1979]. The resulting curve is an empirical characterization for the relationship between space heating loads and outside temperature in a given residence, under typical occupancy conditions and with no use of ancillary heating equipment. Because the fitting method is resistant to outliers, exceptional events have essentially no impact on the derived curve.



a) The data and the fit.



b) Common non-linearities for 3 sites from the 1986-87 heating season.

Figure 2. The non-parametric fit of daily space heating data (normalized by conditioned floor area) to average daily inside-outside temperature difference for 4 ELCAP homes.

In panel a) the heater load normalized by floor area is plotted versus the inside-outside temperature difference; the resulting fit is quite linear. In panel b) several different shapes are displayed. The daily data points are removed to provide a cleaner display. The non-linear foot in the low temperature difference region occurs when the outside air temperature is near the balance point for the structure.

Site 401 has the characteristic heat pump curvature; site 254 has a concave downward shape or "rolloff" in the high delta temperature region which has shown some relationship to basement foundation types.

One important feature of the resulting curve is that it is model free; no a priori assumptions about the *functional* form of the relationship between space heating loads and outside temperature are made, and the curve can assume any reasonable shape (although sharp discontinuities will be smoothed). As our examples illustrate, this flexibility is necessary to be able to accurately characterize residences under a wide variety of conditions such as:

- structures with nonlinear heating systems such as heat pumps,
- structures with large thermal mass and long time constants, where the structure does not fully respond to transient extremes in temperature, and
- time periods in which the average outside temperature is near the balance point of a structure with substantial diurnal variation about that average.

We also note that residuals from a model free curve will not be affected by the suitability of a fitted model, and, consequently, can be straightforwardly analyzed for dependence on nonthermal variables. This point is illustrated in the residual analysis section later in the paper.

One of the early observations in the ELCAP project was that the curve representing the relation between space heating loads and inside-outside temperature difference exhibited substantial non-linearities for a large fraction of the residences. Figure 2 provides four prototypical examples. As noted above, there are a variety of physical effects that can lead to such non-linear fits, and the ability to handle them is one of the principle strengths of the approach outlined here.

Generation of Standardized Annual Space Heating Load Estimates

On the basis of the lowess fits, we are able to generate estimates of space heating requirements under various sets of standard conditions. The basic idea is to select a standard internal temperature, and to generate a set of inside-outside temperature difference data from the selected inside temperature and reference meteorological data set. The non-parametric curve is then used to generate space heating estimates for each day from the temperature difference data. By summing these estimates over a heating season, a standardized annual energy consumption (AEC) is obtained:

$$AEC = \Sigma\ H(T - TMY_i)$$

where $H(\Delta t)$ is the empirical relationship between space heating load and inside-outside temperature, T is the assumed average inside air temperature over the heating season and TMY_i is the mean outside air temperature for the "ith" day from the selected weather year. These estimates represent empirically based predictions of the space heating requirement for a residence assuming a particular average inside temperature, a standard set of weather data, continuous occupancy, and no use of wood stoves or other non-electric space heating devices.

The AEC estimates permit direct comparison of thermal performance for structures operated under very different conditions. Although the weather adjustment is incomplete (no accommodation for differences in solar effects is made), as is the adjustment to standard occupant behavior (different levels of internal gains are not incorporated), the resulting AEC measure has proved to be extremely powerful for determining the relative performance of different groups of residences. Of course, more elaborate versions of this approach, incorporating additional standardization (as for solar gains and internal gains) are possible.

One example of the use of these AEC estimates is presented in Figure 3. AECs were generated from end-use metering data for a number of houses constructed under the Bonneville Power Administration's Residential Standards Demonstration Program (RSDP). By referring all of the structures to standard reference climates and temperature control strategies, an enlightening comparison of homes constructed to a very aggressive conservation standard with homes constructed to current practice and the existing residential stock was possible [Drost, 1987; Miller, 1987].

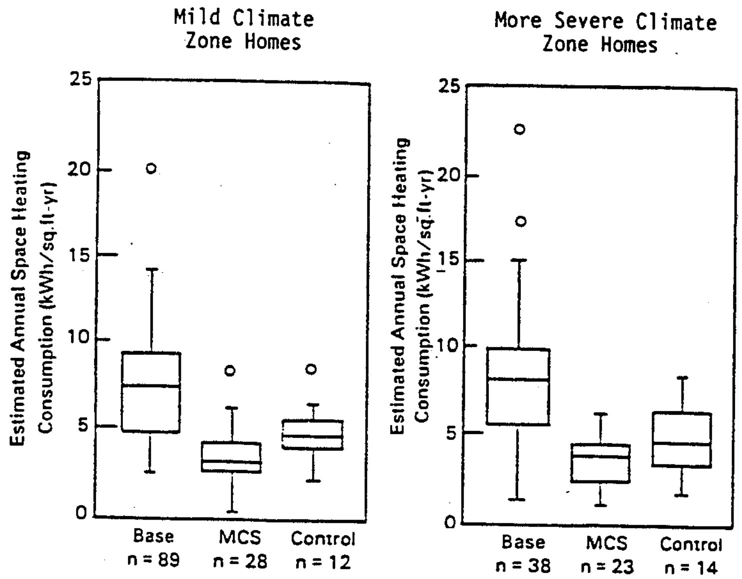


Figure 3. Annual space heating estimates for 204 ELCAP homes from several climate zones split by dwelling types.

AEC distributions are shown for 3 groups of ELCAP monitored structures in Figure 3. Use of AECs allows a powerful comparison of heating requirements across classes and climate zones. The Base homes are roughly representative of the single-family stock of existing homes in the Bonneville service territory. The MCS and Control homes were built as part of the Residential Standards Demonstration Project. The MCS homes were built to the Model Conservation Standards--an aggressive set of proposed building codes; the Control homes were built to represent current building practice. The middle line within each box represents the median datapoint in each distribution. The bottom and top of the box delimits the first and third quartile breaks. The "whiskers" extend to the extremes of the distributions; the most extreme outliers are shown as isolated points. Median MCS consumption estimates are about half that of the Base homes with the Control homes falling in between. This result is true across climate zones.

Generation and Application of Linear Fit

The lowess fits and associated AECs provide our principle characterization of thermal performance. However, we also compute linear fits to the space heating load-temperature data over whatever temperature regime appears well characterized by such fits. In computing the linear fits we make use of an iterative technique that is, again, resistant to outliers. Thus the fit is not affected by isolated data points caused by, for instance, such things as abrupt changes in thermostat set point, furnace repair, and so forth. Selection of the temperature regime over which a linear fit appears reasonable is an automated process, involving repeated expansion of the candidate region and calculation of the resulting rate of change in the fit parameters. As is usually the case, slopes are interpreted in terms of effective shell UA and furnace efficiency, and intercepts in terms of balance points. Comparison of these parameters with UAs calculated using the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) methodology [Conner, 1987] have provided some interesting insight into the role that operation strategy plays in determining thermal performance [Miller, 1987].

As an example, use of the AEC, in conjunction with the ASHRAE calculated UA, provides a way to study the efficiency of heating systems as actually operated in the structure. In Figure 4 the heating system efficiencies of approximately 50 structures are compared for several types of space heating equipment. The comparison index for each site is computed by dividing the AEC by the product of the ASHRAE based UA and effective heating degree days (HDD) for the reference year. The balance point from the linear fit for each structure and the standard weather year are used to compute effective heating degree days for each site. The ease of zoning and absence of duct losses are presumed to account for the superior performance of the baseboard and radiant ceiling homes compared to the forced air homes.

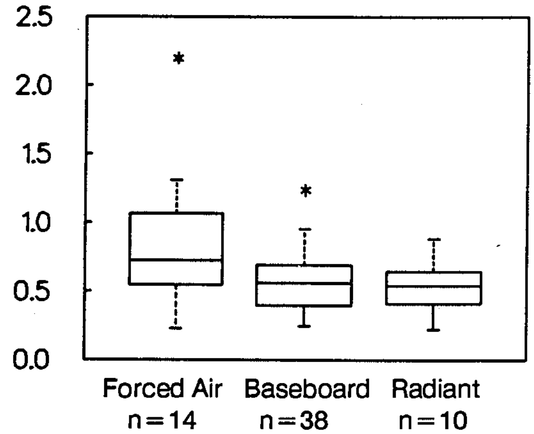


Figure 4. As-operated heating system comparisons (AEC/[UA*HDD]) for 62 ELCAP homes in the colder climate zones.

For each home the AEC is divided by the product of UA (ASHRAE type calculation computed from survey data) and effective heating degree days. The effective heating degree days are computed for each site using the standard weather year and the structure's balance point. Ease of zoning and absence of duct losses presumably account for the lower ratio observed in general for the zonal control systems.

Residual Analysis

For a given building and climate, both daily and annual space heating loads can vary dramatically depending on such factors as the use of wood stoves or other non-electric space heating devices, internal gains, temperature control strategy (e.g. the use of setbacks or zoning), and many others. We investigate the impact of these factors on space heating loads through examination of the residuals between individual data points and the non-parametric space heat-temperature relation. As illustrations of this procedure, we consider the displacement of electrical space heat by wood use, and the role of solar loads in determining space heating loads.

Figure 5 shows the various stages of the wood heat analysis in its simplest form. Individual days are classified on the basis of whether or not the wood stove is used, and the lowess curve is fit to data for only those days in which the wood stove is not used. The difference between the space heating load measured on wood burning days and the space heating load predicted from the lowess curve and the measured outside temperature gives an immediate estimate of the space heat displacement. Summing these estimates over the heating season yields an annual displacement estimate. The very simple procedure illustrated here depends for its success on the fact that there are a sufficient number of data points for non-wood burning days to permit a reliable empirical characterization of the structure; for households in which wood use is very frequent, more sophisticated techniques are required.

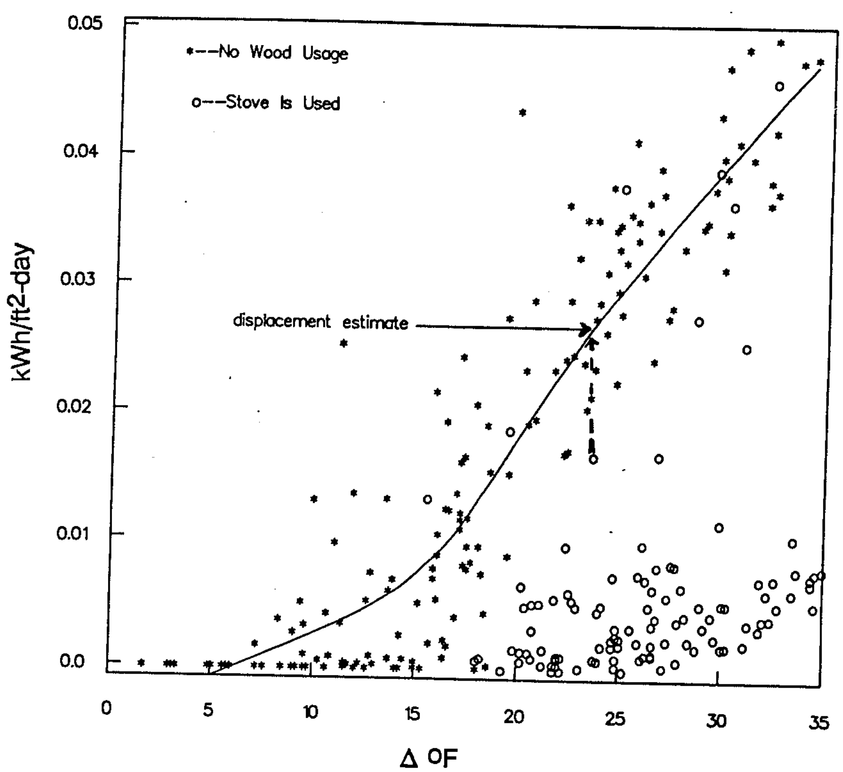
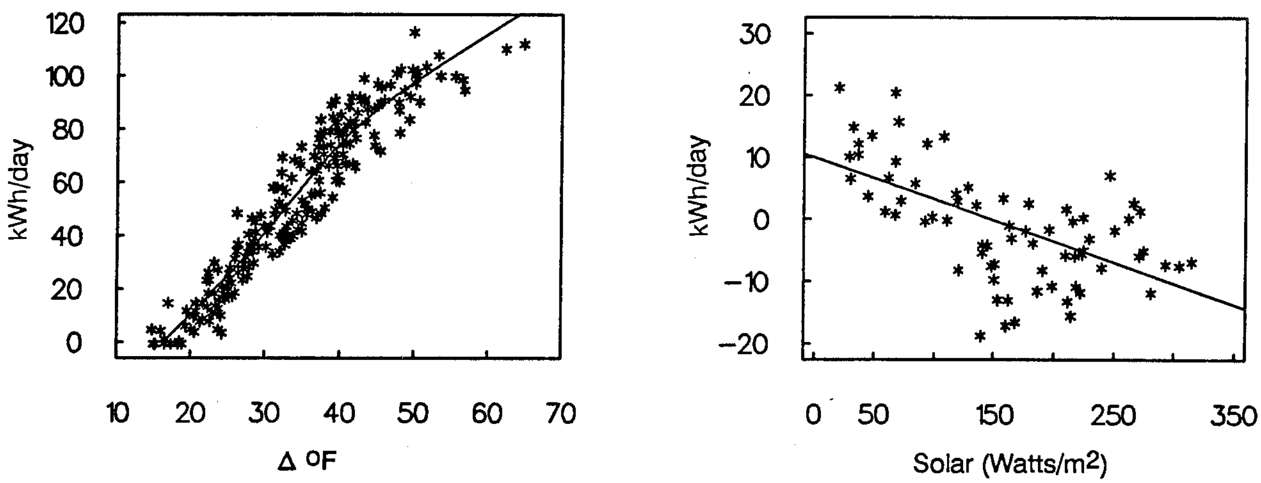


Figure 5. Daytyping for wood use for a single residential heating season.

In this plot days of wood stove use are differentiated from days of total electric heat for space conditioning. The space heating displacement estimate for days on which the wood stove was used is computed from the lowess fit, generated from days of non-wood usage. For this home the total annual load (from the metered data) on wood burning days is 1,322 kWh, the total annual load on non-wood days is 5366 kWh (from the metered data). Using the lowess curve, the total annual estimated heating requirements for the days with wood use is 5866 kWh. This estimate assumes that only the electrical heating equipment is used. Hence the wood stove has replaced about 4,544 kWh/yr of electrical demand for space heat.

It is, of course, true that the daily estimates obtained in this way are subject to the same variability as the initial data. However, because the impact of wood usage on space heating consumption is a dominant effect, it is possible to obtain reasonable estimates of the impact of wood use without taking into account variation in the other factors affecting space heating loads. More generally, it is possible to carry out a multivariate analysis, in which the effects of a variety of factors are considered simultaneously; we are in the process of investigating a number of important questions using this technique. The key point is that the lowess curve provides a measure of typical heating load as a function of temperature. Consequently, the residuals can in fact be directly analyzed to measure the impact of occupant behavior and other factors.

Figure 6 gives an illustrative example from a study of the impact of solar loads on electrical space heating requirements. For the particular home shown 50% of the variance in the residuals from the non-parametric fit of space heat to inside-outside temperature difference is explained by daily solar effects over the heating season. There should in general be no contribution to the residuals from having forced the data to fit an incorrect model.



a) Original data and fit for 1986-87 heating season

b) Residuals from Mar-May 1987 plotted versus mean daily insolation

Figure 6. Using the solar load to explain residuals from the non-parametric fit of daily space heat to mean daily inside-outside temperature difference.

Panel a) displays the daily space heat load versus inside-outside temperature difference. In the adjacent panel b), the deviation of actual space heating load from the "lowess" curve is plotted versus mean daily solar data for days in the spring of 1987. Over the entire heating season, the solar data explain up to 50% of the variation in the residuals from the original fit for this site.

SUMMARY AND CONCLUSIONS

Over the past few years, it has become clear to us that standard methods of thermal performance characterization do not fully exploit the opportunities offered by high time resolution end-use data. The most important failing is that they do not readily support investigation of the role played by the potential behavioral determinants of space heating load. Of almost equal significance is that imposition of a linear model over the entire temperature regime to which structures are exposed during a heating season is not appropriate for many buildings.

In response to the availability of end-use data from ELCAP, Hood River, and other end-use metering projects, we have developed what appears to be a very powerful approach to thermal analysis. The key features of this approach are:

- No assumptions are made about the functional relationship between inside-outside temperature difference and space heating loads rather only that some relationship exists,
- The techniques used are resistant to the effects of outlying data points, so that typical performance is accurately captured,
- It permits comparison of the thermal performance of structures operated in different climates and with different control strategies, and
- It supports investigation of the role of behavioral factors in determining space heating loads as deviations from the typical performance are studied.

We have carried out a number of investigations using the general approach, and results are in preparation for formal publication. It is not possible in the space available here to provide more than a brief overview and a few illustrative examples. However, our experience strongly suggests that approaches of the sort outlined in this paper have enormous value in extracting the information content of electrical load data. In particular, because behavioral factors represent one of the largest uncertainties in load forecasting and conservation planning, the ability to quantitatively determine their impacts on space heating loads is crucial.

ACKNOWLEDGEMENT

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