Determining the Impact of Residential Gas Furnaces on Utilities with Applications to Other End Uses

by

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ABSTRACT

The effort of utilities to avoid building new generating plants and more efficiently produce energy through slowing the increase of peak demand is known as Demand Side Management (DSM). A key factor in the expansion of DSM is accuracy in predicting the impact of various DSM efforts, but universal standards for the calculation of peak demand reduction do not exist. This thesis describes the development and testing of simulation methodologies for determining the energy and peak load impact on electric or gas utilities of the introduction of new technologies.

A FORTRAN program has been written to simulate the impact of a large number of systems on a utility using both temperature level control and energy rate control. Residential gas furnaces are being examined because data from monitored homes is available for comparison with the simulated results. Simulations have been performed with the actual weather data from the metered period. The parameters of internal set point temperatures, loss coefficient, furnace size, and furnace efficiency for each house are taken from normal distributions created with the average and standard deviation of the parameters as determined from the house monitoring study.

Reasonable agreement has been found between simulated and metered average and peak gas use of equal numbers of systems once obvious errors in the metered data

were removed. The agreement between the simulated and measured average use and demand of an ensemble for relatively low (<100) numbers of systems provides confidence in the results of a large number of simulated systems.

A single simulation of a house with the average house characteristics provides a reasonable estimate of the amount of energy used in a day but over-predicts the peak power use of the house. A single simulation of a house with the average house parameters using energy rate control (ERC) matches very closely the average of a large number (≥1000) of thermostat controlled simulations. However, an ERC simulation under-predicts the impact on power demand of changes in internal set point temperature due to night set back because it neglects the thermal capacitance of the house by assuming the internal house temperature is always equal to the thermostat set point. An energy rate control simulation, however, can be performed much more easily than large numbers of temperature level controlled simulations.

The analysis of simulation methodologies is directly applicable to determining the gas or electric utility demand and energy impact of a large number of residential air conditioners and/or solar heating systems. By providing an assessment of methods for predicting the impact of specific end uses on the utility peak load, this work could potentially increase the vigor with which utilities pursue DSM programs.

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The students in the Lab have made my time here enjoyable as well as informative. I can't imagine getting through the long hours of work without people to complain about it with. There have been too many good times to start listing. Thanks to the students that were here before me: Jurgen, Oystein, Bob, Al, Colin, Dean, Dick, Doug, Jorg, Martin, Matthias, Steve, Svein, Tammy, and Todd for passing along the Lab traditions and to the new students: John and John, Kevin, Eric, and Keary who will continue them. Special thanks go out to the students who started here with me: Barrett, Gerold, Mike, Nate, and Tim. I am proud to know you and count you among my friends.

Thanks to my family for their support and reassurance. Mom and Dad always told me I could accomplish anything I put my mind to; I am grateful for that and many other lessons. I finally wish to thank Jenifer for all your help and love. I don't know if I could have done it without you.

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NOMENCLATURE

ROMAN SYMBOLS

Symbol	Definition
A	intercept from WGC regression
B	slope from WGC regression
base	base load of a house determined by WGC
Btuh	Btu/hour
C	house thermal capacitance
cfh	cubic feet of gas per hour
COP	coefficient of performance
c_{pa}	specific heat of air
DSM	demand side management
ERC	energy rate control
$\overline{\text{gains}}$	constant gains of house
h_{si}	outside heat transfer coefficient of house
i_{fg}	heat of condensation of water
I_T	total irradiation on a horizontal surface
kbtu	1000 Btu

ROMAN SYMBOLS cont.

Symbol	Definition
$\dot{m}$	mass flow rate of air due to infiltration
P	electrical power
Q_c	cooling load
Q_{htg}	power output of furnace
RMD	remote metering device
SDHW	solar domestic hot water
$\overline{T}_{amb}$	average ambient temperature for a day
T_{amb}	ambient temperature
T_{bal}	house balance temperature
TOU	time of use
T_R	internal temperature of house
$\overline{T}_R$	average internal temperature of a house for a day
T_{Rhigh}	upper limit of thermostat dead band
T_{Rlow}	lower limit of thermostat dead band
T_{sa}	sol-air temperature
T_{sb}	thermostat set point at night (set back value)
T_{set}	thermostat set point
T_{sp}	thermostat day time set point
TLC	temperature level control
UA	thermal loss coefficient
Use_{htg}	gas use rate of furnace

ROMAN SYMBOLS cont.

Symbol	Definition
w_{amb}	humidity ratio of ambient air
WGC	Wisconsin Gas Company
w_R	humidity ratio of interior air

GREEK SYMBOLS

Symbol	Definition
α	solar absorptance
η	furnace efficiency
λ	furnace control variable
τ	furnace operating time

SUBSCRIPTS

Symbol	Definition
∞	steady state value
i	one of a series

SUPERSCRIPTS

Symbol	Definition
+	quantity included in series only if value is positive

CHAPTER ONE

INTRODUCTION

The efforts of utilities to influence the timing and quantity of energy consumed by their customers in order to reduce peak demand are known as Demand Side Management (DSM). DSM programs allow for more efficient power generation and can postpone the construction of new generating plants. In order to determine the appropriateness of DSM measures, it is necessary to accurately estimate the impact of the program on the utility load profile. Both the magnitude and timing of the energy impact are important. If a rebate were to be given to a single customer for a high efficiency device, the impact on the utility, however minor, could be easily determined with a simulation. Because the individual systems will each behave somewhat differently, the impact of a large number of systems is not simply the product of the single system impact and the number of systems as shown by Grater [1991]. The impact of a large number of systems is more difficult to estimate but is the necessary information to determine the impact of a DSM measure, as these programs typically involve promoting large numbers of systems.

The goal of this research is to develop and test a simulation methodology for determining the energy and peak load impact on electric or gas utilities of the introduction of new technologies. The situation of gas furnace use on a gas utility is studied first because monitored data on house gas use is available to verify a model. The results are then extended to residential air conditioning.

A FORTRAN program will be written to simulate the impact of a large number of systems on a utility. The first example systems examined in this thesis are residential gas furnaces because data from monitored homes is available for comparison with the simulated results. Simulations will be performed using both temperature level control (TLC) and energy rate control (ERC). Temperature level control models the thermostat control used in residences. Energy rate control constantly alters the furnace output to meet the heating load. The actual weather data from the metered period and the average values of the house parameters of internal set point temperatures, loss coefficient, furnace size, and furnace efficiency will be the inputs to the program.

A single simulation of a house with the average house parameters using energy rate control (ERC) will be compared to the average of a large number (≥1000) of temperature level controlled simulations. Each house in the TLC simulations is different, but the house characteristics are drawn from normal distributions created with the average and standard deviation of the characteristics as determined form the monitoring study.

The strengths and limitations of the two control schemes will be discussed and a simulation methodology recommended. The proposed simulation methodology will also be applicable to determining the gas or electric utility demand and energy impact of a large number of other systems such as residential air conditioners or solar heating systems. By providing an assessment of simulation methodologies for predicting the impact of specific end uses on the utility peak load, this work could aid utilities in accurately assessing DSM programs. Such an outcome would be beneficial to both utilities and their customers, as flattened load curves allow for more efficient power generation. Additionally, many systems that are either highly efficient or use alternative fuels but are expensive relative to conventional systems may become economically viable when subsidized by utilities as components of DSM programs.

CHAPTER TWO

BACKGROUND

The load on a utility varies considerably throughout the year and a utility is responsible for meeting the energy needs of its customers at all times. The required generating capacity of an electric utility is thus governed by the peak demand experienced during the year. Many utilities are faced with a steadily increasing yearly energy load; in order to meet an increasing yearly load, electric utilities must periodically build new generating facilities or develop methods to slow the increase of the peak demand relative to yearly load, thus "flattening" the load curve. Traditionally, utilities have almost exclusively utilized supply-side resources by simply building new generation capacity to supply the ever increasing energy use of their customers. The efforts of utilities to meet the energy needs of their customers through manipulating the use of the customers are known as demand-side management and are receiving increasing attention from utilities and public service commissions.

2.1 Incentives for Demand-Side Management

2.1.1 Electric Utilities

There are increasingly strong pressures, both economic and regulatory, on electric utilities to examine demand-side options. Many public service commissions, including Wisconsin's [PSCW, 1991], are now mandating that utilities practice Least Cost Management; balancing supply side and demand side management options to minimize energy costs [NARUC, 1993].

The utility daily demand curve shown in Figure 2.1.1 is typical for an electric utility in the United States. Due to the demands of air conditioning systems, the demand for electricity is highest in the afternoons of the summer months. The peak demand for the utility in the example occurred at 3:00 p.m. Although, the space conditioning load is greatest in the winter, the peak load for electricity occurs in the summer, because most cooling is performed with electricity while most heating is not.

A plot of the demand for power as a function of time within a utility district is known as a utility demand curve. The ordinate is the power demand as a percentage of the utility's peak load and is known as the load factor [Carpenter et al., 1991]. An alternative way to present the load on the utility is with a ordered frequency distribution, shown in Figure 2.1.2, in which the load is placed in descending order. The abscissa is the number of hours for which the load is greater than or equal to the load at that point. The peak load for the period is the left most value, and the minimum value is the right most. All information about the chronological order of the use is lost in an ordered frequency distribution.

As indicated in Figure 2.1.1, the load on an electric utility can be divided into base, intermediate, and peak loads based on the load factor. Utilities can meet the base and intermediate loads very efficiently using nuclear, hydroelectric, or large coal burning facilities which are inexpensive options [Carpenter et al., 1991]. Peak load must be met with small plants that can be brought on-line with little notice and are typically inefficient oil or gas turbines.

The significant results of reducing peak load are lower fuel costs because of the higher efficiency of base load plants and that building new generating capacity can be avoided. A new power plant is extremely expensive to build and can involve a lengthy public approval period. Significant expenditures may be justified to slow or reverse the increase of peak demand and thus postpone the need for adding generating capacity.

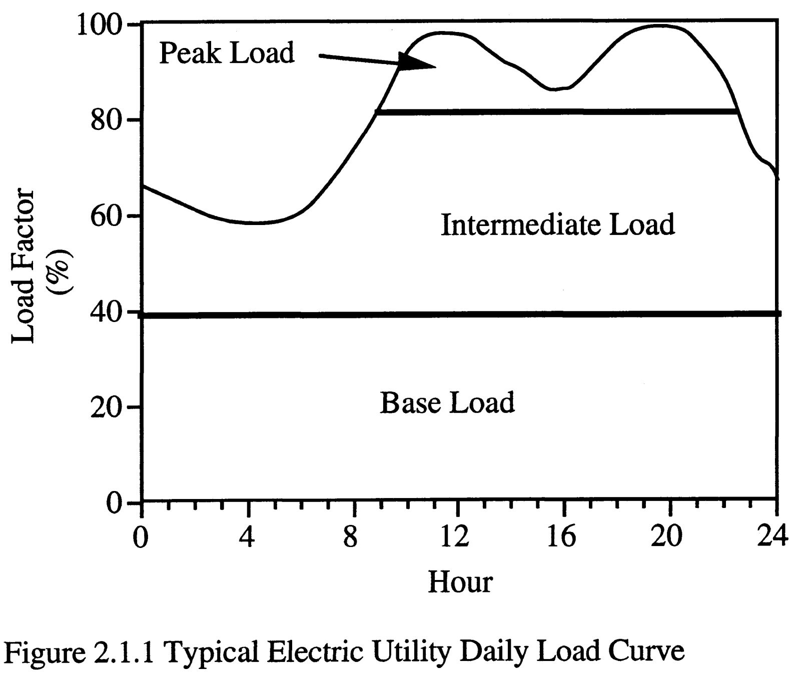


Figure 2.1.1 Typical Electric Utility Daily Load Curve

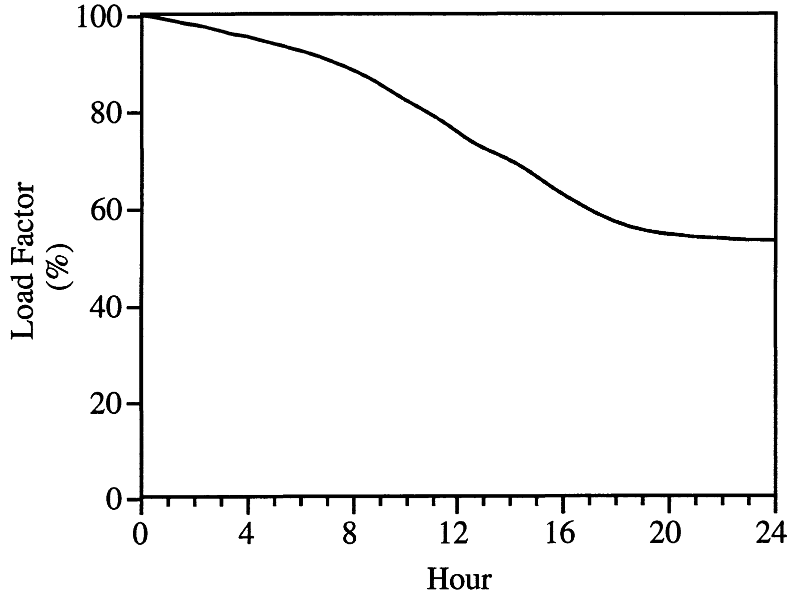


Figure 2.1.2 Ordered frequency distribution of typical electric utility daily load curve

2.1.2 Gas Utilities

The incentives for natural gas utilities to utilize demand-side options are generally less pressing than for electric utilities but are increasing in importance. The prices gas utilities pay to suppliers for gas are often seasonally dependent. There is thus incentive to shift gas use to periods in which the cost to the utility is lower. More importantly, gas utilities typically sign contracts with suppliers several years ahead of time for the amount and timing of gas to be purchased, and significant economic penalties are involved in using more or less gas than was agreed. Gas utilities must thus be careful in predicting gas use, especially for a peak day. Demand side management programs that reduce the peak day demand reduce the chance that the utility will be required by its customers to provide more gas than had been contracted with the suppliers.

2.2 Demand-Side Management Methods

The primary demand-side management strategies are education, load shifting, rebates, and time of use rate schedules. Education can involve sponsoring commercials that advertise the merits of conserving energy. Such issues as the environment, lower energy prices, and decreased reliance on foreign oil may be stressed. Utilities frequently enter into contracts with customers to automatically shift the customers load whereby they compensate the customer for installing equipment to turn off the customer's system during peak times. The compensation is frequently in the form of a reduced "interruptable service rate" for those customers in the program. This strategy is very commonly used with large industrial customers and residential air conditioners. Over 75% and 65% of electric and gas utilities, respectively, offer interruptable service rates [GRI]. Rebates are funds paid to customers to subsidize the purchase of products that are expected to improve the utility demand curve such as energy efficient appliances or added insulation. Rebates for the purchase of compact fluorescent light bulbs are a familiar example. "Time of use" (TOU) rates charge customers different rates for their energy use depending on the timing of the use to provide an incentive for customers to shift energy use from peak times. Frequently, more will be charged for electricity during typical work hours than at night. Seasonal TOU rates are also common. It is noteworthy that some gas utilities offer lower rates in the summer while others offer lower rates in the winter. The factors which influence a utility's decision to shift load thus vary widely between utilities.

2.3 DSM Program Planning and Evaluation

Demand Side Management programs attempt to flatten the utility demand curve. To do this, the peak load can simply be reduced or the peak load can be shifted to off peak times. The latter method is generally preferred by utilities, because the total amount of energy sold is higher.

A literature search to determine the load forecasting methods currently employed by utilities revealed numerous sources on demand side management but very little on load forecasting techniques involving simulations of end use technologies. Several studies have focused on the demand and energy impact of solar domestic hot water (SDHW) systems as components of DSM programs. Studies by Grater [1991] and Beckman et al. [1993] of the impact of SDHW systems on electric utilities involved large numbers of simulations. A study by Carpenter et al. [1991] involved yearly simulations of single SDHW systems. The peak load impact of an ensemble of systems was estimated by statistically analyzing the coincidence of the power consumed by a single system and the utility load curve. Also, several studies [Ewert, 1991; Sim, 1991; Askey, 1984; Vliet, 1985] have monitored samples of SDHW systems installed in residences. No studies on the impact of a large number of space conditioning systems as determined through simulation were found.

Plans for DSM programs necessarily involve both economic and engineering estimates. The economic gain for a utility, and the corresponding appropriate rebate or rate reduction, of a reduction in peak load is determined through economic models that include, for example, the offset cost of building new power plants, lost revenues, and costs of production. The predicted impact on peak load of a program that involves promoting a specific end use is typically determined in two parts. First, the energy reduction of the end use is estimated from the difference in efficiency and the number of systems to be installed. Second, the percentage of those systems operating in the peak period is estimated with a coincidence factor. The determination of coincidence factors seems to be an inexact science, and the precise method varies between utilities.

CHAPTER
THREE

GAS USE OF MONITORED FURNACES

Several years ago (1989), the Wisconsin Gas Company (WGC) undertook a project to determine the load shape of residential gas furnaces. The primary goal was to determine the impact of the load shape, magnitude and timing, of several demand side management schemes, particularly high efficiency furnaces, on the gas use of households. The study involved obtaining information on the characteristics of a sample of houses and then monitoring the gas use of each house in the sample over several heating seasons.

3.1 Monitoring Procedure

Whole house, as opposed to end use specific, gas consumption data was recorded with remote metering devices (RMDs). These devices attach to the house's gas meter, record gas consumption for several five minute periods, and then telephone the data in to a central data acquisition unit. The consumption data is recorded in units of cubic feet of gas at five minute intervals. The RMD counts ticks of the gas meter, so the recorded use for a five minute period is not exactly the use for the period. If half a cubic foot of gas is used in the 5 minute period, but the meter counted a tick near the end of the previous period; the recorded use for the period will be zero. Errors of plus or minus one cubic foot per 5 minutes are thus possible with this system. Whole house data was recorded to avoid the added expense and inconvenience to customers of installing submeters on internal gas lines. Whole house data gives the use of the furnace, hot water heater, stove, and any other gas consuming devices within the house.

3.2 Extent of Information

The information received from the WGC study consists of two separate files: a large, 91 Mb as received, data file of RMD recorded 5 minute consumption data and a spreadsheet of house parameters. The data is from a monitoring study of approximately 100 homes with gas furnaces, but reliable data does not exists for all houses. Some of the metered houses are not included in the house parameter file, and some of the houses in the parameter file are not in the metered file. Only approximately 20 of the houses could be definitively determined to exist in both data files.

The spreadsheet of house characteristics contains data for 80 houses although 5 minute metered data could not be definitively assigned to many of the houses. Some of the parameters are missing for some houses, and not all the parameters were used in the simulations to be explained later. Table 3.2.1 below shows the relevant house characteristics that were determined in the survey. The parameters used from the survey data in the simulation program were the furnace size, furnace efficiency, thermostat day setting, thermostat night setting, house floor area, and three results of data analysis performed by Wisconsin Gas Company: slope, intercept, and base load. The Appendix gives a slightly modified version of the house characteristics data file.

Table 3.2.1: House parameters determined in WGC survey

PARAMETER	UNITS
Design Cooling Load	kbtu/hr
Design Heating Load	kbtu/hr
Total Floor Area	ft^2
Overall Wall R-Value	F-ft^2/Btuh
Wall Net Area	ft^2
Overall Glazing R-Value	F-ft^2/Btuh
Glazing Total Area	ft^2
Overall Roof R-Values	F-ft^2/Btuh
Roof Total Area	ft^2
Furnace Input Size	kbtu/hr
Furnace Steady State Efficiency	%
Thermostat Setting	F
Setback Setting	F
Number of People in House	
Base load	Therms per month
Slope	cfh/F
Intercept	cfh
Annual Heating Usage	Therms
Actual Peak Day Usage	cu.ft.

The intercept (A) and slope (B) for each house are the result of a regression analysis of the daily average whole house gas use versus the daily average ambient temperature. The average gas use for a house is characterized by

$$Use = A + B\overline{T}_{amb} \qquad (3.2.1)$$

The slope is thus a measure of the loss coefficient of the house and the intercept is the predicted average gas use of the house on a day with an average ambient temperature of 0 °F. The whole house gas use includes furnace use and a base load which is due to such uses as gas stoves and gas hot water heaters. The estimation of base load was "by means of monthly billing data or by means of RMD consumption figures in the summer months" [WGC, 1993]. The gas use of each house furnace for a given ambient temperature is given by

$$Use_{htg} = A + B\overline{T}_{amb} - base \qquad (3.2.2)$$

The five minute metering data is for 117 days during the 89-90 and 90-91 heating seasons. With five minute data, the actual gas draw of the ensemble as a function of time throughout the day for days of different weather conditions can be determined. The number of houses for which data exists for each day varies from 94 to 1 as shown below, but house characteristics could not be found for most of the houses. The small number of houses for some of the early days is due to not all RMDs having been installed. The variation among later dates may be due to some RMDs malfunctioning and then being repaired or replaced. The RMDs were removed from four houses near the beginning of the study due to incompatibility with the customer's telephone equipment.

Another two units malfunctioned early in the study but were promptly replaced. An inspection in the summer of 1990 of 90 units found 3 units to be inoperable and another 5 units miscounting [WGC, 1993]. It is unclear what was done with these units and the data from these units may be in the monitored file. The number of accounts for which data exist for each day is shown in chronological order in Figure 3.2.1. The monitoring for the 1990/91 heating season began on 12-19-90.

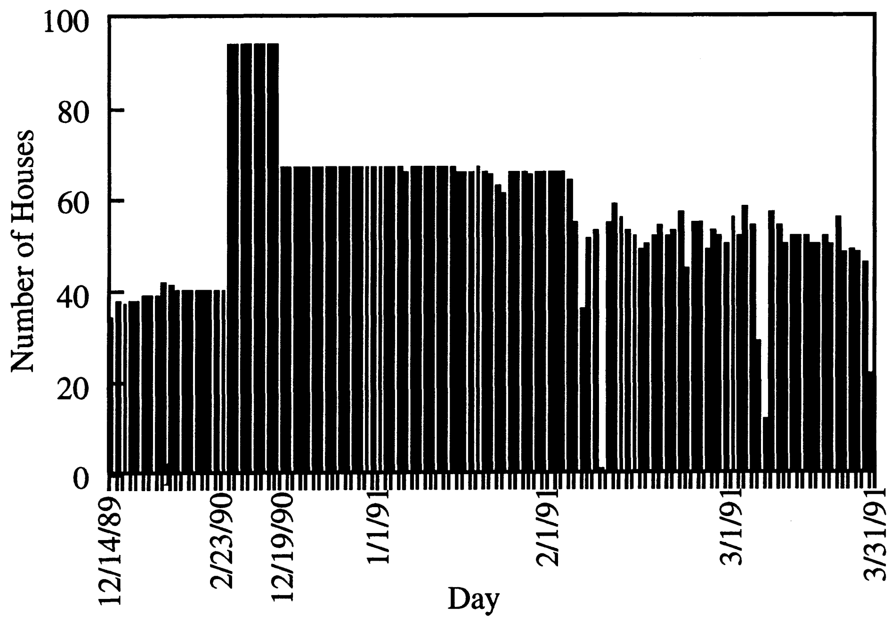


Figure 3.2.1: Number of monitored houses for each day during the 89/90 and 90/91 heating seasons

3.3 General Observations

The gas use of individual homes was expected to be easily interpreted. For example, on cold days, the gas use should be nearly constant and at the level of the furnace input size, because the furnace will be on most of the day. Much of the gas use furnace input size, because the furnace will be on most of the day. Much of the gas use data were found to be less easily explained than was initially hoped. When examining plots of individual gas use generated from the metered data, it is important to remember that the meter counts use in cubic feet and records every 5 minutes. Only integer values are recorded. When converting the data to standard units of cubic feet of gas per hour (cfh), the integer values of cubic feet per 5 minutes are multiplied by 12, so the resulting gas use figures must then be multiples of 12. Thus, fluctuations in the data of 12 cfh may only reflect the metering technique rather than a true change in the gas use of the house.

The metered gas use for some houses on some days are easily explained. Figures 3.3.1 and 3.3.2 are for the same house (account 9511) on the days of 3-1-90 and 12-21-89 respectively. The furnace input size for account 9511 is listed as 75 cfh, so all of the use is apparently due to the furnace. The metered use for most of the time the furnace is apparently operating is 72 cfh, but some difference between a furnace's name plate size and its actual capacity is expected. The average ambient temperatures for the two days are 34 °F and -10 °F, and the furnace is on for a significantly larger portion of the day on the colder day. The fluctuation in use during the evening of 12-21-89, is likely due to the gas use for the period being between 72 and 60 cfh. When the gas use is between two integer values, the meter will count part of a tic higher than the actual use for one period and then part of a tic less than the actual use for the next period. The longer furnace operating time in the hours between about 4:00 a.m. and 8:00 a.m. is probably due to turning up the thermostat. This household did practice night set back and the thermostat set points were 70 °F and 64 °F according to the house parameter data file.

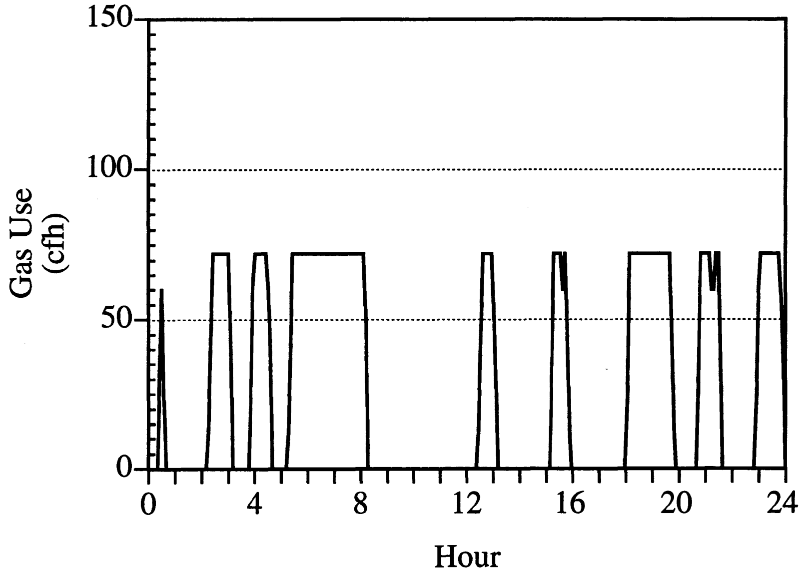


Figure 3.3.1 Gas Use (5 min.) for Account 9511 on 3-1-90

($\overline{T}_{amb}$ = 34 °F)

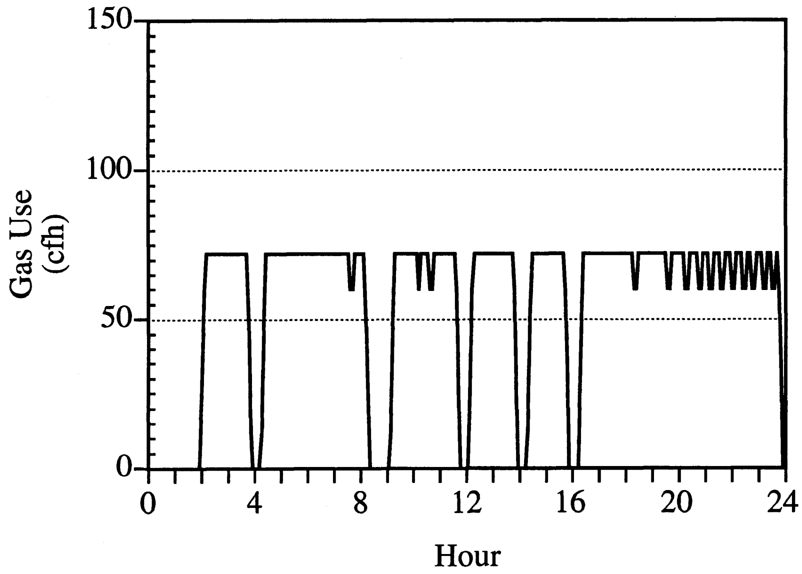


Figure 3.3.2 Gas Use (5 min.) for Account 9511 on 12-21-89

($\overline{T}_{amb}$ = -10 °F)

Not all houses had a use pattern which is so easily explained. Figures 3.3.3 and 3.3.4 are for a different house (account 5632) but the same days as for Figures 3.3.1 and 3.3.2. The furnace input size for account 5632 is listed as 100 cfh. The source of the gas use is less clear than for the account 9511 house. The use from midnight to 3 a.m. on 3-1-90 is probably a constant use of less than 12 cfh. The use from 4 until 7:30 a.m. may be from the furnace cycling quickly. If the furnace is on or off for less than 5 minutes, the recorded use will be lower than the furnace capacity. A furnace cycling on and off for less than 5 minutes at a time will show use fluctuating between high values less than the furnace capacity and low values greater than zero. The periods of seemingly constant use of 48 cfh on 12-21-89 may also be due to furnace cycling but, since this is a cold day, the values would be expected to be nearer furnace capacity. The constancy of the use for these periods lends some doubt to this conclusion however.

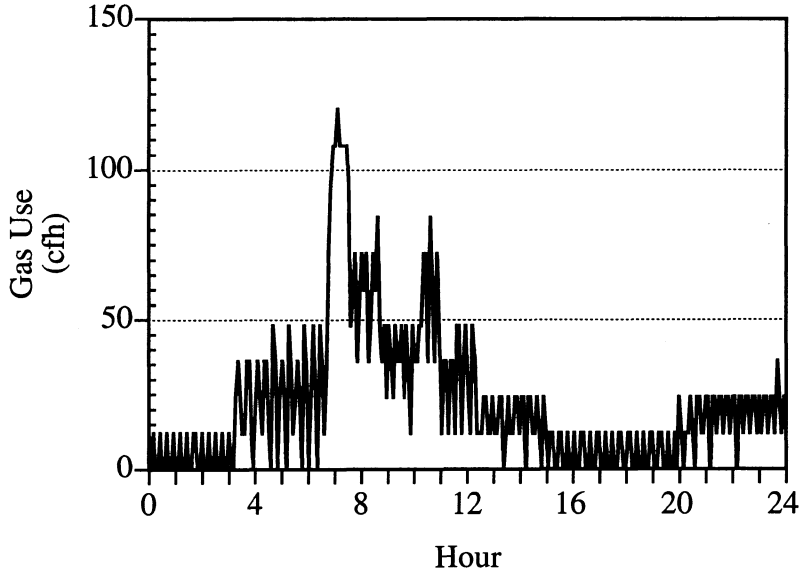


Figure 3.3.3 Gas Use (5 min.) for Account 5632 on 3-1-90

($\overline{T}_{amb}$ = 34 °F)

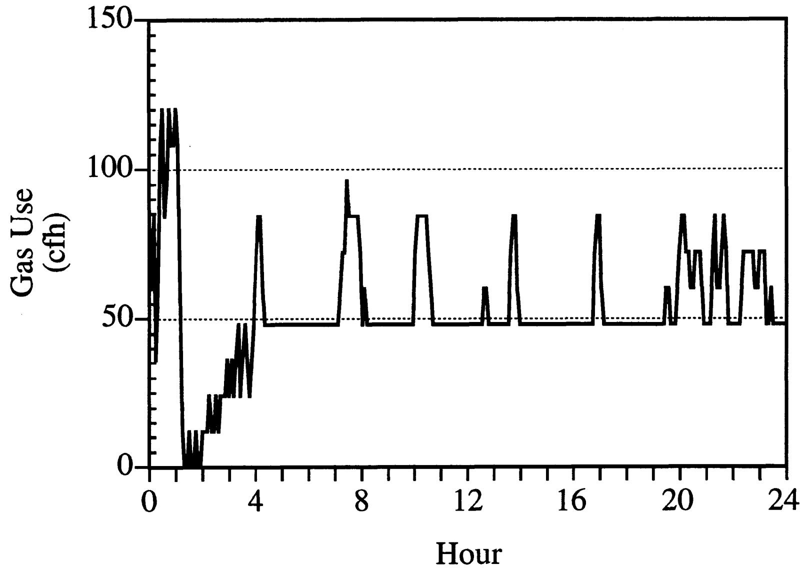


Figure 3.3.4 Gas Use (5 min.) for Account 5632 on 12-21-89

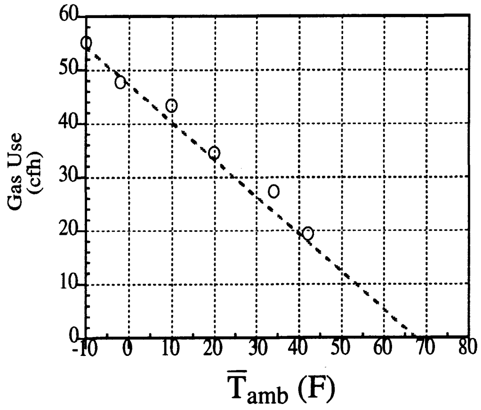
($\overline{T}_{amb}$ = -10 °F)

The gas use for some houses for some days defies physical interpretation. The recorded gas use for some houses is zero for entire days. Also, some gas recordings are impossibly high. The following section discusses the evaluation of the data.

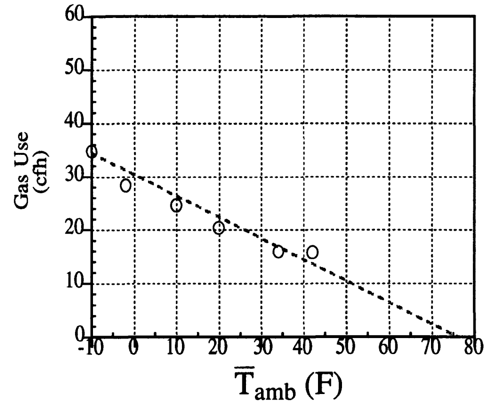
3.4 Checks for Data Errors

During the analysis of the 5 minute data, recordings were found that defied physical interpretation. The reliability of the monitoring data was then tested with several methods. Both the survey data and the five minute metering data were examined.

The house characteristics determined in the survey were checked qualitatively for reasonableness and appeared reasonable. The results of the WGC regression analysis were checked in by plotting the gas use for several randomly chosen houses as predicted by the regression. Also, the RMD acquired gas use for each house for days with a range of average ambient temperatures were plotted together with the predicted use line. The gas use as predicted by the slope and intercept generally agrees well with the 5 minute monitoring data as shown in Figure 3.4.1. A certain amount of scatter about the line is expected since such factors as wind velocity, solar incidence, and occupant behavior are not included in the regression. The use for sunny, calm days should fall below the line, while the use for a day in which the wind speed and infiltration are high will fall above the line. In conclusion, the coefficients of the WGC regression were found to be reasonable for the houses evaluated.



Account 9511



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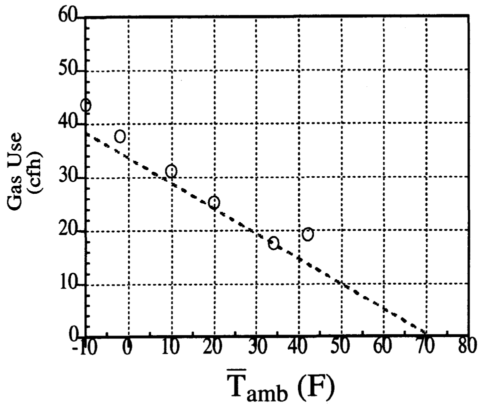
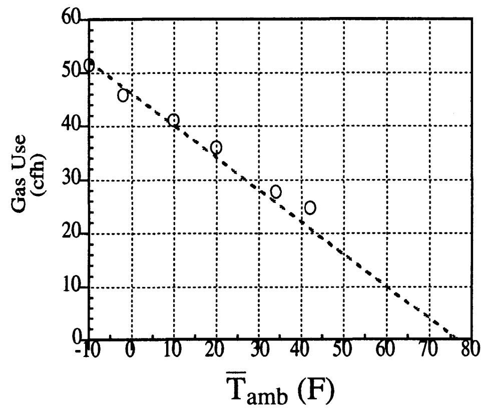
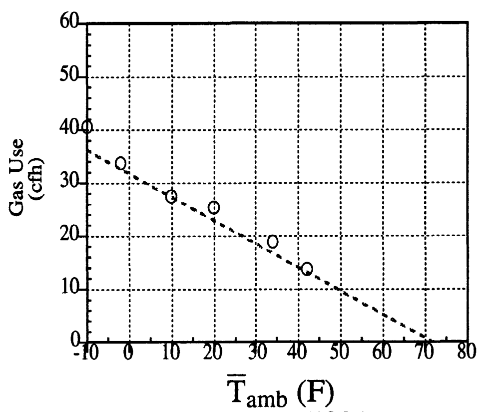


Account 6332



Account 1422



Account 7821

Figure 3.4.1 Actual average daily gas use and gas use as predicted from regression for 5 houses and 6 days

The average ambient temperature for each day included in Figure 3.4.1 is shown in Table 3.4.1. The balance temperature, the ambient temperature above which no heating is required, for each house can not be read directly from Figure 3.4.1, because the gas use shown is whole house data. In order to determine the balance temperature, the base load due to water heating and cooking must be subtracted from the whole house consumption. As shown in Chapter 5, the balance temperatures of the monitored houses range from approximately 60 °F to 70 °F, which are reasonable values.

Table 3.4.1 Average ambient temperature for days used to compare actual and predicted use

Day	Average Ambient Temperature $\overline{T}_{amb}$ (F)
12-18-89	10
12-20-89	-2
12-21-89	-10
2-26-90	20
3-1-90	34
3-2-90	42

The five minute monitoring data is too extensive to check closely for errors. A simple and very conservative check was performed by scanning the data set for readings which exceed 40 cubic feet in 5 minutes, which is twice the largest furnace capacity of the ensemble and 4 times the average furnace capacity. Exactly 450 such readings were discovered. These gas use readings are obviously in error, because no physical process in the these residences can consume gas at this rate. An example of daily use in which such an error occurred is shown in Figure 3.4.2. Note that the error checks in this section were performed in the units of cubic feet of gas use in 5 minutes (cu.ft./5 min). This rather awkward unit was used, because it the unit of the raw data. In later chapters, the more standard unit of cubic feet per hour (cfh) is used.

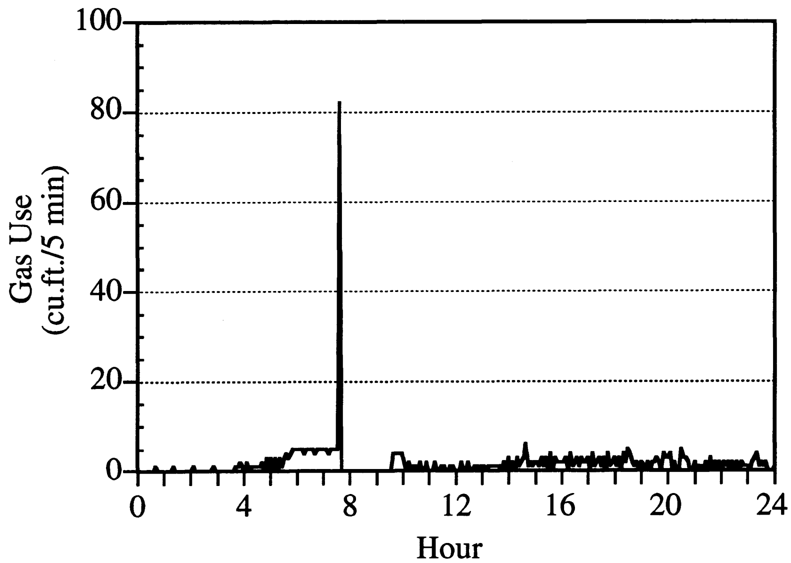


Figure 3.4.2: Gas Use on 5 minute basis for Account 6332 on
1-3-91 ($\overline{T}$amb = 20 °F)

According to the house parameters data file, the furnace capacity for house 6332 is 8.33 cu.ft./5 min. (100 cfh), and thus the spike in use at about 7:45 a.m. could not have occurred. Even averaging the use over the following two hours does not produce reasonable values. Another obvious error is that the metered use for some houses is zero for entire days. That no gas should be used on a winter day seems very unlikely. The source of these errors is unknown but could have occurred in the recording of the data by the meter, the transfer of data over the phone lines to the central recorder, or in the transfer of the file to magnetic tape.

The use of every monitored house for several single days was plotted. The use of each house is placed in series. The use was monitored on a 5 minute basis, so each house has 288 data points per day. Unfortunately, as shown in Figure 3.4.3, the monitored gas use data for some days has drastic errors. On 1-3-91, the data for 32 houses contain unreasonably high readings as defined above. The high readings for several more houses are very suspicious, but do not exceed the cut off of 40 cu.ft./5 min. There are also houses for which no use was recorded for the entire day. As a result, the metered gas use for nearly every house on this day apparently contain errors.

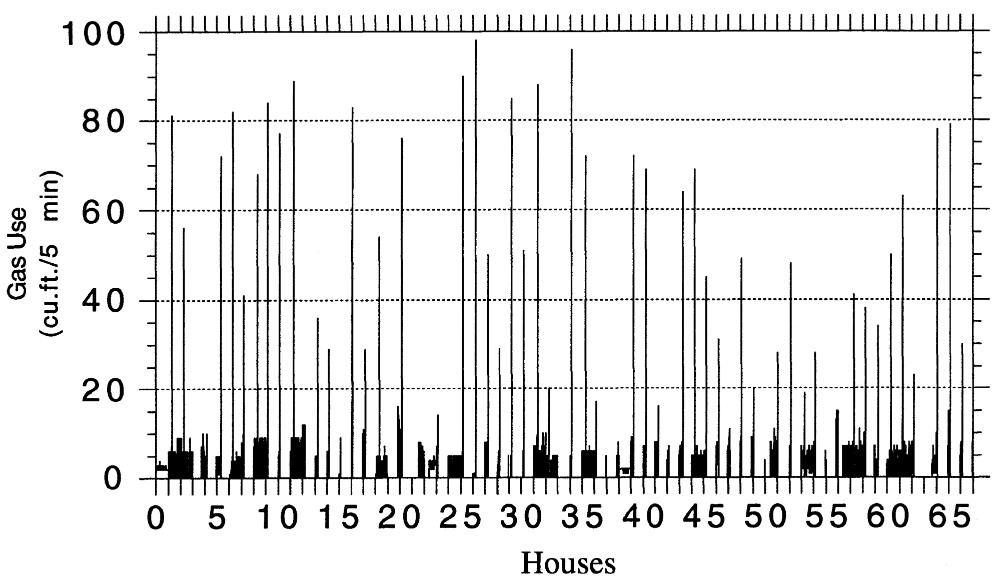


Figure 3.4.3: Sequential gas use of all 67 houses on 1-3-91

As shown in Figures 3.4.4. and 3.4.5, the data for some days seems to be more reliable. Consequently, the comparisons of the simulation results and the monitored data in Chapters 4 and 6 were restricted to days in which few obvious errors occurred. The task of removing flawed data in order to permit a broader comparison would have been extremely time consuming. Also, simply removing the obvious errors from a day's recordings does not justify confidence in the remaining data for that day. There are also undoubtedly less obvious errors throughout the data set.

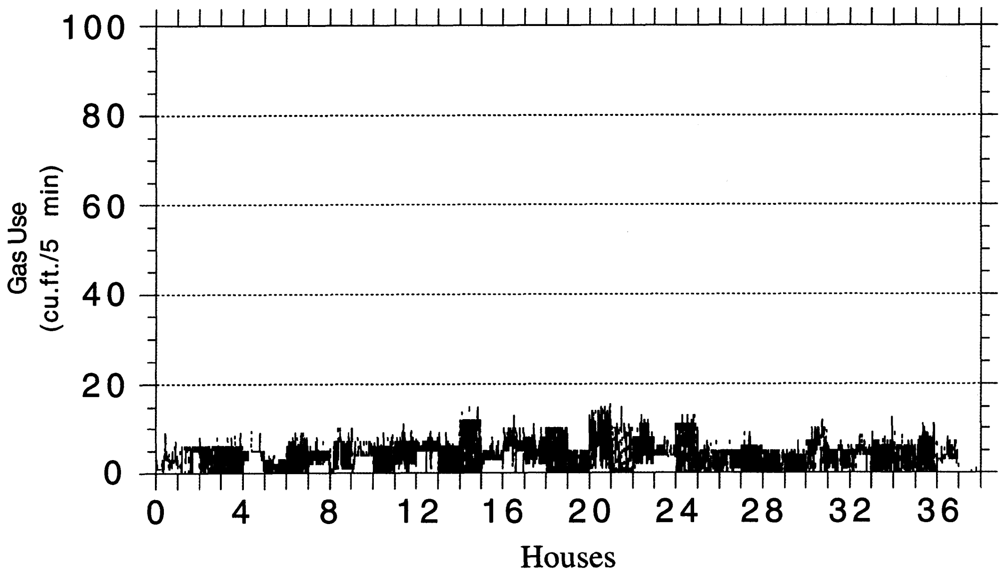


Figure 3.4.4: Sequential gas use of all 38 houses on 12-21-89

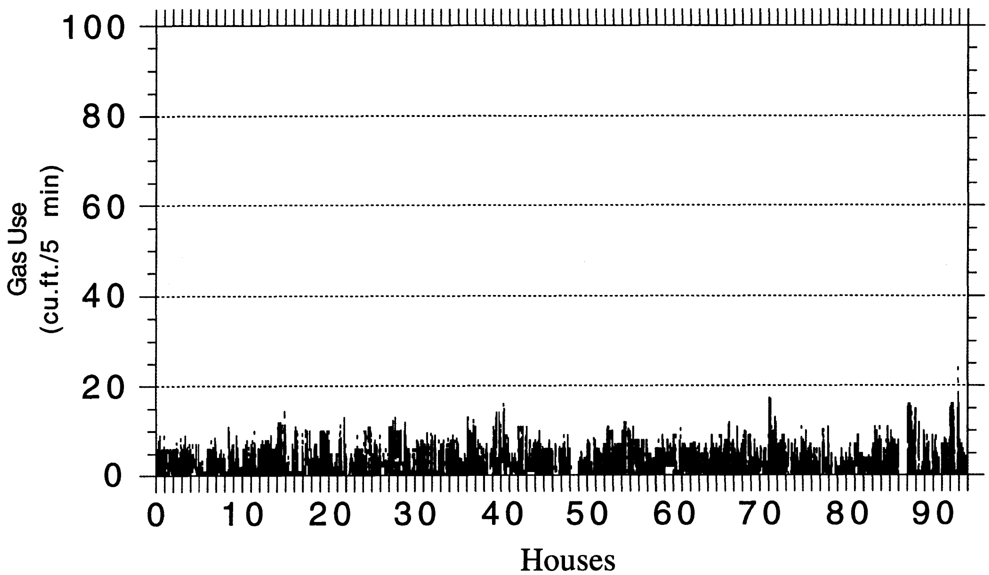


Figure 3.4.5: Sequential gas use of all 94 houses on 3-1-90

3.5 Base Load

In order to compare the results of a gas furnace simulation with metered whole house consumption, an estimate of the gas use from non-furnace sources must be subtracted from the whole house gas use. This section describes the determination of the non-furnace gas use or "base load".

3.5.1 Determination of Base Load Through Regression

The base load for each house was estimated by Wisconsin Gas "by means of monthly billing data or by means of RMD consumption figures in the summer months" [WGC, 1993]. The base load is the non-temperature dependent gas use of the house, so it is ostensibly the gas use from sources other than the furnace. The nature of the other gas consuming sources within each house was not included in the survey but could be gas stoves or gas water heaters. Faulty meters may also create an apparent base load. The base loads estimated by the WGC for each house are shown in the house characteristics data file in Appendix E.

3.5.2 Hot Water Load

The average energy used to meet the hot water load of an ensemble of houses was determined in a separate study by Beckman et al. [1993]. The study involved TRNSYS simulations of electric water heaters in Sacramento, CA and used the WATSIM program developed by EPRI to characterize the water loads. The size and efficiency of the water heaters and the hot water load shape were randomly assigned to each of the 200 TRNSYS simulations. The electricity used by the ensemble was determined by summing the electric use from each of the simulations.

3.5.3 Scaling of Base Load

The electrical hot water load explained above was used to determine the shape of the base load for the monitored houses. It was assumed that a major portion of the non-furnace gas use of the houses would be similar to the electric use of the Sacramento hot water heaters. The supplied energy use of a number of gas water heaters will be larger than an equal number of electric water heaters, because gas and electric water heaters typically have efficiencies of approximately 70% and 100% respectively. The percentage of the monitored houses which had gas water heaters and the efficiency of these furnaces is not known. The percentage of houses with gas stoves is also unknown. In light of these sources of uncertainty, it was somewhat arbitrarily decided that the average base load from the survey data would be scaled such that half of the base load would be constant and the other half follow the hot water shape. The resulting base load shape is shown in Figure 3.5.1. This estimate of the average base load was subtracted from the metered whole house gas use of a sample of houses in Chapter 6 in order to compare the results of simulations of furnace gas use with metered data.

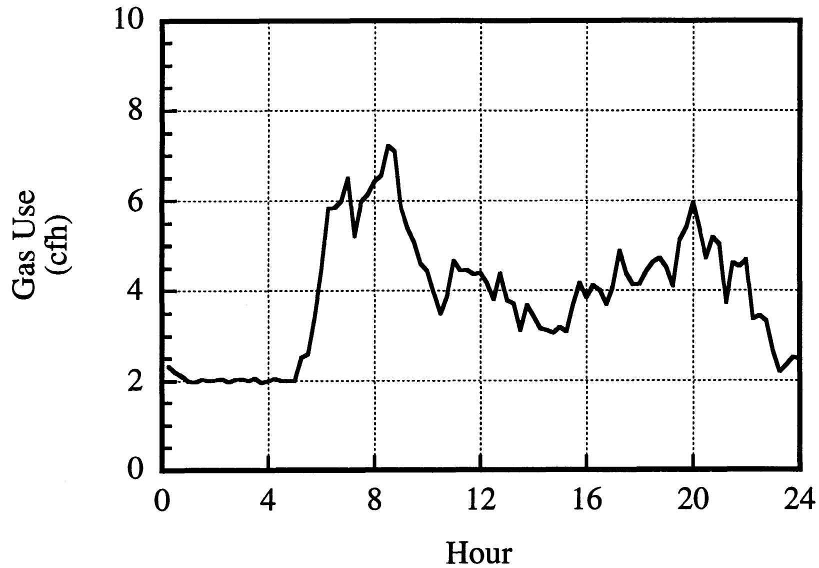


Figure 3.5.1: Scaled average base load.

3.6 Summary

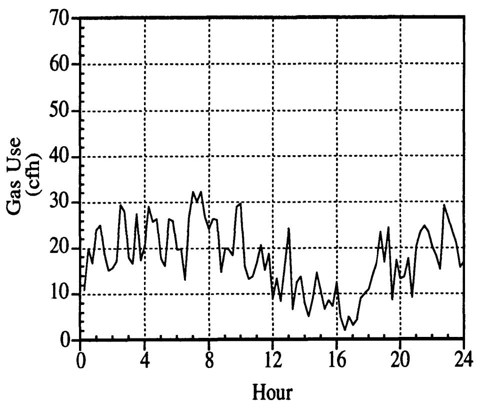
The study of residential gas consumption performed by the Wisconsin Gas Company will provide the house characteristics necessary as inputs to the simulation program for gas furnaces. Although significant numbers of obvious errors were found in the 5 minute metered gas use data, a sufficient number of days with few obvious errors were found to provide a sample of plots of the average gas consumption of an ensemble of houses. These plots, once the average base load is subtracted from the whole house gas use, will allow a comparison of simulations of furnace gas use with the metered data.

CHAPTER
FOUR

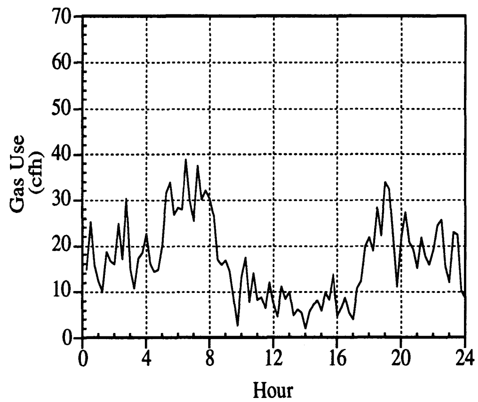
RESULTS FOR MONITORED GAS FURNACES

4.1 Effect of Number of Systems

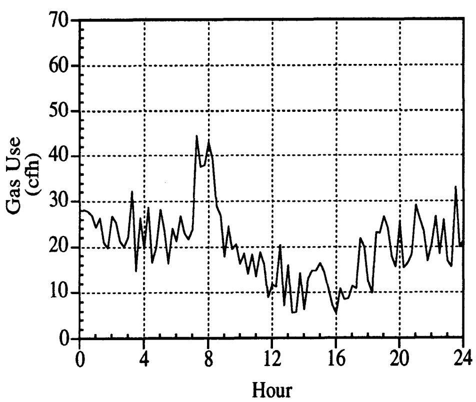
In order to examine, with monitored data, the effect of the number of systems in the ensemble on the gas draw of the ensemble, it is necessary to compare the gas use for different houses on the same day. The use for different days will be from a different number of systems and this effect will be confounded with the effect of different ambient temperatures. Figures 4.1.1, 4.1.2 and 4.1.3 below show the average gas use of all of the monitored houses on 3-1-90 and 12-21-89 averaged from 5 minutes to a 15 minute time step. For these days, 94 and 38 houses were monitored, and the average ambient temperatures were 34°F and -10°F respectively. These days were selected for analysis because they are, respectively, the peak day of the 1989-90 heating season and a much milder weather day for which many houses were monitored. The plots were created by summing the use of groups of houses. The use of all of the houses for that day is also shown. No house is included in more than one of the groups of the same sample size. The scaled base load explained in Chapter 3 has been subtracted from the average gas use from the RMD acquired whole house consumption data.



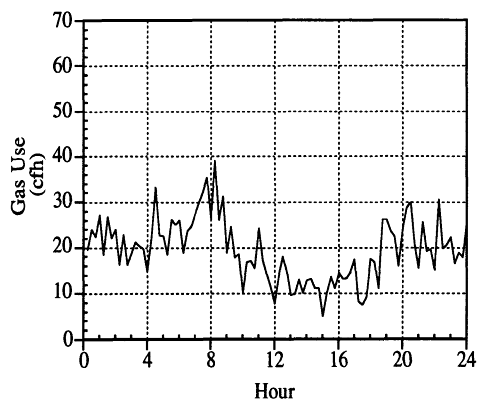
20 Houses (Group A)



20 Houses (Group B)

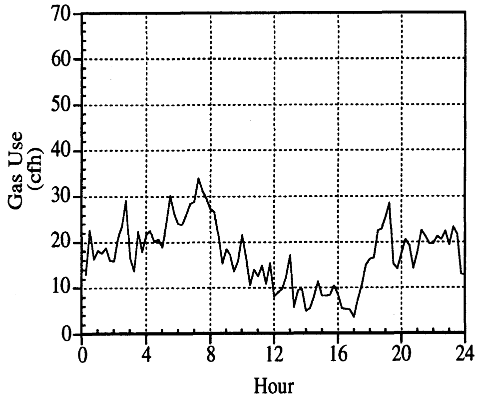


20 Houses (Group C)

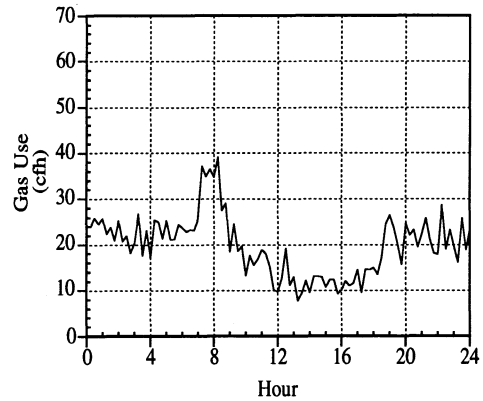


20 Houses (Group D)

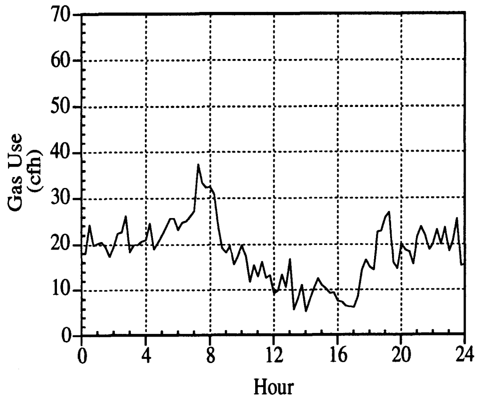
Figure 4.1.1: Average gas use of ensemble on 3-1-90 ($\overline{T}$amb = 34 °F) for 4 samples of 20 houses with the scaled base load subtracted.



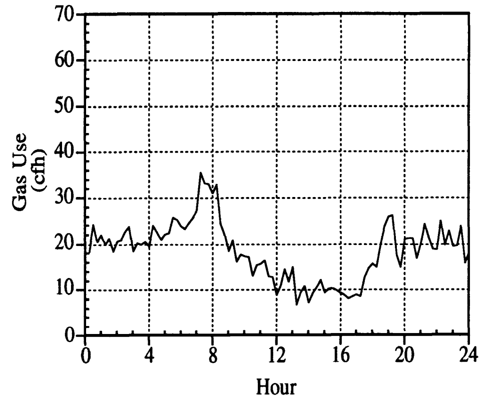
40 Houses (Group AB)



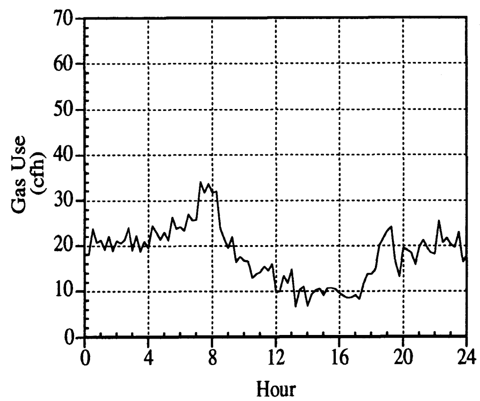
40 Houses (Group CD)



60 Houses (Group ABC)



80 Houses



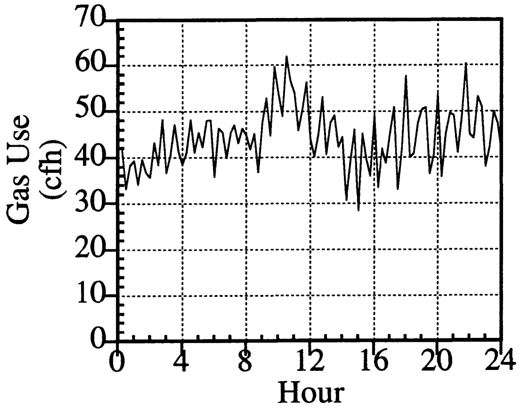
All 94 Houses

Figure 4.1.2: Average gas use of ensemble on 3-1-90 ($\overline{T}amb$ = 34 °F) for several sample sizes with the scaled base load subtracted

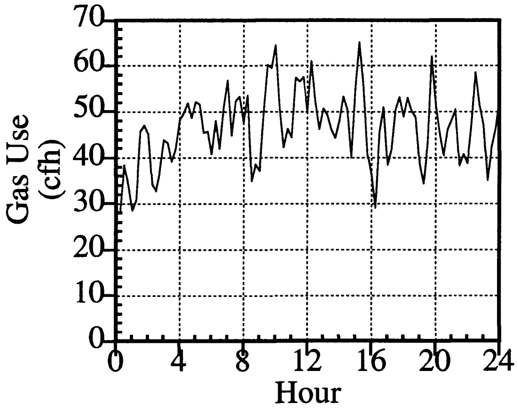
The basic load shape exhibited by each of the plots is qualitatively similar, but there are differences between the groups. As shown in Table 4.1.1, the average and peak use for the day vary between groups by as much as 20% and 37% respectively for 3-1-90. The average and peak use for 12-21-89 vary by as much as 5% and 9% respectively as shown in Table 4.1.2. The magnitude of the variation, and thus peak use, generally decreases with more houses. More surprisingly, the location of the peak changes from plot to plot.

Table 4.1.1 Average and peak gas use figures for 3-1-90 for several sample sizes

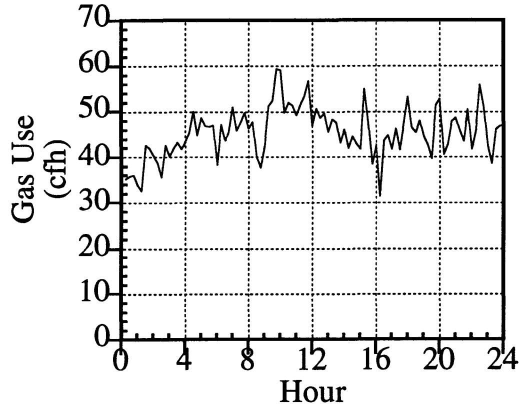
Number of Houses	Average Use (cfh)	Peak Use (cfh)
20 (A)	17.7	32.4
20 (B)	16.9	39.0
20 (C)	20.2	44.4
20 (D)	19.5	39.0
40 (AB)	17.3	33.9
40 (CD)	19.8	39.1
60 (ABC)	18.3	37.4
80	18.6	35.5
94	18.3	34.2



19 Houses (Group A)



19 Houses (Group B)



All 38 Houses

Figure 4.1.3 Average gas use of ensemble on 12-21-89 ($\overline{T}$amb = -10 °F) for several sample sizes with the scaled base load subtracted

Table 4.1.2 Average and Peak gas use figures for 12-21-89 for several sample sizes

No. of Houses	Average Use (cfh)	Peak Use (cfh)
19 (a)	44.4	62.0
19 (a)	46.6	65.1
38	45.5	59.5

The addition or subtraction of a few houses from the monitored pool can significantly alter the apparent gas use. It is thus dangerous to extrapolate the peak use of all of the houses in a utility's district from a sample of even 100 houses. The underlying shape, however, can be determined from a relatively small sample.

4.2 Effect of Period of Analysis

The period of analysis is a very important parameter in determining the peak use of an ensemble of furnaces. Figures 4.2.1 and 4.2.2 show the monitored gas use of all the monitored houses for 12-21-89 and 3-1-90. The gas use is shown on the original 5 minute metering period and for longer periods of analysis created by averaging the 5 minute data. As would be expected, the oscillation of the curves decreases with longer periods of analysis. The effect of the period of analysis decreases with an increase in the number of systems. Increasing the period length flattens the use curve and so has a larger effect on a severely varying use curve than on a smooth one. Use curves become smoother with an increase in the number of systems as will be shown clearly in Chapter 6.

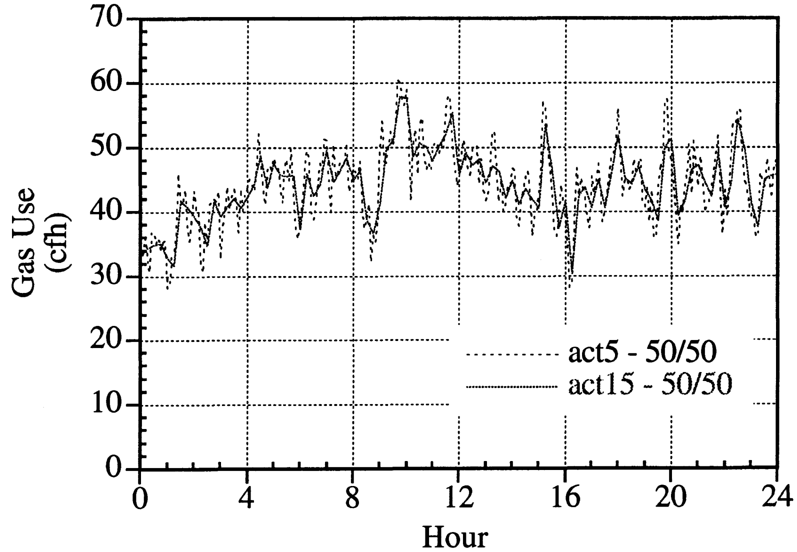


Figure 4.2.1: Average gas use of 38 houses on 12-21-89 ($\overline{T}$amb = -10 °F) with the scaled base load subtracted on 5 and 15 minute basis

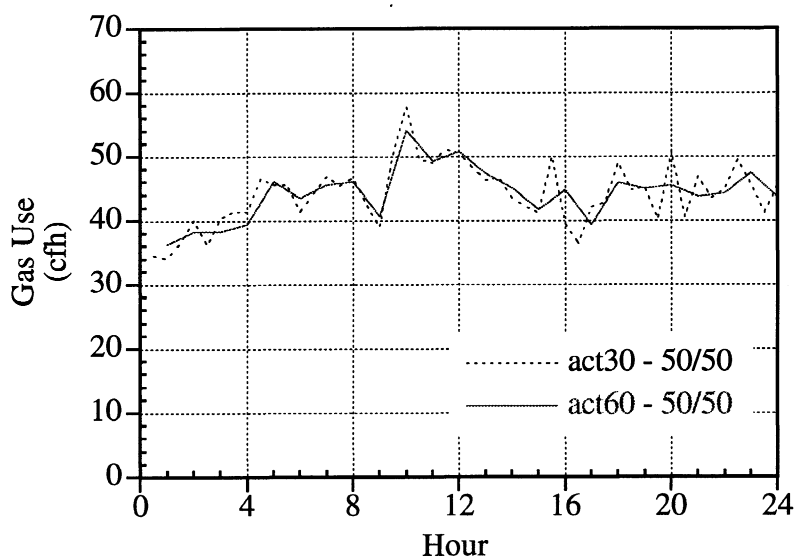


Figure 4.2.2: Average gas use of 38 houses on 12-21-89 ($\overline{T}$amb = -10 °F) with the scaled base load subtracted on 30 and 60 minute basis

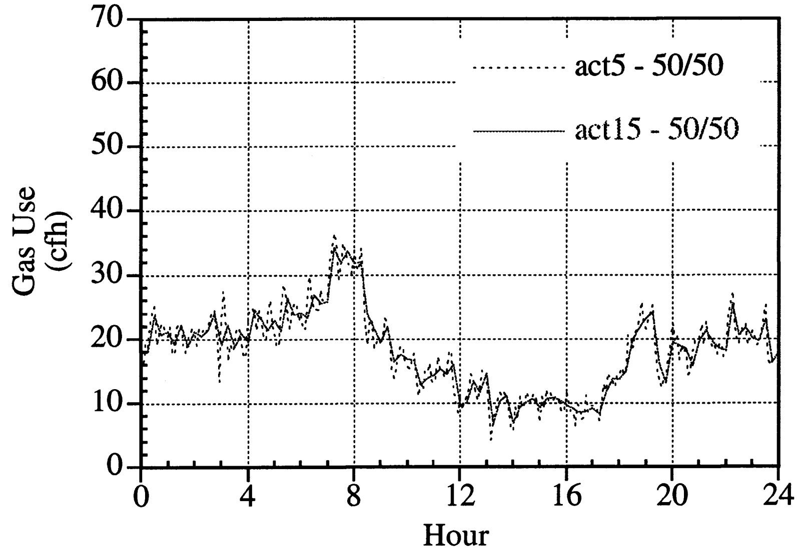


Figure 4.2.3: Average gas use of 94 houses on 3-1-90 ($\overline{T}$amb = 34 °F) with the scaled base load subtracted on 5 and 15 minute basis

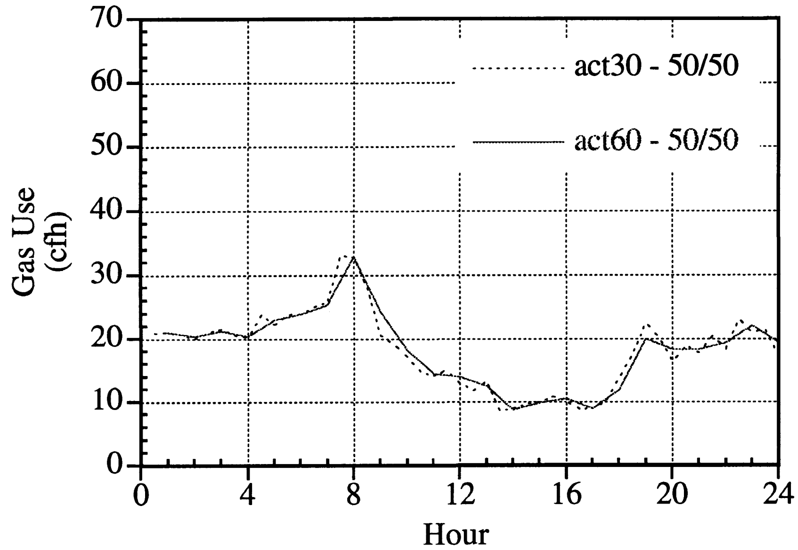


Figure 4.2.4: Average gas use of 94 houses on 3-1-90 ($\overline{T}$amb = 34 °F) with the scaled base load subtracted on 30 and 60 minute basis

The peak gas usage of all of the houses on each day is shown in Table 4.2.1. As expected the gas use averaged over an hour is flatter than 5 minute averages. The peak use for 3-1-90 and 12-21-89 on a 5 minute basis are 11% and 12% higher respectively than the peak on an hourly basis. The average daily use is the same for any period of analysis, because the longer periods are simply created from averaging shorter periods.

Table 4.2.1: Peak use of ensemble for different periods of analysis

Period of Analysis (minutes)	3-1-90 ($\bar{T}amb$ = -34 °F)	12-21-89 ($\bar{T}amb$ = -10 °F)
5	36.4	60.3
15	34.2	57.9
30	33.0	57.7
60	32.9	54.1

Comparisons of the two days are complicated, because not all of the same accounts are monitored for both days. Data on 94 and 38 homes respectively exists for the days 3-1-90 and 12-21-89. Of the 38 possible repeat accounts, only 25 have been determined to be matches with another 9 as possible matches. Of the 34 possible and probable matches, home characteristics can be definitely matched for 20 with another 11 possible. Of these 31, complete house data exists for 26. The differences in the gas use for the two days are thus the result not only of different ambient conditions and numbers of systems.

CHAPTER FIVE

RESIDENTIAL GAS FURNACE MODEL

The information to be gained from an analysis of monitored gas use as performed in Chapter 4 is important but limited. The data base containing the monitored gas use is extensive, containing data for 117 days and from 1 to 94 houses per day. However, the impact of no more than 94 furnaces can be determined, because the use from more than one day can not be added together without confounding the effect of the number of houses with weather effects. The data base and the costs required to install the monitoring equipment which would be needed to directly analyze a large number of (over 1000) systems would be prohibitively large. In order to determine the impact of a very large number of systems, as would typically be of interest to a utility, a computer simulation model of the houses and furnaces was written using the characteristics from the monitoring study as inputs. This model was used to perform large numbers of simulations to determine the impact of an ensemble of systems. Simulations have been performed using both temperature level control and energy rate control.

5.1 Mathematical Description

5.1.1 Thermal Loads

A simple model was chosen for calculation of the thermal loads on each house. This model assumes that a house behaves thermally as if the interior of the house is at a single time varying temperature. The heat loss is directly proportional to the product of the conductance (UA) and the temperature difference between the interior of the house and the ambient, and all thermal gains are modeled as constant with time. Several refinements to this model such as including the effects of humidity, wind, and solar gains were considered but disregarded. The effect of humidity was neglected because of its small effect on heating loads. Wind and solar can have large impacts on heating loads but were not included in the available weather file. Also, the regression performed by the WGC ignored these factors. The effects of the different temperatures and insulation qualities within a house on the thermal load could be included with a multi-zone building. The increased accuracy of a multi-zone model was not considered to be worth the increased complexity.

The heating load on a single house, neglecting the transient effects of wind, humidity, and solar, was modeled as

$$\text{Load} = UA(T_R - T_{amb}) - \text{gains} \tag{5.1.1}$$

or

$$\text{Load} = UA(T_{bal} - T_{amb}) \tag{5.1.2}$$

The house balance temperature is the ambient temperature above which the gains balance the thermal load and no heating is required and is given by

$$T_{bal} = T_R - \frac{gains}{UA} \quad (5.1.3)$$

5.1.2 Temperature Level Control

A lumped capacitance model was chosen to describe the thermal behavior of a house because of its relative simplicity. This model assumes that a house behaves thermally as if the interior of the house is at a single time varying temperature. The furnace is controlled by a thermostat which is triggered when the interior temperature reaches a limit. Because the furnace output is controlled based on the internal temperature, the control scheme is known as temperature level control. The equation governing the internal temperature (T_R) of a lumped capacitance (C) and single loss coefficient (UA) house while undergoing heat loss to the environment at T_{amb} and heat input (Q_{htg}) by a furnace is

$$C\frac{dT_R}{dt} = \lambda Q_{htg} + gains - UA(T_R - T_{amb}) \quad (5.1.4)$$

where the gains are from sources such as appliances, people, and solar radiation through windows. Gains actually vary with time, but were considered to be constant in the model. The furnace control variable λ is set to one or zero for the “charging” and ”discharge” periods respectively. A schematic of the energy flows in a house as modeled by the lumped capacitance model is shown in Figure 5.1.1.

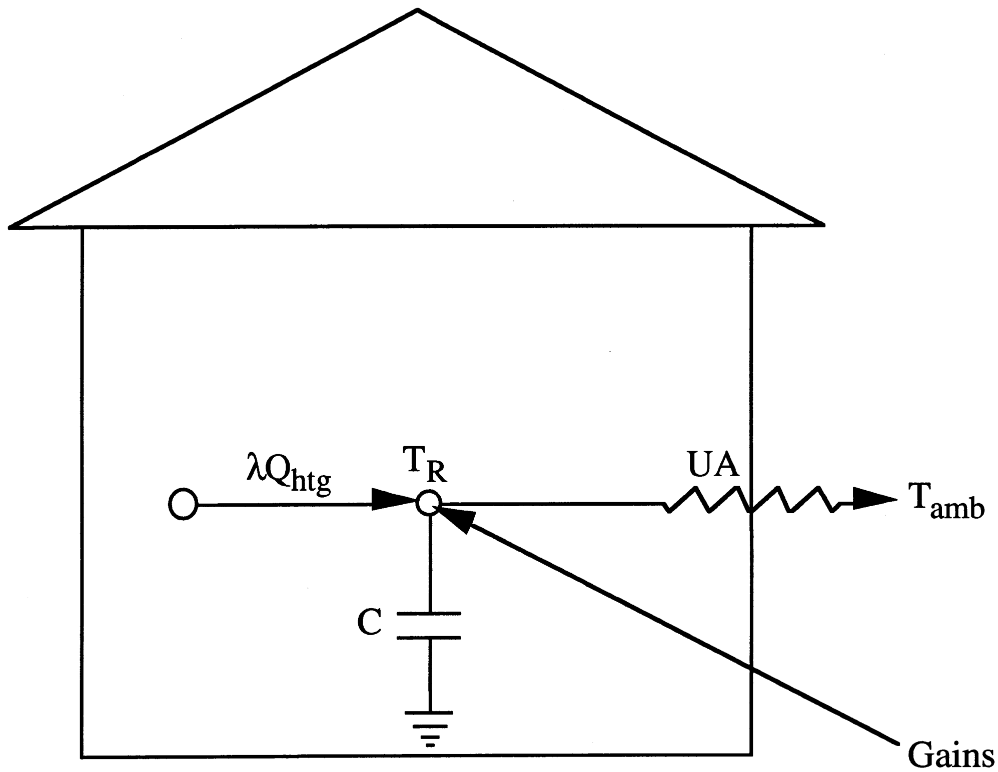


Figure 5.1.1: Energy flows in a house

The equation for the time required for the house to change from an internal temperature T_1 to another temperature T_2 is

$$\tau = -\frac{C}{UA}\ln\frac{\left[T_2 - T_{amb} - \frac{\langle \lambda Q_{htg} + gains \rangle}{UA}\right]}{\left[T_1 - T_{amb} - \frac{\langle \lambda Q_{htg} + gains \rangle}{UA}\right]} \tag{5.1.5}$$

or

$$\tau = -\frac{C}{UA}\ln\frac{T_2 - T_{\infty\lambda}}{T_1 - T_{\infty\lambda}} \tag{5.1.6}$$

where $T_{\infty\lambda}$ is the steady state internal temperature of the house.

$$T_{\infty\lambda} = T_{amb} + \frac{\lambda Q_{htg} + gains}{UA} \tag{5.1.7}$$

The behavior of the internal house temperature is shown in Figure 5.1.2 for a simulation using temperature level control. The gas use of the furnace is a step function of zero when the furnace is off and Use_{htg} when the furnace is running. The internal temperature is always exponentially approaching a steady state value, but the particular value, $T_{\infty 1}$ or $T_{\infty 0}$, changes with the ambient temperature and the furnace status. The upper and lower limits of the dead band have been defined as T_{Rhigh} and T_{Rlow}.

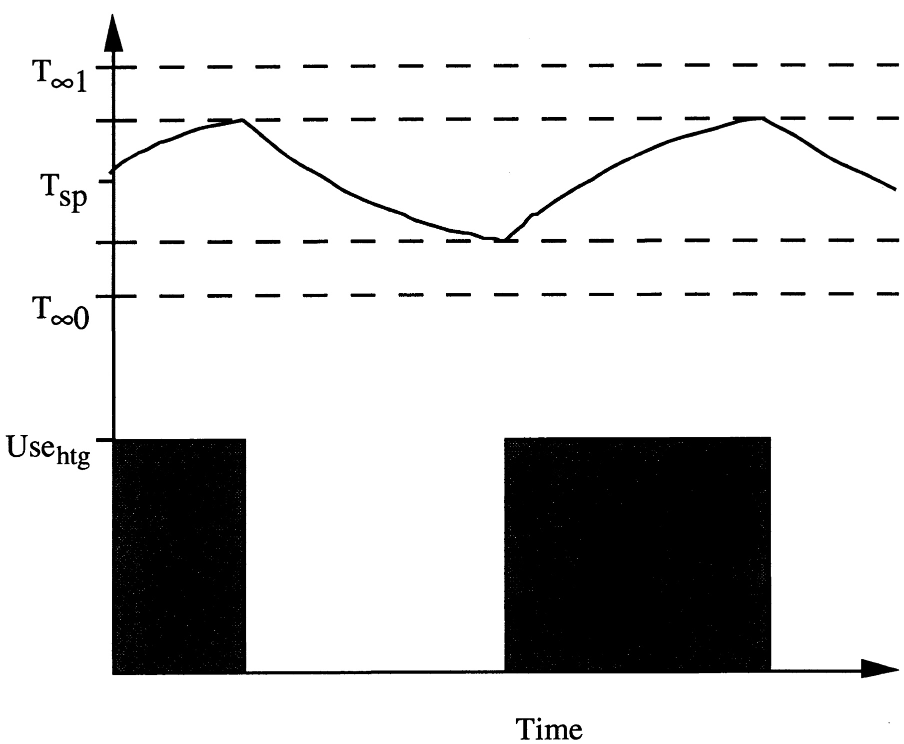


Figure 5.1.2: House internal temperature and gas use during furnace cycle when controlled by temperature level control

An analytical solution for the total demand of a number of houses in terms of average house properties was attempted by summing a series of Equation 5.1.4 as shown in Equation 5.1.8. The attempt was unsuccessful due to the transcendental and nonlinear nature of Equation 5.1.4 in terms of the house properties such as C and T_R.

$$\Sigma\left(\lambda Q_{htg}\right)_i = \Sigma\left(C\frac{dT_R}{dt}\right)_i - \Sigma gains_i + \Sigma[UA(T_R - T_{amb})]_i \qquad (5.1.8)$$

If the capacitance term is neglected, the average demand of a number of systems is equal to the average thermal load minus the average gains.

5.1.3 Energy rate control

In addition to performing simulations with temperature level control, the program also performs a run using energy rate control. This method continually adjusts the furnace output to exactly meet the heating load on the house over the time period at which weather data is input (15 minutes). Note that the gas use of a single house will behave very differently from the load if the furnace is controlled by a thermostat as shown in Figure 5.1.2. For that situation if the load is continuous, the gas use will be a step function. The gas use of a single furnace is, however, continuous in a simulation using energy rate control (ERC) but at a level of output less than the furnace capacity. Since most actual furnaces are incapable of operating at other than their full capacity, an ERC simulation does not provide realistic results for the gas use of a single system. The thermal mass of the house is neglected when using ERC, because the internal temperature of the house is assumed to remain at the set point and to change immediately when the set point is changed. However, ERC is expected to provide good energy results because over a day both control schemes must meet the thermal load. The gas use is determined by

$$Use_{htg} = Q_{htg} / \eta \qquad (5.1.9)$$

where

$$Q_{htg} = UA(T_R - T_{amb}) - gains \qquad (5.1.10)$$

5.2 Determination of Model Parameters

As explained in Chapter 3, the daily gas use of each house was regressed by the WGC as a function of daily average ambient temperature. The average gas use of each house for a day with average ambient temperature $\overline{T}_{amb}$ was thus characterized by

$$Use = A + B\overline{T}_{amb} \qquad (5.2.1)$$

The whole house gas use includes furnace use and a base load which is due to such uses as gas stoves and gas hot water heaters. The gas use of each house furnace for a given ambient temperature is given by

$$Use_{htg} = A + B\overline{T}_{amb} - base \qquad (5.2.2)$$

Following this characterization, the balance temperature of each house is

$$T_{bal} = -\frac{(A - base)}{B} \qquad (5.2.3)$$

Equation 5.2.2 can be derived by combining and integrating equations 5.1.9 and 5.1.10 over a day and dividing by the length of a day. The resulting average gas use for the day is

$$Use_{htg} = \frac{1}{\eta}\left(UA\,\overline{T}_R - \overline{gains}\right) - \frac{UA}{\eta}\overline{T}_{amb} \tag{5.2.4}$$

The relationships between the parameters in the two characterizations are seen to be

$$A - base = \frac{1}{\eta}\left(UA\,\overline{T}_R - \overline{gains}\right) \tag{5.2.5}$$

and

$$B = -\frac{UA}{\eta} \tag{5.2.6}$$

The gas use of many houses and house furnaces for a given ambient temperature are given, respectively, by

$$\Sigma Use_i = \Sigma\left(A_i + B_i\overline{T}_{amb_i}\right)^{+} \tag{5.2.7}$$

and

$$\Sigma Use_{htg_i} = \Sigma\left(A_i + B_i\overline{T}_{amb_i} - base\right)^{+} \tag{5.2.8}$$

The plus sign indicates that the quantity on the right side of the expression is only included in the summation when it is positive. The slope is always negative. Were the plus sign not included, then the average whole house and furnace use of the ensemble for a given ambient temperature would by predicted, respectively, by

$$\overline{Use} = \overline{A} + \overline{B}\,\overline{T}_{amb} \quad (5.2.9)$$

and

$$\overline{Use}_{htg} = \overline{A} + \overline{B}\,\overline{T}_{amb} - \overline{base} \quad (5.2.10)$$

The presence of the plus sign causes the average furnace gas use to become nonlinear with ambient temperature above the lowest balance temperature of the ensemble as shown in Figure 5.2.3. Once the ambient temperature is greater than the balance temperature of a house, the gas use for the furnace is zero rather than negative, so the resulting average for the ensemble is higher than would be predicted by ignoring the plus sign. The small shaded region in Figure 5.2.3 indicates the error in ignoring the plus sign. Figure 5.2.3 is a plot of both Equations 5.2.7 and 5.2.9 using values of the house parameters from the WGC survey data file. It is evident from the figure that the balance temperatures of the monitored houses range from approximately 60 °F to 70 °F as this is the temperature range where the two curves differ.

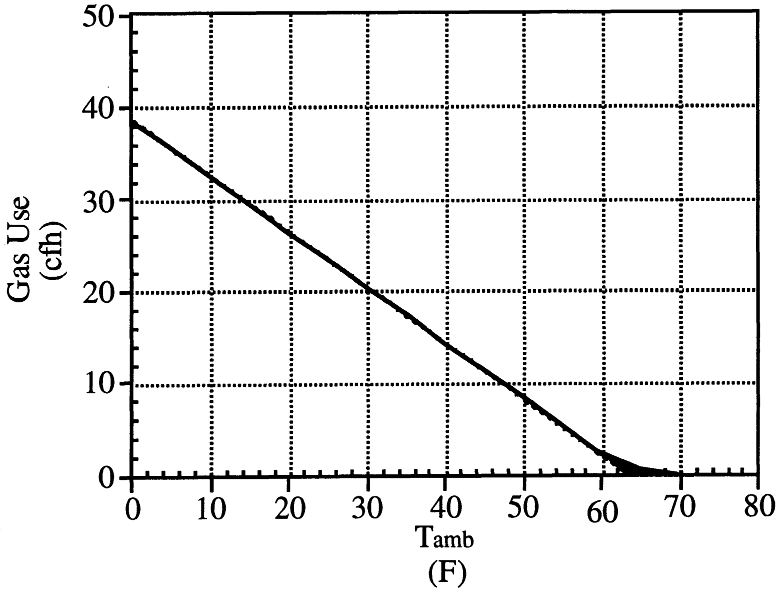


Figure 5.2.3: Predicted average daily gas use of ensemble from Equations 5.2.4 and 5.2.6

The results for the sum of the temperature level control runs will be correct at all temperatures, even above the balance temperatures of some houses, because the furnace of a house will not turn on above the balance temperature. The energy rate control run with the average values of the house parameters will follow the straight line in Figure 5.2.3 and will consequently over predict gas use at high ambient temperatures. The temperature on the days of interest, however, are well below typical balance temperatures.

5.2.1 Parameters randomized

The parameters used to describe the systems in the simulation were taken from the WGC survey file described in Chapter 3. The average slope, intercept, and base load are used to determine the average UA and the average constant gains of the ensemble. As described below, the loss coefficient determined by WGC had to be modified before it could be used in the model. Both the original (slope) and modified (UA) values are listed below. The parameters randomized and their average and standard deviation, where applicable, are shown in Table 5.2.1.

Table 5.2.1: Randomized house parameters

Parameter	Average	Standard Deviation
T_{sp} (F)	69.9	2.39
T_{sb} (F)	66.2	4.66
Furnace size (cfh)	95.0	28.1
Furnace η (%)	84.6	9.52
Floor area (ft^2.)	1300	454
B (cfh/F)	0.61	
A (cfh)	42.6	
base (therms/month)	1.13	
UA (cfh/F)	0.51	0.106

5.2.2 Randomization Procedure

5.2.2.1 Thermal capacitance

The monitoring data provides no direct information on the thermal capacitance of the surveyed houses. The capacitance for each house was estimated as the product of the floor area and a typical value of thermal capacitance per unit floor area for residential construction of 80 kJ/m^2-C [Mitchell and Beckman, 1989].

5.2.2.2 Thermal loss coefficient (UA)

The slope from the WGC regression is the dependence of whole house gas use on ambient temperature. The whole house gas use is assumed to consist of the weather independent portion (i.e., the base load) and the furnace use. The slope is thus the dependence of the furnace gas use on ambient temperature. The relationship between the dependence of furnace gas consumption and the house thermal loss coefficient is shown in equation 5.2.4. The average UA for the ensemble was determined as the average of the product of each slope and efficiency rather than the product of the average slope and efficiency.

5.2.2.3 Constant thermal gains

The monitored data provides no information on the non-furnace heat gains in the houses. The daily average gains can be estimated, however, from the UA, intercept, base load, furnace efficiency, and average internal temperature for the day with equation 5.2.5. By using the average values of house parameters, only the average daily average gain is determined. The gain is then assumed to be constant over the day. The average internal temperature for a day ($\overline{T}_R$) is determined from a time weighted average of thermostat set point temperatures.

$$\overline{T}_R = (8T_{sb} + 16T_{sp})/24 \qquad (5.3.6)$$

5.2.2.4 IMSL STAT routines

The IMSL statistical routines used to create the arrays of house parameters are RNNOA, SSCAL, and SADD [IMSL, 1987]. The RNNOA routine creates an array of pseudo-random numbers in a standard normal distribution with a mean of zero and standard deviation of unity. The seed for the randomization is taken from the system clock, so a different array is created each time the subroutine is called. The original array is multiplied by the supplied standard deviation with the SSCAL routine to create an array with mean of zero and the desired standard deviation. The supplied mean of the parameter set is then added to each element in the array. The final result is a normally distributed array with the desired mean and standard deviation for each parameter. The actual mean of the array is never precisely the desired mean. The difference between the desired and supplied means decreases with increasing array length. Differences of approximately 5% and 0.1% respectively are typically observed for array sizes of 30 and 100,000.

5.3 Program Flow

5.3.1 Simulation Flow for Temperature Level Control of One House

All simulations are started 6 hours before the period of interest in order to avoid the effects of the starting condition. Weather files are created to accommodate this early start time, so a weather file for a day is 30 hours long. The program first opens the weather and output files to be used later. The user is then prompted to input the desired duration, time step, and number of systems for the simulation. The desired weather input and thermostat set back schedule are also selected. The thermostat set back schedule is the times at which the thermostat set point changes for any house and the percentage of houses which change at each time. The three set back schedules examined are shown in Chapter 6. The values of the parameters listed in Table 5.2.1 are included in the program. For a single simulation, the parameters for the house are set to the average values which are converted into SI units. If actual weather is to be used as the forcing function, the selected weather file is read and an array of ambient temperatures in degrees Celsius created.

The constant gains for the house are determined as described in section 5.2.2.3. For one simulation, the initial condition is that the house internal temperature is exactly at the thermostat set point and the furnace is on. The thermostat set point is defined as the temperature at the center of the thermostat dead band.

The value of the thermostat set point is determined for each time step according to the selected distribution of set point change times. A subroutine is then called which returns the times required for T_R to reach the next several thermostat limits, due to oscillating through the dead band, by utilizing equation 5.1.4 with the furnace status, T_{amb}, and the value of T_R at the beginning of the time step. The exact time required for T_R to reach a thermostat set point, T_{Rhigh} or T_{Rlow}, is calculated. If the calculated time is longer than the time step, the subroutine ends. If the calculated time is shorter than the time step, the time required to reach the other side of the dead band is calculated. The use is then assigned to the minutes within the time step. The value of T_R at the end of the time step is then found with equation 5.1.4. One output of a single simulation is the heater gas draw per minute. For one house, the draw is the heater's full gas draw capacity when on, zero when off, and a fractional draw on the minutes in which the heater turns on or off. The furnace cycling on the selected time step is then created by averaging the minute by minute output. The time step does not effect the accuracy of the simulation. The on/off cycling is determined to a fraction of a second. The length of the time step only effects the weather input period and the averaging of the gas use.

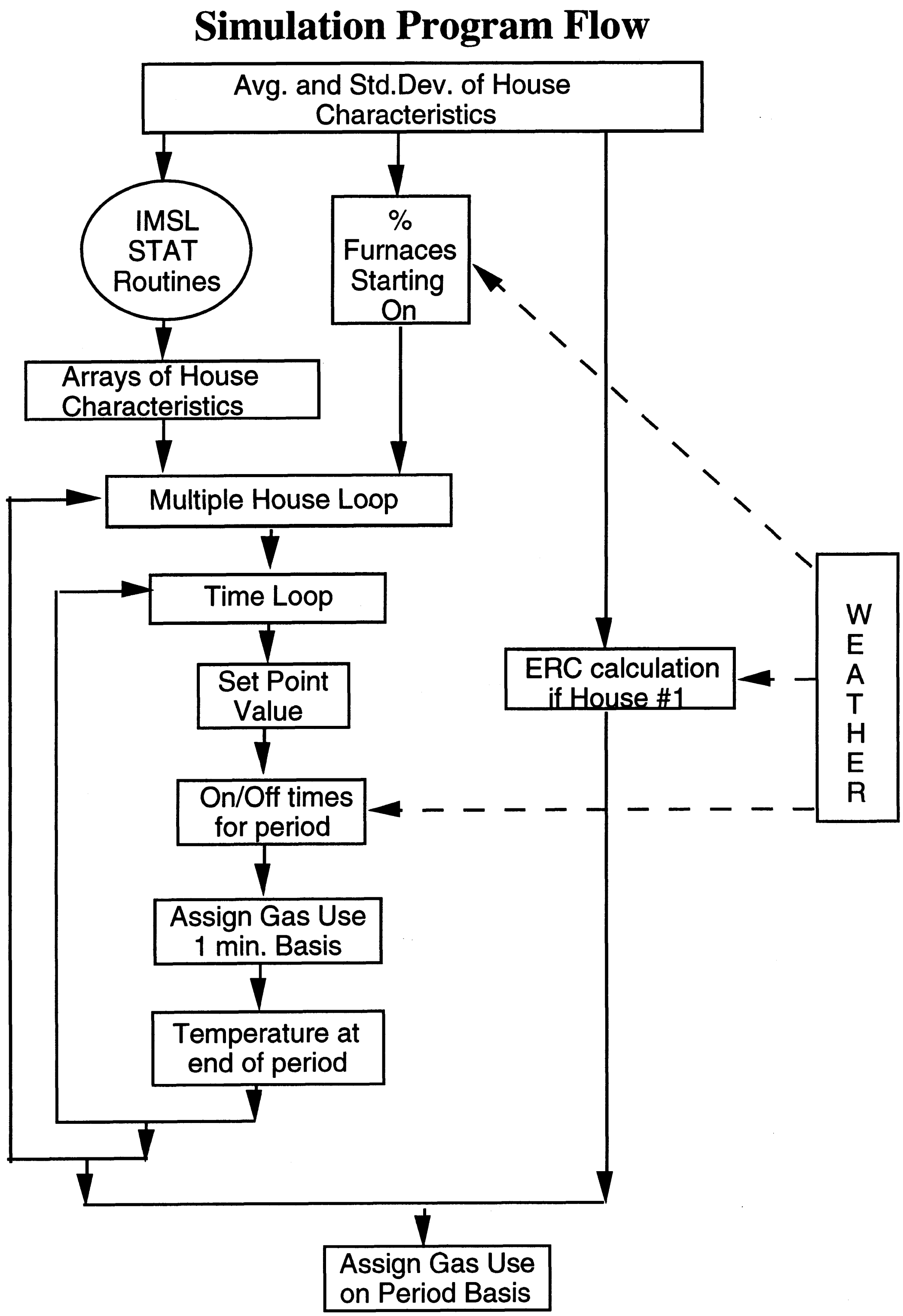


Figure 5.3.1: Simulation Program Flow Chart

5.3.2 Simulation Flow for Multiple Temperature Level Control Simulations

The majority of the calculations for multiple simulations is the same as for a single simulation. All houses are started at the thermostat set point as for a single simulation, but not all furnaces are on. The percentage of houses whose furnaces begin on is determined such that the use in the first period is the expected value for the ambient temperature from Equation 5.2.6. This initial condition is used to minimize the initial fluctuations, but such fluctuations still exists as shown in Chapter 6.2. For multiple simulations, the parameters for the houses are read from the arrays created by the IMSL STAT routines from the values of average and standard deviation for the ensemble. The calculation of furnace on and off times and the subsequent assigning of use to time periods occurs after the house parameters for the house are read from the parameter arrays.

Each house's gas draw for each minute of the time period is determined one house at a time while a running total for each minute is maintained. The use is then summed for each period of analysis, averaged, and printed to a data file.

5.3.3 Energy Rate Control Run

The ERC run is performed with the average values of loss coefficient, internal set point temperature, and constant gains of the ensemble. The ERC run is performed in the first loop of the program, so it occurs once in every run. The results of the ERC run are calculated in the same subroutine which calculates the on and off times for the furnace for the TLC runs. One Use value is determined for each time step, so no averaging needs to be performed.

CHAPTER
SIX

SIMULATION RESULTS

In this chapter, the results of temperature level controlled simulations will first be compared to the remote metering device (RMD) acquired gas consumption data from the WGC study. It will be shown that the temperature level controlled simulations using actual weather recordings and house parameters derived from measured parameters can reasonably match monitored consumption data when equal numbers of systems are compared. The effects of the distribution of thermostat set point change times and the size of the ensemble of houses on the gas use of the ensemble are then shown. Finally, the limitations of using a single energy rate controlled simulation to determine the gas use of a large number of houses and a technique for overcoming the limitation are discussed.

6.1 Comparison of Actual and Simulated Gas Use

As shown in Chapter 4, the metered gas use data is reliable for some days. The average use of an ensemble of houses on several reliable days is compared to the results of TLC simulations run with the actual weather and the same numbers of systems as were monitored. The goal is to show that the simulation produces reasonable results. With the simulation tested, the results of a larger number of simulations can be trusted. It is not possible to directly compare a large number of simulations to the metered data, because the data set contains a maximum of 94 houses on a single day.

6.1.1 Rationale for Choosing Days

The days to be compared were chosen based upon the perceived reliability of the 5 minute metered data and the average ambient temperature for each day. A range of ambient temperatures was desired, so the average ambient temperature of the selected days range from -10 °F to 42 °F. The checks performed on the metered data are explained in more detail in Chapter 3. There were a few obvious errors in the data for the analyzed days, but they were not removed. As explained in Chapter 4, removing the data for certain houses based on the presence of "obvious" errors was not deemed valuable because of the unavoidably arbitrary procedure for finding errors.

6.1.2 Inputs to Program

The simulation program was run with the measured ambient temperature for each day. The weather file is on a 15 minute basis. The weather for each day begins at 6 p.m. on the day before, because as will be explained below, the program must be run for a few hours to damp the effects of the initial condition before reliable results can be obtained. The values for the average and the standard deviation for the house parameters used in the simulations are shown in Figure 5.2.1. The houses used to create the average and standard deviations are not the precise houses for which 5 minute metered data exists for the compared days, because the house characteristics file includes houses not monitored during these six days out of the two seasons of the study. Some of the metered houses are not included in the house parameter file, and some of the houses in the parameter file are not in the metered file. Rather than drastically reducing the size of both files by removing houses that were not in both files, it was decided to use as large a sample as possible to create the averages of the house parameters.

6.1.3 Results of Comparison

The results of the simulation program are compared to the RMD acquired gas use data in Figures 6.1.1, 6.1.2, and 6.1.3. For each day, the same number of systems as were monitored were simulated with temperature level control. The plots show the average gas use of the ensemble of furnaces on a 15 minute basis for the monitored and simulated houses. The number of systems compared and the average ambient temperature for each day are shown in Tables 6.1.1 and 6.1.2. The simulations were performed with the best estimate of the night set back schedule shown in Figure 6.6.3. As noted in Chapter 3, an estimate of the base load profile has been subtracted from the metered data in order to separate furnace gas use from the whole house gas use.

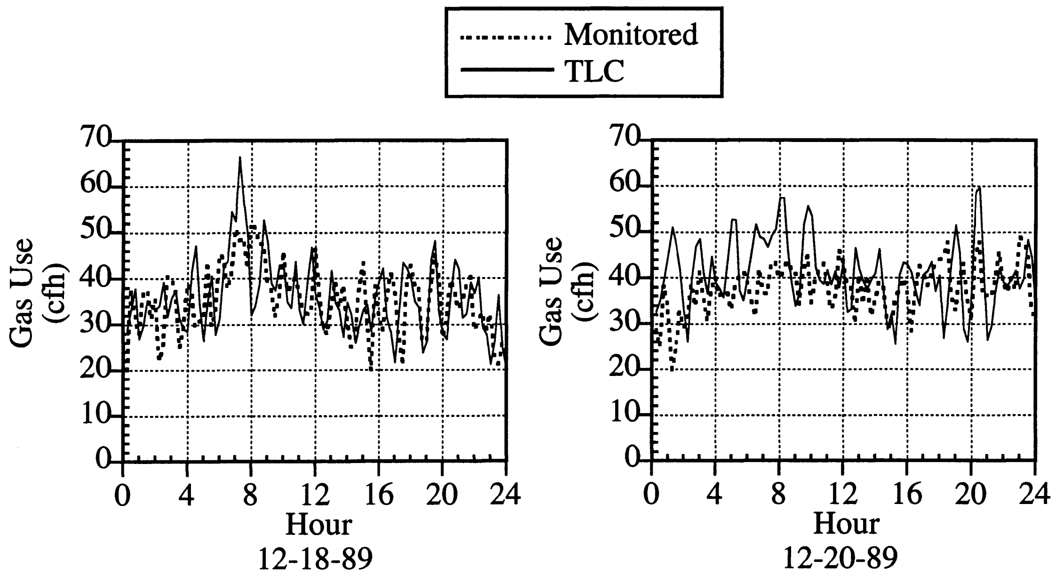


Figure 6.1.1: Comparison of measured and simulated furnace gas use with 38 and 39 systems for 12-18-89 and 12-20-89

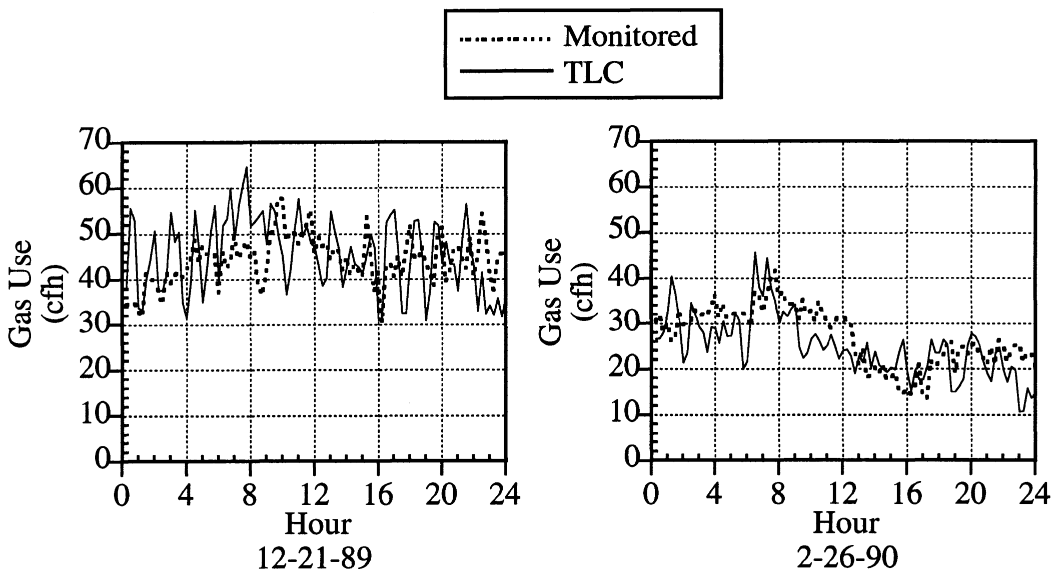


Figure 6.1.2: Comparison of measured and simulated furnace gas use with 38 and 94 systems for 12-21-89 and 2-26-90

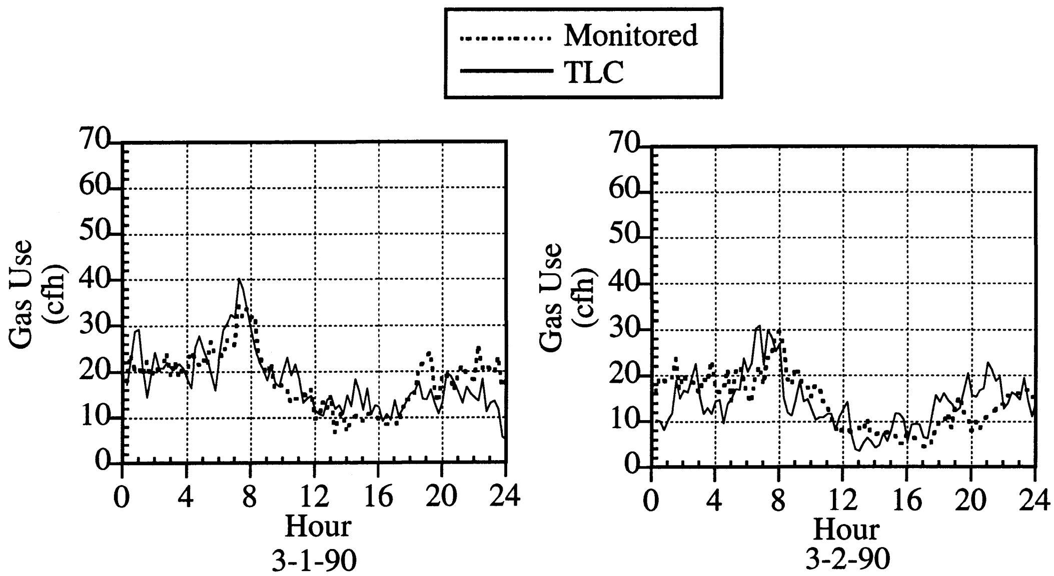


Figure 6.1.3: Comparison of measured and simulated furnace gas use with 94 systems for 3-1-90 and 3-2-90

The simulation is compared to the monitored data on the basis of the average and peak gas use and the shape of the use curve. The simulations generally match the shape of the measured data rather well. They show the same variation over the course of the day, with gas consumption lowest in the afternoon when the ambient temperature rises. The morning peak due to most households turning up the thermostat can be clearly seen. The average and peak gas use for the simulations and the measured data are compared in Tables 6.1.1 and 6.1.2 respectively. The average and peak gas use for the 6 days are an average of 5% and 18% higher than the monitored use.

Table 6.1.1: Comparison of measured and simulated furnace gas use with equal numbers of systems for 6 days

Day	Number of Systems	Average T_{amb} (°F)	Average Actual Use (cfh)	Average TLC Use (cfh)	Average ERC Use (cfh)	Ratio of $\frac{TLC}{Actual}$
12-18-89	38	10	29.2	35.8	35.3	1.23
12-20-89	39	-2	37.8	41.3	41.8	1.10
12-21-89	38	-10	44.2	45.4	46.6	1.03
2-26-90	94	20	27.0	25.0	25.3	0.93
3-1-90	94	34	18.3	18.0	17.7	0.98
3-2-90	94	42	14.2	14.2	14.5	1.00
					Average	1.05

Table 6.1.2: Comparison with equal numbers of systems of measured and simulated peak furnace gas use for 6 days

Day	Number of Systems	Average T_{amb} (°F)	Peak Actual Use (cfh)	Peak TLC Use (cfh)	Peak ERC Use (cfh)	Ratio of $\frac{TLC}{Actual}$
12-18-89	38	10	46.5	66.5	40.1	1.43
12-20-89	39	-2	49.0	59.8	45.6	1.22
12-21-89	38	-10	57.9	64.6	50.4	1.12
2-26-90	94	20	41.8	45.7	31.7	1.10
3-1-90	94	34	34.2	40.4	23.5	1.18
3-2-90	94	42	29.6	30.9	19.7	1.04
					Average	1.18

Some difference between the simulated and monitored data is expected in both the average gas use and the shape of the load curve for several reasons. The distribution of set back times used in the simulations is probably less smooth than the true distribution of the monitored houses, and as will be shown below, the predicted peak load decreases with smoother set back distributions. Also, the simulation lumps the time dependent effects of solar incidence, wind, and occupant level into a single constant value of gains. Thus, the simulated use for sunny, calm days should be larger than the actual use because the solar gains for the day will be higher than the average value used in the simulation. Also, even if the simulations predicted furnace gas use perfectly, they would not perfectly match the monitored use. There is significant uncertainty in the shape of the base load which was subtracted from the monitored whole house data. Also, as shown in Chapter 4, the average and peak use of an ensemble of monitored houses can change significantly if some of the houses are replaced with others. The consistent overestimation of peak load is largely due to the larger fluctuations in the simulated gas use. The larger fluctuations in the simulated use are irrelevant in predicting the gas use of a large number ($\geq$1000) of furnaces, because the magnitude of the fluctuations decrease with increasing numbers of systems.

6.2 Effect of Initial Conditions

A series of simulations with constant weather as the forcing function was performed to determine the effect of initial conditions independent of weather induced effects. The program begins with every house's internal temperature at the set point. The percentage of furnaces operating at the beginning of the simulation is set equal to the steady state percentage of furnaces operating at the initial ambient conditions. The results of TLC simulations performed for constant ambient temperatures of -30°F and 20°F for 1000 houses are shown in Figure 6.2.1. Only the gas use of the ensemble for the first 6 hours of the simulation is shown, because the use does not change after this point.

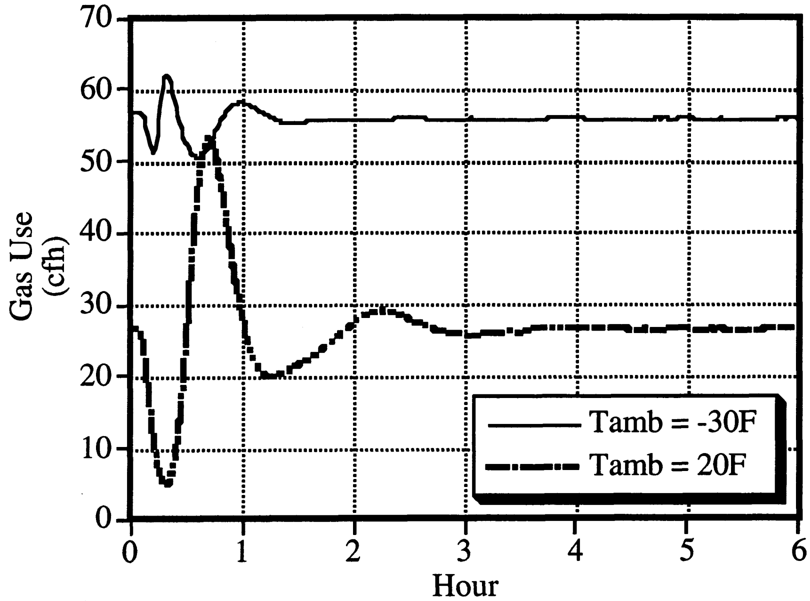


Figure 6.2.1: Simulated gas use for 1000 TLC houses for constant T_{amb} of -30°F and 20°F for the first 6 hours of the simulation

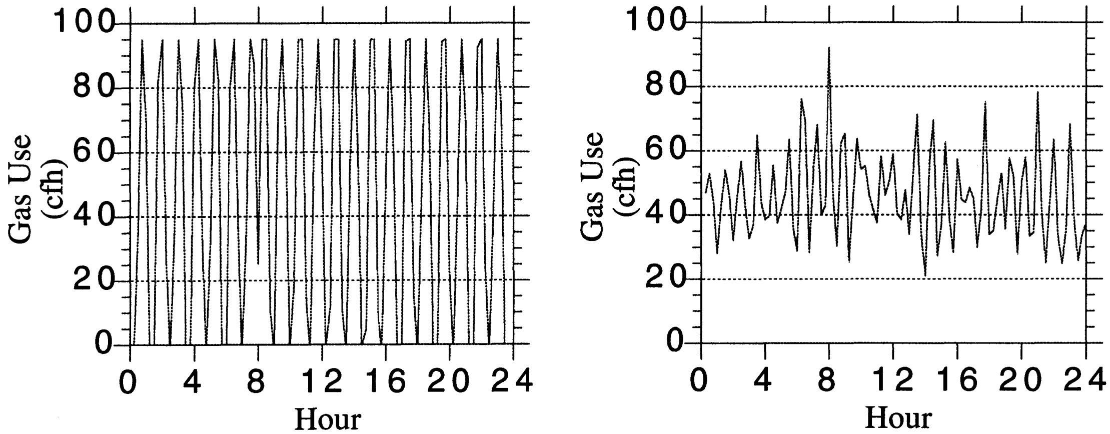
After the initial transient response caused by the initial condition, the gas draw oscillates around the value predicted by a simulation using energy rate control for a house with the average house parameters. The smoothness of the gas use increases with number of simulations as will be shown below, but the basic shape of the initial transient is independent of the number of simulations. The initial behavior is apparently due to a level of coincidence in the timing of the furnace cycles caused by the initial condition before they become randomly distributed. The effect of the initial condition is negligible after approximately four hours as indicated by Figure 6.2.1. All simulations with real weather were started 6 hours before the time period of interest in order to avoid the initial response.

6.3 Effect of Period of Analysis

The effect of the period of analysis on the shape of the ensemble gas use curve has been shown in Chapter 4 for monitored data. The effect is the same for simulated use, as increasing the period of analysis is simply performed by averaging the use for shorter periods. Increasing the length of the period of analysis smoothes the use curve. This smoothing is less pronounced for large numbers of systems, because the use curve is smooth even with short periods of analysis.

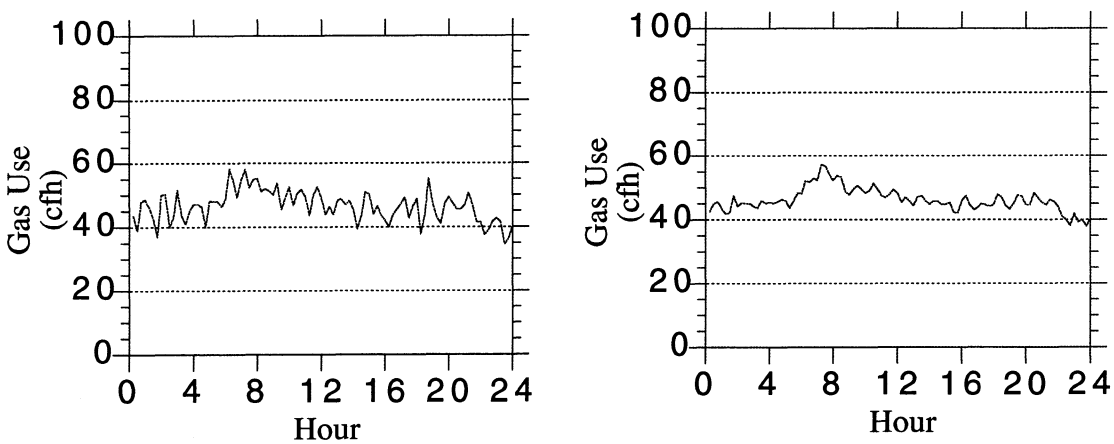
6.4 Effect of Number of Systems

In order to show the effect of the number of systems on the average gas use of the ensemble, temperature level controlled simulations were performed for 12-21-89 for a range of sizes of groups of systems. The simulations were performed with the best estimate of the distribution of furnace set point change times (shown in Figure 6.5.3). The results of the simulations are shown in Figures 6.4.1, 6.4.2, and 6.4.3 for different numbers of houses. The results for 10,000 and 100,000 simulations are the same as for 1000 simulations.



1 House 10 Houses

Figure 6.4.1: Average furnace gas use on 12-21-89 as determined from simulations the smooth set back schedule for ensemble sizes of 1 and 10 houses



100 Houses 1000 Houses

Figure 6.4.2: Average furnace gas use on 12-21-89 as determined from simulations with the smooth set back schedule for ensemble sizes of 100 and 1000 houses

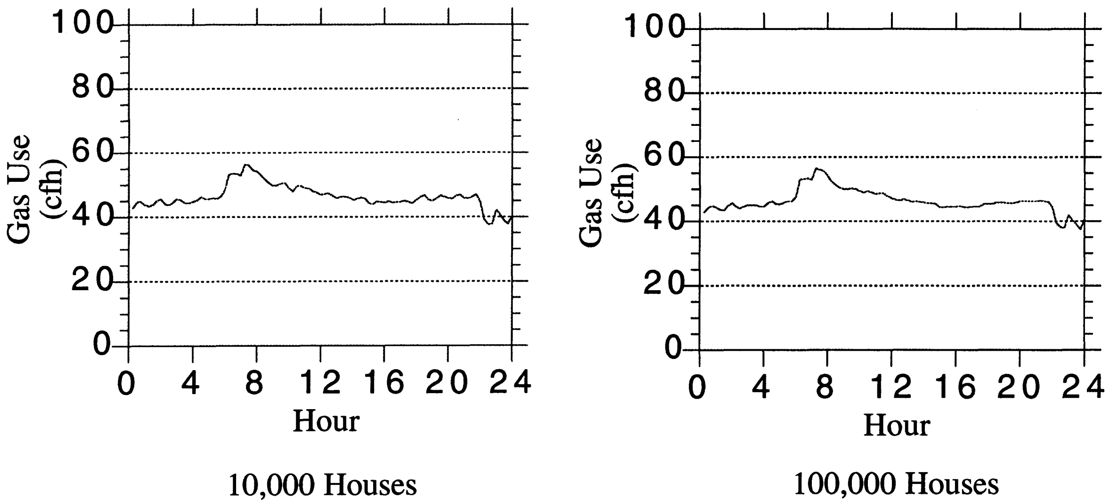


Figure 6.4.3: Average furnace gas use on 12-21-89 as determined from simulations with the smooth set back schedule for ensemble sizes of 10,000 and 100,000 houses

Figure 6.4.4 is a load duration curve for the simulations of gas use on 12-21-89 (Figures 6.4.1 - 6.4.3). The gas use for each simulation is placed in descending order, so the peak use for each simulation is the intercept on the gas use axis. The curve for a single furnace is not a perfect step although the furnace is either on or off. The single furnace curve would be a perfect step if the period of analysis were infinitesimal. For finite periods, the gas use includes periods in which the furnace is on for only a portion of the period. As expected, the peak use decreases with an increase in the number of simulations. The curves becomes more smooth with increasing numbers of systems, because the coincidence between systems decreases. For a small number of systems, chances are high that many of the furnaces will be on at the same time at some point within the day causing a peak. For a larger number of systems, the probability of many more furnaces being on at the same time than would be on when the cycles are randomly distributed decreases. The use for 1000, 10,000 and 100,000 systems are practically indistinguishable, and the differences between 100 and 100,000 systems are small.

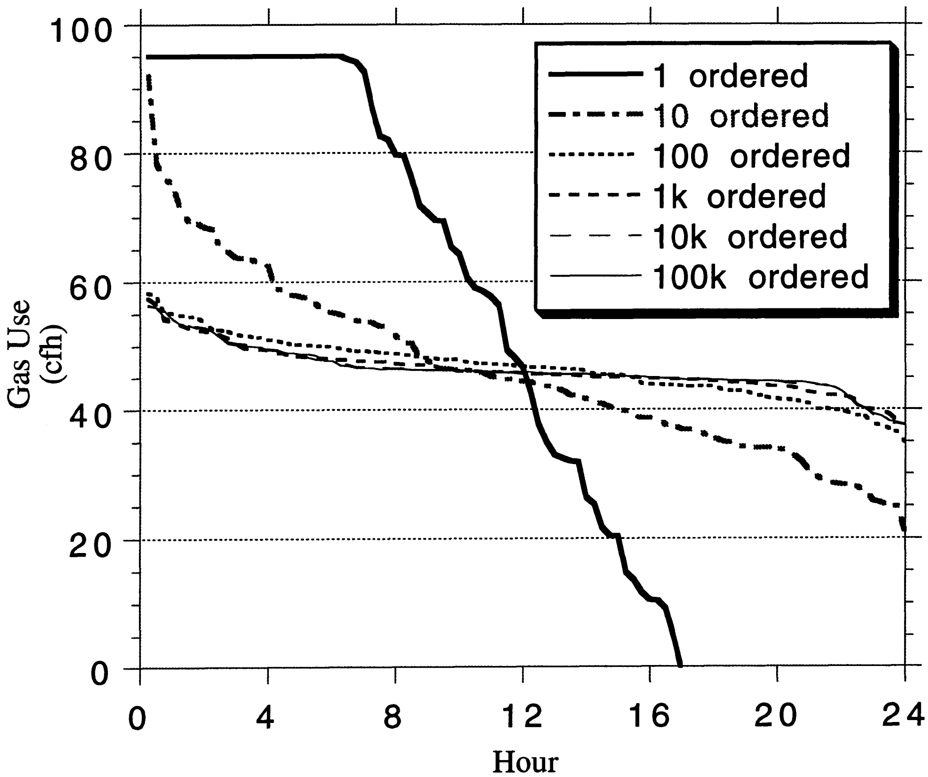


Figure 6.4.4: Load duration curve of average furnace gas use on 12-21-89 as determined from TLC simulations with set back schedule C for several ensemble sizes

The gas use as predicted from a single energy rate control and 100,000 temperature level control simulations for 12-21-89 are compared in Figure 6.4.5. The results of the two methods are almost identical away from changes in the thermostat set points. Slight differences, even away from changes in the thermostat set points, are expected, because the ERC simulation uses the set point rather than the true average internal temperature to calculate the heating load. The ERC simulation responds much less drastically to the set back because it does not include the house's thermal mass (see Section 6.5). The peak use for the ERC simulation is thus lower than for the TLC simulations.

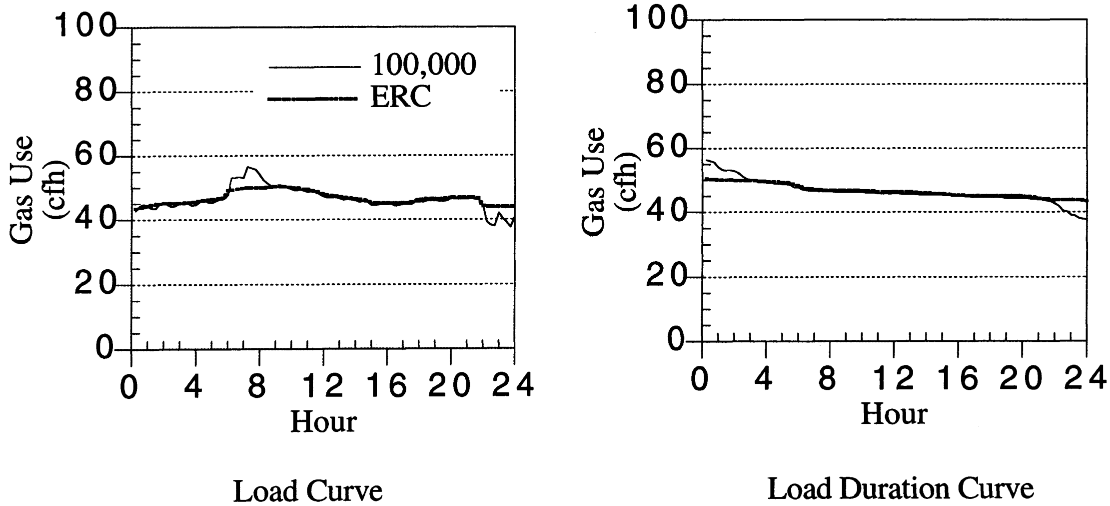


Figure 6.4.5: Average furnace gas use on 12-21-89, in original order and ranked, as determined from 1 ERC and 100,000 TLC simulations with set back schedule C

6.5 Effect of Night Set-Back

An individual house thermostat will typically be programmed to change the set point twice per day for night set back. In general, not all houses in an ensemble will have thermostats set to change at the same time. The distribution of set back times for the ensemble has a very large impact on the peak use of the ensemble, because it introduces coincidence into the furnace cycles of the ensemble. To clearly show the effect of the distribution of set back times unconfounded with weather effects, simulations were performed with a constant ambient temperature for a day for three distributions of thermostat set back times.

The three distributions are shown in Figures 6.5.1, 6.5.2 and 6.5.3. In the first scheme, the thermostat set points of all houses in the ensemble change at the same time (7:00 a.m. and 11:00 p.m.). In the second scheme, the set points change at three times over a period of two hours, and the changes occur on the hour. The morning turn up occurs at 7:00, 8:00, and 9:00 a.m. and the night set back occurs at 10:00 p.m., 11:00 p.m. and midnight. The most realistic set back scheme tested involved a smoother distribution of set point change times for the ensemble as shown in Figure 6.5.3. The morning turn up occurs over a two hour period from 5:45 to 7:45 a.m. and the turn down occurs from 9:45 to 11:45 p.m.. It was assumed that most thermostats will be set to change on the hour, fewer on the half hour, and even fewer at other times. For this scheme, unlike the previous schemes, internal set point changes were allowed to occur within the hour.

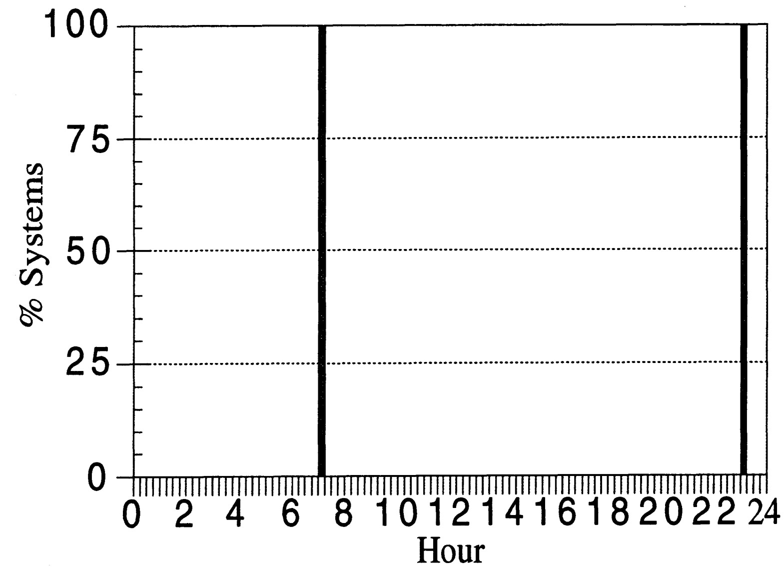


Figure 6.5.1: Thermostat set point change times distribution (A)

in which changes occur at one whole hour

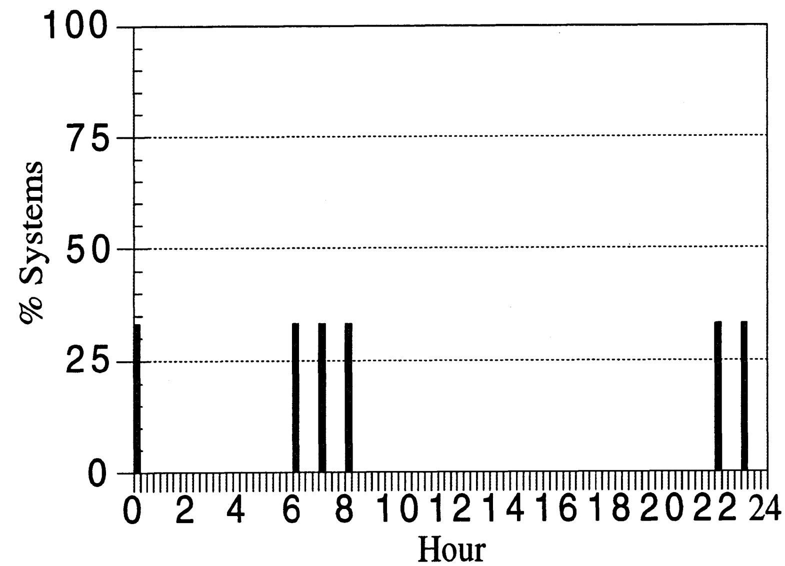


Figure 6.5.2: Thermostat set point change times distribution (B)

in which changes occur at three whole hours

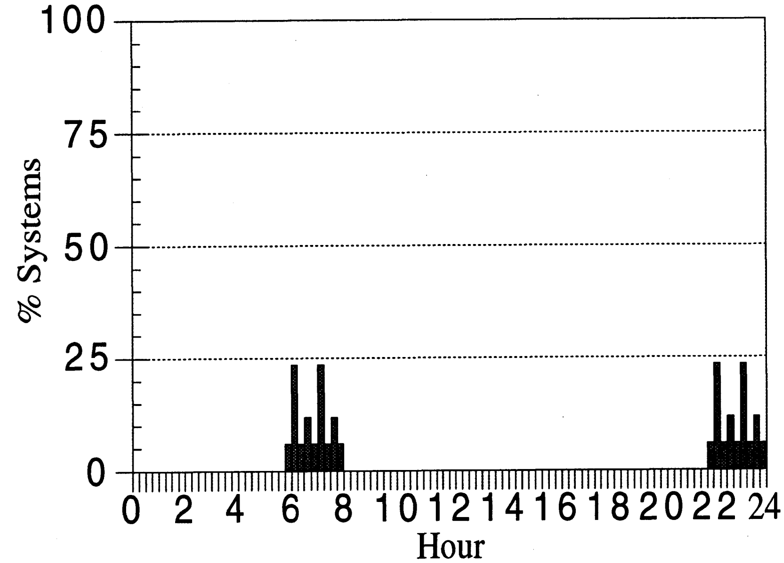
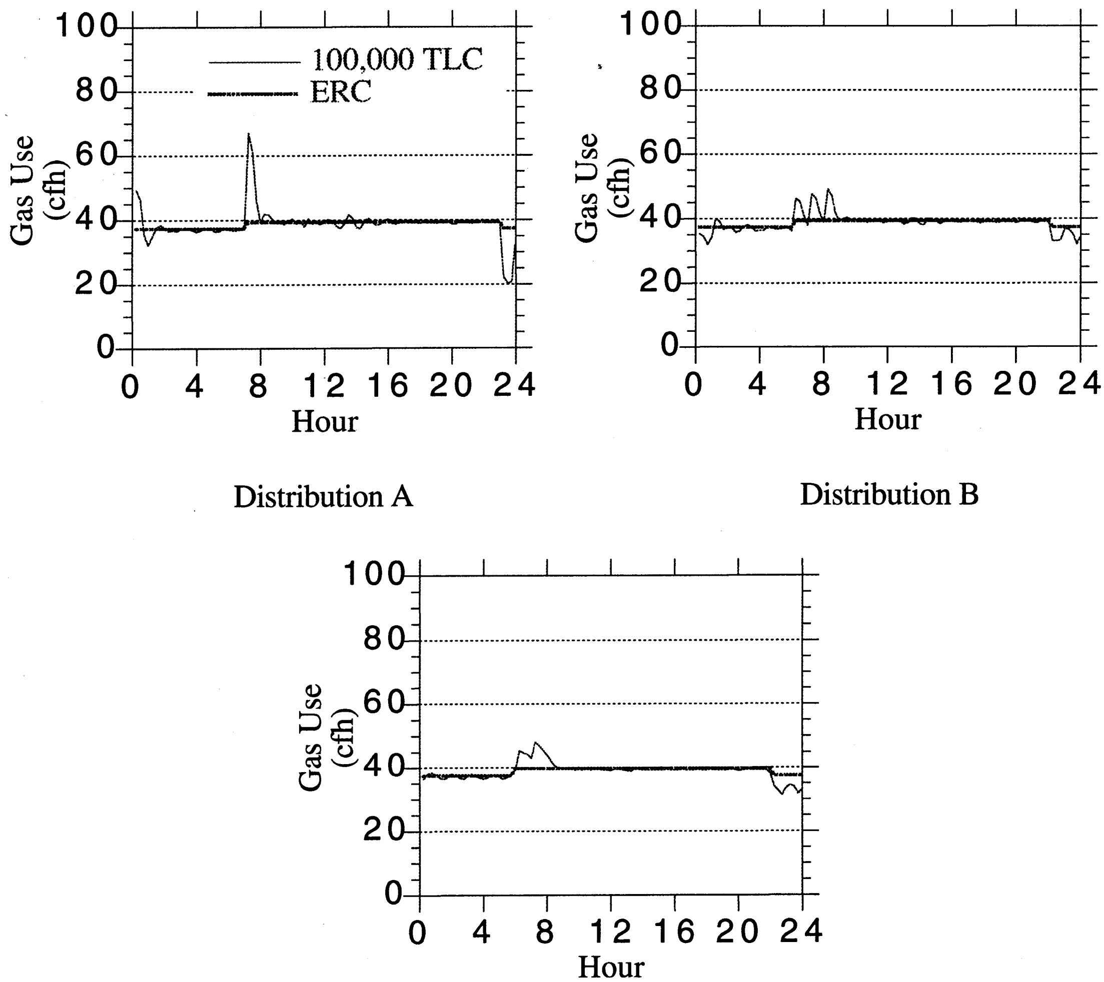


Figure 6.5.3: Distribution (C) of thermostat set point change times

The results of the simulations for the three set back distributions shown above are shown in Figure 6.5.4. For each distribution, a single ERC and 100,000 TLC simulations were performed. For each distribution, the TLC simulations respond to the set point changes with a large change in use. The gas use as predicted from the ERC simulation barely changes when the set point changes. The peak use of the ensemble as determined from the TLC simulations decreases from distribution A to B to C, because the degree of coincidence in the furnace cycles of the ensemble created by each distribution decreases.



Distribution C

Figure 6.5.4: Average furnace gas use for constant ambient temperature of $T_{amb} = 0$ °F as determined from 1 ERC and 100,000 TLC simulations with thermostat set point schedules A, B, and C

A sharp increase in the gas use as predicted from the temperature level control simulations immediately follows the increase of at least some of the houses' thermostat set points. Figures 6.5.5, 6.5.6, and 6.5.7 show the three possible responses of a temperature level controlled house to a sudden increase in the set point. In response A, the furnace was off before the set point change but was forced to turn on immediately after the change. In response B, the furnace is on before the change but will remain on for a longer period of time than if the set point had not been increased, because the furnace must heat the house up to the new set point. The furnace in response C is off before the change and is not forced to immediately turn on after the change. However, it will turn on more quickly after the change than it would have without the change. A large ensemble of houses will likely contain houses which respond in all three of these ways. An average of the responses leads to an increase in use of the ensemble after the thermostat set point increase. An analogous response follows the decrease in the set point at night.

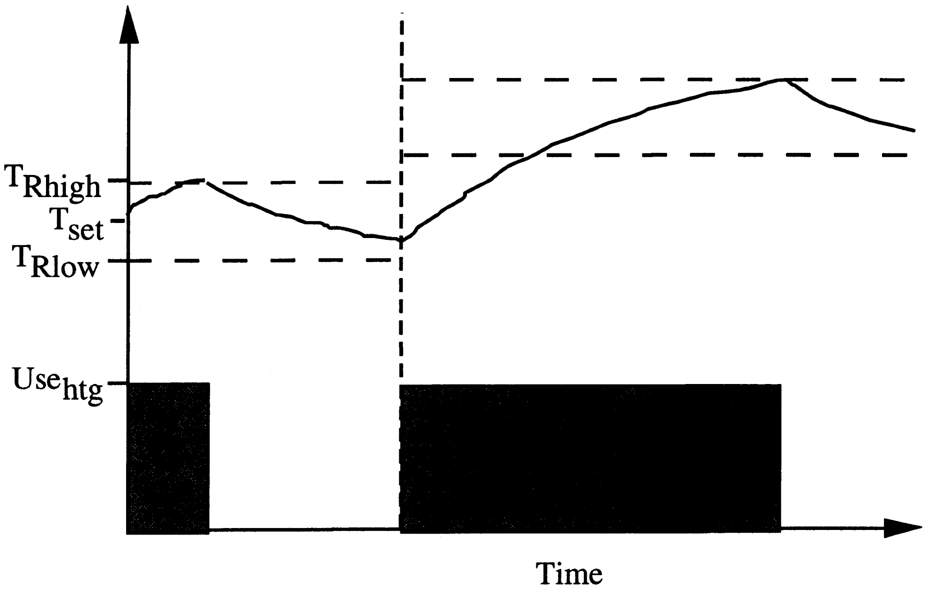


Figure 6.5.5: Response (A) of furnace gas use and internal house temperature to a thermostat set point change

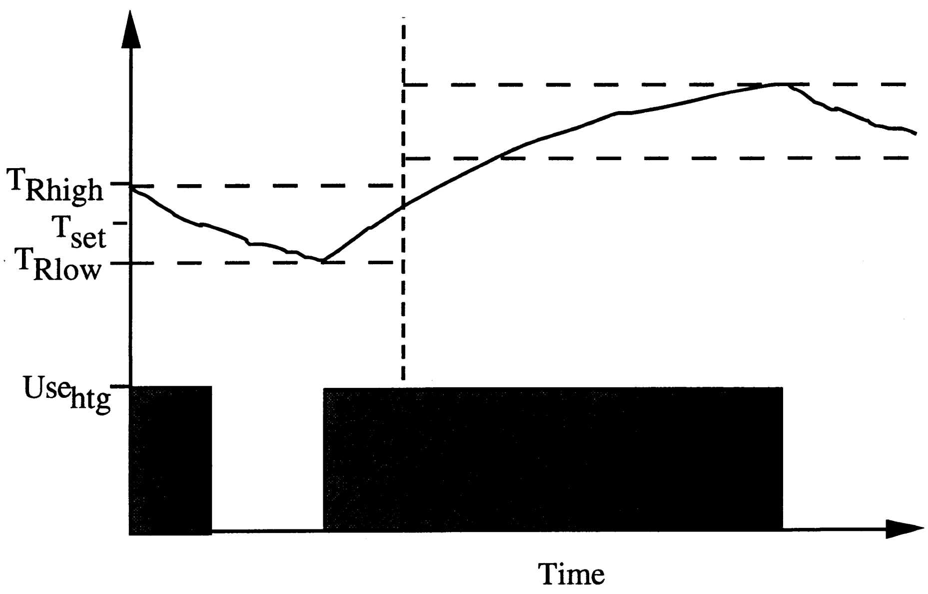


Figure 6.5.6: Response (B) of furnace gas use and internal house temperature to a thermostat set point change

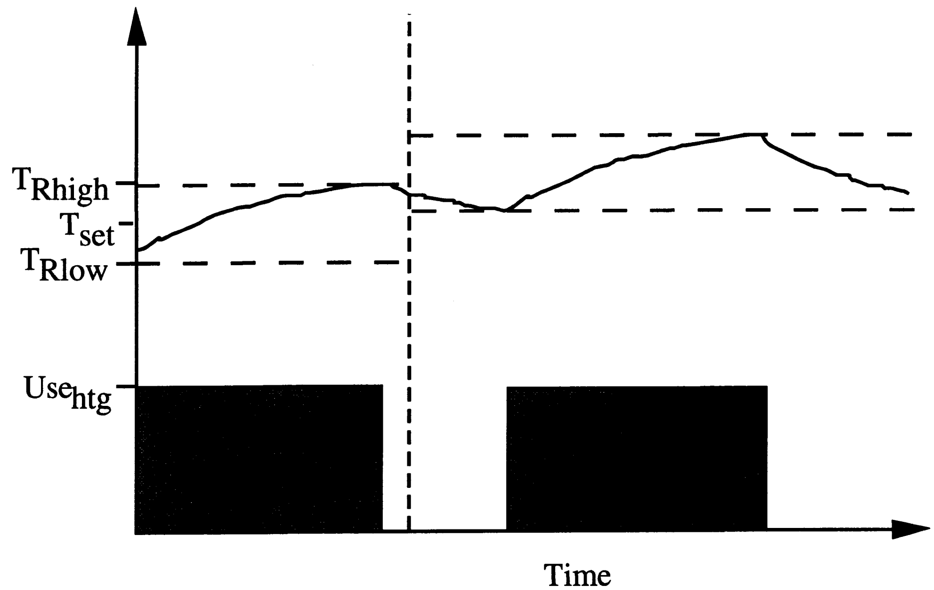


Figure 6.5.7: Response (C) of furnace gas use and internal house temperature to a thermostat set point change

A single energy rate control simulation agrees almost exactly with a large number of TLC simulations except for time immediately after the set point change. A limitation of the ERC assumption is that it can not reflect the increase in gas use of a large number of systems following an increase in the set point. The response of an ERC house to a set point increase is shown in Figure 6.5.8. The ERC simulation does not include the effect of the house thermal capacitance, because in the calculation of furnace use, the house internal temperature is assumed to always be equal to the thermostat set point. When the set point changes, the house temperature is immediately assumed to change. The furnace does not have to heat up the house; it only maintains the house temperature. The furnace use does increase slightly after the set point change, because the load, which is proportional to the temperature difference between the ambient and the set point temperature, increases. The increase is slight, so the actual internal temperature will only slowly increase to the new set point.

The average use of the ERC and TLC simulations are equal. The area between the ERC and TLC curves during the morning set point increase is equal to the area between the ERC and TLC curves near night set back. In each case, the area is equal to the energy required to heat the average thermal capacitance of the ensemble the temperature difference between the old and new set points. The missing response might be added to the ERC simulation with a scaled capacitance correction. The amount of energy to be added or subtracted from the ERC simulation is given by the product of the average thermal capacitance and the temperature difference between the old and new set points, but the distribution of the energy over time is unclear. The shape of the capacitance correction depends upon the shape of the distribution of set point change times but in a complicated manner. It was not possible to determine the precise shape of the capacitance correction corresponding to a given set back distribution using physical reasoning.

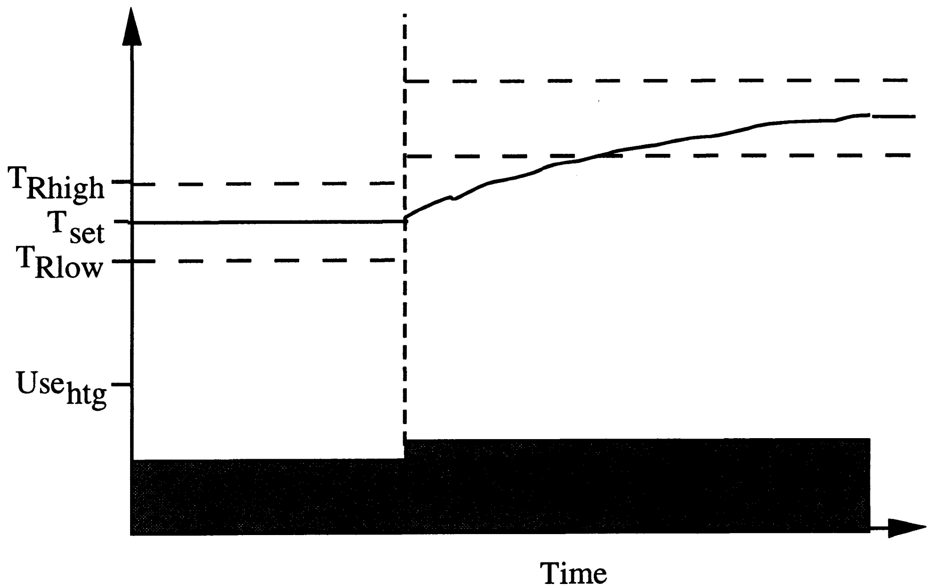


Figure 6.5.8: Response of furnace gas use and internal house temperature to a thermostat set point change for a single ERC controlled house

A single TLC simulation with very narrow dead bands will show an increase in gas use for an ensemble after a set point change with a single simulation as shown in Figure 6.5.9. However, the increase in use after the set point change will be unrealistically high. For a very narrow dead band, the furnace will cycle very quickly. When this cycling is averaged to a useful period of evaluation such as 5 or 15 minutes, the use will appear as the heavy lines in the figure. The furnace must turn on a very short time before the change or at the change because only furnace responses A and B are possible. The predicted gas use with this method will be different from that of the ERC simulation immediately after the set point change and no closer to the use of a large number of TLC simulations.

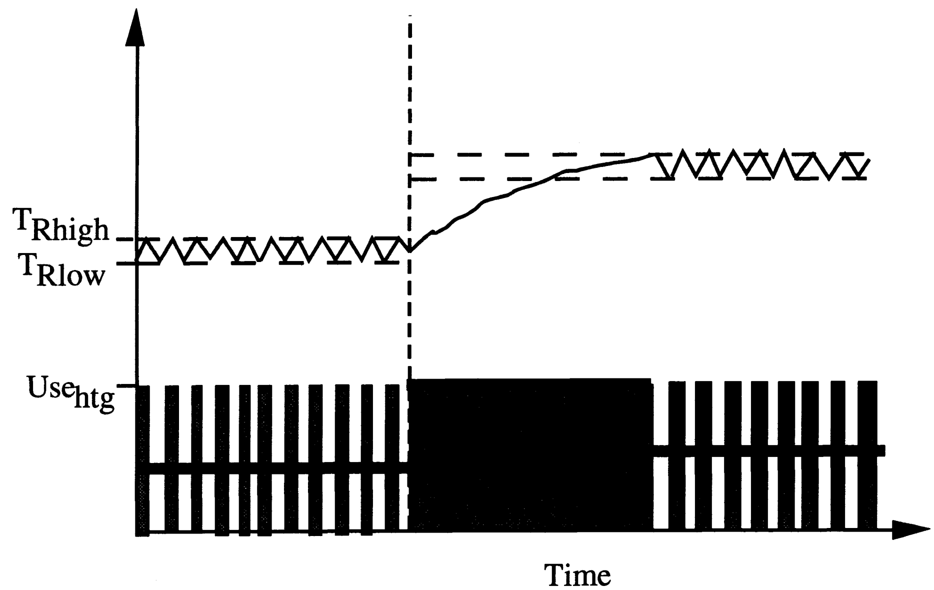


Figure 6.5.9: Response of furnace gas use and internal house temperature to a thermostat set point change for a single TLC controlled house with a very small dead band

6.6 Conclusions

The simulation program, using temperature level control, has been found to agree reasonably well with monitored gas use data once an estimate of the base load shape was subtracted from the whole house data. This agreement provides confidence in the results of the simulation when large numbers of simulations are performed. Increasing the number of simulations was found to decrease the coincidence in the furnace cycles of the ensemble, so the predicted peak load of the ensemble decreases.

The distribution of thermostat set point change times was found to have a large effect on the peak load of the ensemble as determined from a large number of temperature level control simulations. Smoother distributions create less coincidence in the furnace cycles. Both a single temperature level control simulation with a very small dead band and a single energy rate control simulation were found to match the predictions of a large number of temperature level control simulations of the utility impact of an ensemble at times away from the set point changes. A single temperature level control simulation with a very small dead band yields unrealistic predictions of the impact of set point changes. A single energy rate control under-predicts the change in the ensemble use caused by a change in set point, because it neglects the house thermal capacitance.

CHAPTER
SEVEN

IMPLICATIONS FOR AIR CONDITIONING

The main cause of a typical electric utility's summer peak is air conditioning, so programs that shift or reduce the electricity use of air conditioners in a utility's district are prime candidates for demand side management programs. A simple program is to offer rebates for the purchase of highly efficient air conditioners. In this chapter, the simulation methodology developed in Chapter 6 is applied to residential air conditioners to determine the impact of a large number of air conditioners on the utility load curve. The effect of a change in the average coefficient of performance (COP) of an ensemble of residential air conditioners on the utility peak load will be determined. Though the thermal loads are not the same as for heating, air conditioners posses the same operating character as furnaces. They respond to room thermostats and turn on to full capacity and off to zero use. The effect of summing a large number of systems will thus be the same as for furnaces.

7.1 Mathematical Description of Model

A relatively simple cooling load model is used in the residential air conditioning simulation. The effects of ambient temperature, solar insolation, and humidity on the loads are considered, but the detailed effects of window orientation are not included. The cooling load (Q_c) on a house is modeled as

$$Q_c = 0.2UA\,(T_{sa} - T_R) + 0.8UA(T_{amb} - T_R) + \dot{m}c_{pa}(T_{amb} - T_R) + \dot{m}(w_{amb} - w_R)i_{fg} \tag{7.1.1}$$

where the sol-air temperature (T_{sa})is defined as

$$T_{sa} = T_{amb} + \frac{\alpha I_T}{h_{si}} \tag{7.1.2}$$

The effect of solar insolation is included through the use of a sol-air temperature in the calculation of the heat gain through the roof in the first term of the equation. The horizontal solar radiation is used, so the assumption is that the heating effect of the radiation is only significant on the roof. The 0.2 scaling factor on the first term accounts for the area of the roof being 20% of the total external area of the house. The second term is the conduction through the rest of the external walls of the house. The third and fourth terms are the sensible and latent portions respectively of the infiltration load.

As shown in Chapter 6, the impact on the utility of a large number of systems, in the absence of significant changes in the internal set point of the houses, can be determined from the use of a single house with the average characteristics of the ensemble modeled with energy rate control. The electrical power consumed (P) due to air conditioning of the average house modeled with energy rate control is

$$P = \frac{Q_c}{COP}$$

7.2 Simulation Procedure

The ERC simulation was performed with the equation solving program EES; the EES program is included in the Appendix. The weather data used as the forcing function for the simulation were taken from TMY data for Madison, Wisconsin. The particular day modeled, August 1, was hot and sunny although there is a sharp increase in the humidity in the afternoon. The value of the house loss coefficient UA is from the Wisconsin Gas survey data and is the same as was used in the furnace simulations. It was not necessary to perform large numbers of TLC simulations, because the relationship between the two simulation methodologies was established in Chapter 6. Thermostat set-back was not included in the simulation

7.3 Results

The use of a large number of residential air conditioners, as determined from a single ERC simulation with the average system characteristics, on the electrical load curve is shown in Figures 7.3.1 and 7.3.2 for two values of the average COP of the ensemble. The spike in use at 4:00 p.m. is due to an increase in the latent infiltration load caused by a large increase in the humidity for this hour. The solar radiation remained high in this hour however. The combination of sunshine and a sharp increase in humidity suggest that it was both raining and sunny for this hour, so the presence of the spike should be regarded as an aberration. The effect of increasing COP on the peak load on the electric utility is clearly shown in the ordered frequency distribution plot. An increase in COP yields an equivalent reduction in peak and total consumption.

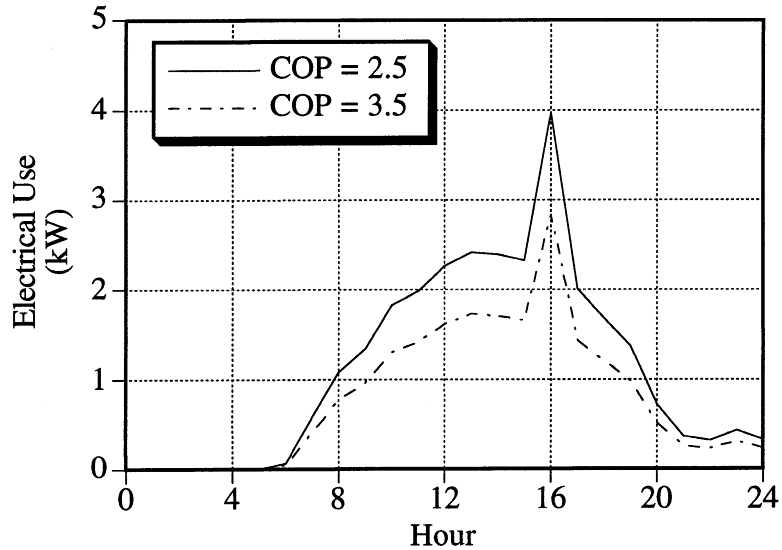


Figure 7.3.1: Electricity use for air conditioning for COPs of 2.5 and 3.5 from energy rate control simulations of single systems

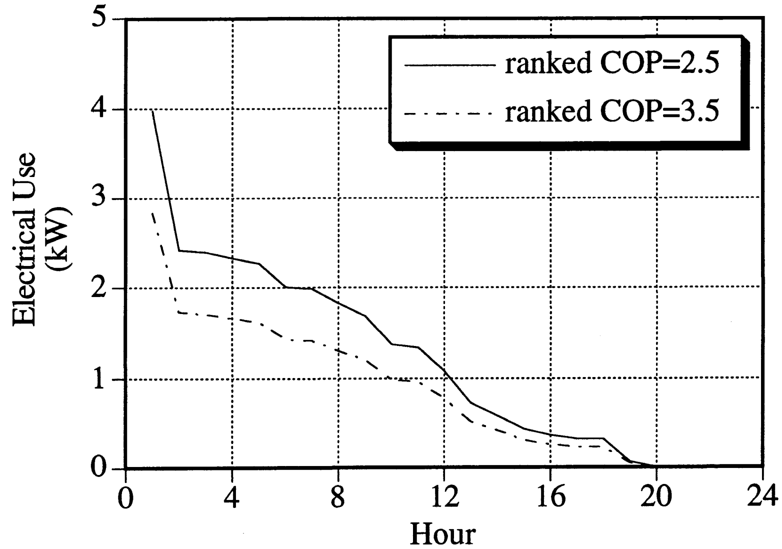


Figure 7.3.2: Ordered electricity use for air conditioning for COPs of 2.5 and 3.5 from energy rate control simulations of single systems

The analysis does not include the effect of behavioral factors such as thermostat set back. The actual peak load impact will be greater than predicted if a significant fraction of the houses in the utility district turn the thermostat set point down in the late afternoon, as this will introduce coincidence in the air conditioner cycles. A large number of TLC simulations would provide a better estimate of the peak load reduction only if the distribution of thermostat change times were known in detail. For purposes of estimating the energy impact, the ERC simulation can be used with confidence.

CHAPTER
EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

An assessment of methods for predicting the utility impact of a large number of systems has been described. A simulation program for residential gas furnaces was developed and satisfactorily compared to monitored gas use data. The results of large numbers of temperature level controlled simulations were then compared to the results of a single energy rate control simulation. Finally, an energy rate control simulation of residential air conditioners was performed.

8.1.1 Monitored Data

Some useful information can be gained from monitoring gas use on intervals as short as 5 minutes, but such a short interval is not required for developing a simulation model to predict the gas use of a large number of houses. For some houses, it was possible to clearly determine, from the 5 minute data, the number of furnace cycles on a day and the maximum length of time the furnace remained on. Such information may be of interest to a utility, but it is of little interest in determining the gas use of a large ensemble of houses. Also, short recording intervals create tremendous amounts of data that are then difficult to check for errors. For the purposes for this study, recordings on a 15 minute basis could have been used to establish the reasonableness of the results of the simulations.

The factors determined in the WGC survey of number of floors, presence of a basement, heating status of basement, weatherization quality, number of people living in the house, air changes per hour, age of house, income level of household, and R-values and areas of walls, windows, and roofs may be of use to a utility in predicting the market penetration of a new technology but are unnecessary in determining the impact of a given number of such systems. The necessary information for the development of this model were the loss coefficient, base load, constant gains, furnace size and efficiency, floor area, and thermostat set points. The distribution of thermostat set-back times was also needed but was not determined in the study.

8.1.2 Simulation Methodology

The most precise prediction of the utility impact of an ensemble of systems will be gained from performing several hundred temperature level controlled simulations with a prediction of the weather for the period and the distribution of thermostat set back or other forcing function. It is not necessary to perform more than a thousand simulations. The accuracy of the simulation will depend largely on the degree to which the weather prediction matches the actual weather and the accuracy of the predictions of other forcing functions and the house characteristics.

A single temperature level control simulation with a very small dead band will predict the utility impact of an ensemble at times away from the set point changes but will yield unrealistic predictions of the impact near the set back change. A single energy rate control simulation will inaccurately predict the impact of an ensemble near the thermostat set point change times but will be accurate at other times. An ERC simulation under-predicts the change in the ensemble use caused by a change in set point, because it neglects the thermal mass of the houses. The effect of thermal capacitance could be added to an ERC simulation, and in light of the other uncertainties involved in predicting the utility impact of an ensemble, the uncertainty which would be inherent in the shape of the scaled capacitance correction seems tolerable. The results of a large number of TLC simulations will also be uncertain, because there will likely be significant uncertainty in the set point change time distribution. A single ERC simulation is also much simpler to perform than a large number of TLC simulations.

8.2 Recommendations

1. A more detailed model could easily be developed for both the heating and cooling loads. The adequecy of the lumped capacitance model should be checked through comparison with ASHRAE load calculation methods such as the CLTD/CLF method. Once the loads are established, however, the simulation procedure for determining the utility impact of a large number of systems has been established.

2. The simulation model should be considered when deciding what system characteristics to monitor. In order to determine the average loss coefficient of the ensemble, it should be sufficient to determine through regression the dependence of the total district use on ambient temperature. This could be determined with a study in which the daily energy consumption of a sample of houses and daily average ambient temperature is recorded for a heating season. Even more simply, the total draw on the utility for each day would be sufficient if this information is more easily gained.

3. The distribution of thermostat set-up and set-back times in the utility district should be determined in future monitoring studies for energy systems controlled by thermostats. In order to determine the load shape of a space conditioning end use, it is not sufficient to know only the average set-up and set-back times of the ensemble; the distribution of times is also required. It will likely be difficult to accurately determine the distribution of set-up and set-back times in a utility district, as many users may change the thermostat setting manually at irregular times.

4. The results presented for the electric load curve for an ensemble of residential air conditioners has not been tested versus monitored data. Such a comparison should be performed in order to validate the model. A more complicated load model for calculation of cooling loads may be required. However, it is expected that the ERC simulation is a valid indicator of energy use.

APPENDIX A

GAS FURNACE SIMULATION PROGRAM

```
*****************************************************************
**********************                        ************************
**************                                       *****************
*********                                                ************
*****    RESIDENTIAL GAS FURNACE SIMULATION PROGRAM    ******
*********                                                ************
**************                                       *****************
************************                      ************************
*****************************************************************
*
      IMPLICIT NONE
      COMMON/BLOCK0/qhtgAvg
      COMMON/BLOCK05/UAAvg,TspAvg,TsbAvg
      COMMON/BLOCK01/Tamb(800),fracton
      COMMON/BLOCK015/gainscon,rad(800),flarea
      COMMON/BLOCK1a/UA,C,house,hpfs
      COMMON/BLOCK1a7/Tset
      COMMON/BLOCK1b/Trlow,Trhigh,Trinfon,Trinfoff,Tend
      COMMON/BLOCK12/qhtg,time,tnext1,tnext2,heater
      COMMON/BLOCK127/simper,szsimper
      COMMON/BLOCK1346/Nsims
      COMMON/BLOCK2/endtime,j
      COMMON/BLOCK23/Qsum(10000)
      COMMON/BLOCK3/Qsumax,Nmins,ibig
      COMMON/BLOCK34/Qnorm(10000,1),DFper(800)
      COMMON/BLOCK346/lperiod
      COMMON/BLOCK35/avgeff
      COMMON/BLOCK5/IntAvg,Nsimpers
      COMMON/BLOCK567/checksb
      COMMON/BLOCK6/dumtemp,TambF,dumday,Nhours
      COMMON/BLOCK7/checkset,Tsp,Tsb
*
      INTEGER Nsims,nrand,lperiod,Nhours,Nmins,Nwst,Nwend,Nsimpers
      INTEGER simper, house, heater,ibig,i,j,jmin,szsimper,simperday
      INTEGER checksb,dumtemp,dumparam,dumsol,dumday
*
      REAL TambF,Tamb,rad
      REAL cperAAvg,hph,hpfs,hpfe,hptsp,hptsb,hpfla,hpua,hpInt,avgeff
      REAL hpfsstd,hpfestd,hptspstd,hptsbstd,hpflastd,hpuastd
      REAL qhtgAvg,flarea,cAvg,UAAvg,TspAvg,TsbAvg,IntAvg,fracton
      REAL qhtgstd,cstd,UAstd,Tspstd,Tsbstd
      REAL cap(100001),U(100001),qhtgary(100001)
      REAL Tspary(100001),Tsbary(100001)
      REAL cmin,UAmin,c,UA,qhtg,Tsp,Tsb,Tset
      REAL Tdeadband,Tbalance,gainscon
      REAL Trlow,Trhigh,Trinfon,Trinfoff
      REAL Tend,Tstart,Tstop,Tinf
      REAL ton,toff,tnext1,tnext2,time,endtime
```

```
      REAL dumh,dumhp,checkset
      REAL c1,c2,c3,c4,c5,c6,c7,c8
      REAL Qsumax,Qsum,Qnorm,mean,DFper
*
      OPEN(unit=21,file='temp1218p.dat',status='old')
      OPEN(unit=22,file='temp1220p.dat',status='old')
      OPEN(unit=23,file='temp1221p.dat',status='old')
      OPEN(unit=24,file='temp22690p.dat',status='old')
      OPEN(unit=25,file='temp3190p.dat',status='old')
      OPEN(unit=26,file='temp3290p.dat',status='old')
      OPEN(unit=27,file='temp1591p.dat',status='old')
      OPEN(unit=28,file='temp1891p.dat',status='old')
      OPEN(unit=29,file='temp1991p.dat',status='old')
*
* *** LOOP to make many runs ****
      ibig = 1
*       DO 500 ibig = 1,31
      OPEN(unit=15,file='junk.dat',status='new')
*       OPEN(unit=11,file='Qnorm1.dat',status='new')
      OPEN(unit=12,file='Qnorm2.dat',status='new')
      OPEN(unit=13,file='linear.dat',status='new')
*
      WRITE(6,*)'INPUT # OF SIMULATIONS'
      READ(5,*)Nsims
      WRITE(6,*)'INPUT # OF HOURS OF SIMULATION'
      READ(5,*)Nhours
      WRITE(6,*)'INPUT LENGTH OF TIMESTEP OF SIMULATIONS'
      READ(5,*) lperiod
      WRITE(6,*)'INPUT "1" IF TEMP IS "REAL" OR "0"'
      READ(5,*)dumtemp
      IF (dumtemp .EQ. 1) THEN
        WRITE(6,*)'INPUT 1 FOR 12-18-89     OR'
        WRITE(6,*)'INPUT 2 FOR 12-20-89'
        WRITE(6,*)'INPUT 3 FOR 12-21-89'
        WRITE(6,*)'INPUT 4 FOR 2-26-90'
        WRITE(6,*)'INPUT 5 FOR 3-1-90'
        WRITE(6,*)'INPUT 6 FOR 3-2-90'
        WRITE(6,*)'INPUT 7 FOR 1-5-91'
        WRITE(6,*)'INPUT 8 FOR 1-8-91'
        WRITE(6,*)'INPUT 9 FOR 1-9-91'
        READ(5,*)dumday
      ELSE
         WRITE(6,*)'INPUT TEMPERATURE IN F'
         READ(5,*) TambF
      END IF
      WRITE(6,*)'INPUT "0" IF NO SETBACK OR DISTRIBUTION "1","2","3"'
      READ(5,*)checksb
*
      Nmins = 60*Nhours
```

```
      szsimper = 15
      Nsimpers = Nhours*60/szsimper
      print*,'szsimper =',szsimper
      print*,'Nsimpers =',Nsimpers
*
      CALL COMMENTS
      print*,'out of comments'
*
************************************************************
*              Old assumed parameters                      *
*     Cavg = 80.                                           *
*     Cstd = 30.                                           *
*     UAperAf = 2.5                                        *
*     Ustd = 1.0                                           *
*  Design temperature for determining furnace capacity     *
*-      Tamin = -28.9                                      *
*  Average house capacitance (KJ/m^2 C) and loss coef (W/m^2 C)  *
*     cavg = 80.                                           *
*     UAperAf = 2.5                                        *
*  Average house areas (floor and external) m^2            *
*-      flarea = 150.                                      *
*  Gains and losses in (KW) for each house generated assuming  *
*  4 people within house and 8000kW-hr per year electricity    *
*  use.                                                    *
*     gapp = 0.910                                         *
*     gpeo = 0.480                                         *
*     qbt =  1.345                                         *
**  Design heating load (KW) for house #house              *
*     qhtg = 1.2*UA*(23.0 - Tamin)                         *
************************************************************
************ Read parameters of monitored houses ******************
*
      dumparam = 1
      IF (dumparam .EQ. 0) THEN
        Do 20 i = 1,33
          Read(6,*) hph,hpfs,hpfe,hptsp,hptsb,hpfla,hpua
          qhtgary(i) = hpfs*(hpfe/100.)*.293
          cap(i) = cavg*hpfla/10.764
          U(i) = hpua*.5274
          Tspary(i) = (hptsp-32.) * 5./9.
          Tsbary(i) = (hptsb-32.) * 5./9.
 20     CONTINUE
        avgeff = .846307
        UAAvg = 0.51354*.5274
        TspAvg = (69.88 - 32.) * 5./9.
        qhtgAvg = 95.04*avgeff*.293
        IntAvg = 42.6*.293
      ELSE
*********  average values from morgnbo3.txt  ****************
```

```
      cperAAvg = 80.
      hpfs = 95.04
      hpfe = 84.6307
      hptsp = 69.88
      hptsb = 66.15
      hpfla = 1300
*       hpua = 0.61
      hpua = 0.51354
      hpInt = 42.6
*
      WRITE(13,*)'House 1 furnace size',hpfs,'ft^3/hr'
*
      hpfsstd = 28.111
      hpfestd = 9.517
      hptspstd = 2.3888
      hptsbstd = 4.6621
      hpflastd = 453.59
*       hpuastd = .17675
      hpuastd = .015806
*
      qhtgAvg = hpfs*(hpfe/100.)*.293
      avgeff = hpfe/100.
      flarea = hpfla/10.764
      cAvg = CperAAvg*hpfla/10.764
      UAAvg = hpua*.5274
      TspAvg = (hptsp-32.) * 5./9.
      TsbAvg = (hptsb-32.) * 5./9.
      IntAvg = hpInt*.293
*
      cstd = 0.2*cAvg
      qhtgstd = hpfsstd*(hpfe/100.)*.293
      UAstd = hpuastd*.5274
      Tspstd = hptspstd * 5./9.
      Tsbstd = hptsbstd * 5./9.
****************************************************************
** qhtgAvg,qhtgstd [=] kW        hpfs,hpfsstd [=] kbtu/hr   **
** cAvg,cstd       [=] kJ/c      CperAAvg  [=] kJ/m^2-C  **
** UAAvg,UAstd     [=] kW/c      hpua,hpuastd [=] ft^3/hr-F **
** Tsp,Tsb         [=] C         hptsp,hptsb [=] F       **
** IntAvg          [=] kW        hpInt   [=] kbtu/hr   **
**                                        **
************    hpua is load UA not use    ********************
********** hpua = average of slope*efficiency *****************
**********     UAAvg is load UA not use     *****************
************ qhtg,IntAvg is output not use *******************
***** IntAvg is use(not output) of furnace (kw) at 0 F*********
**                                        **
** 1 kbtu/hr = .293 kW   1m^2 = 10.764 ft^2          **
** 1 kbtu/F-hr = .5274 W/c                      **
```

```
******************************************************************
*
**  Generate Capacitance (KJ/C), loss coefficient (W/C), furnace
**  capacity (KW), and set point (C) for all 'houses'.
**  Fill arrays Cap,U,qhtgary,Tspary,Tsbary.
*
       nrand = Nsims
       CALL RNNOA(nrand,Cap)
       CALL SSCAL(nrand, Cstd, Cap, 1)
       CALL SADD(nrand, CAvg, Cap, 1)
       CALL RNNOA(nrand, U)
       CALL SSCAL(nrand, UAstd, U, 1)
       CALL SADD(nrand, UAAvg, U, 1)
       CALL RNNOA(nrand,qhtgary)
       CALL SSCAL(nrand, qhtgstd, qhtgary, 1)
       CALL SADD(nrand, qhtgAvg, qhtgary, 1)
       CALL RNNOA(nrand,Tsbary)
       CALL SSCAL(nrand, Tsbstd, Tsbary, 1)
       CALL SADD(nrand, TsbAvg, Tsbary, 1)
       CALL RNNOA(nrand,Tspary)
       CALL SSCAL(nrand, Tspstd, Tspary, 1)
       CALL SADD(nrand, TspAvg, Tspary, 1)
     END IF
******************************************************************
**  Read TMY Data file - create arrays of solar radiation and
**  ambient temperature
******************************************************************
     Nwst = 1
     Nwend = Nwst + Nsimpers - 1
     DO 30 i = Nwst, Nwend
       IF (dumtemp .EQ. 1) THEN
         IF (dumday .EQ. 1) THEN
           Read(21,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 2) THEN
           Read(22,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 3) THEN
           Read(23,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 4) THEN
           Read(24,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 5) THEN
           Read(25,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 6) THEN
           Read(26,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 7) THEN
           Read(27,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 8) THEN
           Read(28,*,err=200,end=30) TambF
         ELSE IF (dumday .EQ. 9) THEN
           Read(29,*,err=200,end=30) TambF
```

```
        END IF
      END IF
******************************************************************
*   normal radiation in KJ/m^2 for (previous?) hour  rad(i) = kW
******************************************************************
*        IF (dumsol .EQ. 1) THEN
*          IF (dumday .EQ. 1) THEN
*            Read(31,*,err=200,end=30)c1,c2,c3,c4,c5,c6,c7,c8
*          ELSE IF (dumday .EQ. 2) THEN
*            Read(32,*,err=200,end=30)c1,c2,c3,c4,c5,c6,c7,c8
*          ELSE IF (dumday .EQ. 3) THEN
*            Read(33,*,err=200,end=30)c1,c2,c3,c4,c5,c6,c7,c8
*          ELSE IF (dumday .EQ. 4) THEN
*            Read(34,*,err=200,end=30)c1,c2,c3,c4,c5,c6,c7,c8
*          ELSE IF (dumday .EQ. 5) THEN
*            Read(35,*,err=200,end=30)c1,c2,c3,c4,c5,c6,c7,c8
*          ELSE IF (dumday .EQ. 6) THEN
*            Read(36,*,err=200,end=30)c1,c2,c3,c4,c5,c6,c7,c8
*          END IF
          rad(i) = c4
*        ELSE
          rad(i) = 0.
*        END IF
      Tamb(i) =  (TambF - 32.) * 5./9.
*
*** Inialize Qsum to allow for multiple runs ***
*
      DO 29 j = 1,szsimper
        jmin = (i-1)*szsimper + j
        Qsum(jmin) = 0.0
29      Continue
30    Continue
    CLOSE(21)
    CLOSE(22)
    CLOSE(23)
    CLOSE(24)
    CLOSE(25)
    CLOSE(26)
    CLOSE(27)
    CLOSE(28)
    CLOSE(29)
*******************************************************************
****  Run simulation for house=1,Nsims houses for hour=1,Nhours hours
*******************************************************************
    Qsumax = 0.0
    CALL GAINER
    print*,'after gainer called, gainscon =',gainscon
    CALL START
*
```

```
    DO 200 house = 1,Nsims
      dumh = house/100.
      dumhp = dumh - int(dumh)
      IF (dumhp .EQ. 0) Then
        print*,house
      END IF
****************************************************************
**  Assign house #house parameters from arrays                **
**  C (KJ/C) and UA (kW/C) minimums 1/5 of average values     **
****************************************************************
      cmin = 0.2*cAvg
      UAmin = 0.2*UAAvg
      IF((house .EQ. 1) .AND. (dumparam .EQ. 1)) THEN
        c = cAvg
        UA = UAAvg
        qhtg = qhtgAvg
        Tsp = TspAvg
        Tsb = TsbAvg
      ELSE
        c = cap(house)
        UA = U(house)
        qhtg = qhtgary(house)
        Tsp = Tspary(house)
        Tsb = Tsbary(house)
      ENDIF
      IF (c .LT. cmin) THEN
        c = cmin
      END IF
      IF (UA .LT. UAmin) THEN
        UA = UAmin
      END IF
      IF (house .LE. 10) THEN
       WRITE(15,600)house,c,UA,qhtg,Tsp,Tsb
      END IF
****************************************************************
**********    Run Simulation for house #house    ***************
****************************************************************
      Qsumax = Qsumax + qhtg
      checkset = Float(house)/Float(Nsims)
      Do 150 simper = 1,Nsimpers
*
****************************************************************
****      set interior setpoint accounting for night setback **********
****************************************************************
*
        CALL SETPOINT
        CALL TIMES
*
*** Now have times to reach 1st, 2nd, 3rd, .. limits  *******
```

```
*
        CALL ADD
      IF(house .EQ.1) then
****       write(15,*)'after ADD, simper =',simper
      END IF
*****************************************************
******      Calculate temperature at end of hour          ******
*****************************************************
        IF (heater .EQ. 0) THEN
          Tstop = Trlow
          Tinf = Trinfoff
          Tstart = Trhigh
        ELSE
          Tstop = Trhigh
          Tinf = Trinfon
          Tstart = Trlow
        END IF
*****   account for heat up or cool down longer than 1 hr  ********
        IF (j .EQ. 1) THEN
          Tstart = Tend
          IF (simper .EQ. 1) THEN
            Tstart = Tset
          END IF
        END IF
*
*  Calculate temperature at end of hour accounting for overheat
*  from the environment and then "opening windows"
*
        Tend = Tinf + (Tstart - Tinf)*exp(-UA*endtime/c)
        IF (Tend .GT. Trhigh) THEN
          Tend = Trhigh
        END IF
*
*
150     CONTINUE
200   CONTINUE
*
    CALL WRITER
    write(15,*)'after WRITER, simper =',simper
*temp      CALL STATS()
*temp 500   Continue
 600  FORMAT(i4,1x,f10.4,1x,f6.4,1x,f8.4,1x,f8.4,1x,f8.4)
    CLOSE(13)
    CLOSE(15)
    STOP
    END
```

```
*
*********************************************************************
*******************************     *********************************
*****************************        *******************************
***************************           ******************************
*****************************        *******************************
*******************************     *********************************
*********************************************************************
*****************1111111111111111111111111*********************
****************                                  ******************
********         Subroutine to calculate percent houses on for 1st hour         ***
****************                                  ******************
*****************1111111111111111111111111*********************
*********************************************************************
*
      SUBROUTINE START
      IMPLICIT NONE
      COMMON/BLOCK0/qhtgAvg
      COMMON/BLOCK05/UAAvg,TspAvg,TsbAvg
      COMMON/BLOCK01/Tamb(800),fracton
      COMMON/BLOCK015/gainscon,rad(800),flarea
      REAL qhtgAvg,UAAvg,TspAvg,Tsbavg,fracton,Tamb
      REAL gsolar,gainscon,rad,flarea
      gsolar = 0.0
*temp      gapp = 0.910
*temp      gpeo = 0.480
*temp      qbt =  1.345
*temp      gains = gapp + gpeo + gsolar
      fracton = (UAAvg*(TspAvg - Tamb(1)) - gsolar - gainscon)/qhtgAvg
      RETURN
      END
*
*********************************************************************
*****************1111111111111111111111111*********************
****************                                  ******************
********         Subroutine to calculate on and off times for each hour         ****
****************                                  ******************
*****************1111111111111111111111111*********************
*********************************************************************
*
      SUBROUTINE TIMES
      IMPLICIT NONE
      COMMON/BLOCK01/Tamb(800),fracton
      COMMON/BLOCK1a/UA,C,house,hpfs
      COMMON/BLOCK1a7/Tset
      COMMON/BLOCK1b/Trlow,Trhigh,Trinfon,Trinfoff,Tend
      COMMON/BLOCK12/qhtg,time,tnext1,tnext2,heater
      COMMON/BLOCK127/simper,szsimper
      COMMON/BLOCK1346/Nsims
```

```
      COMMON/BLOCK015/gainscon,rad(800),flarea
      INTEGER simper,heater,j,house,Nsims,szsimper
      REAL Tamb,Ta,rad,gsolar,gainscon,hpfs
      REAL Trinfon,Trinfoff,thetinfon,thetinfoff,Tend
      REAL Tset,Tdeadband,Trlow,Trhigh,thetlow,thethi
      REAL Tstart,Tstop,Tinf,tnext1,tnext2,time
      REAL c1on,c2on,c1off,c2off,qhtg,flarea,C,UA,Tbalance
      REAL ton, toff,checkst,fracton,linrat,linuse,ERC
*
*************************************************************
*  Constants (kW) and (C) for house #house in hour #hour      **
*  gsolar assumes 10% of direct normal absorbed               **
*************************************************************
*
* Internal temperature limits (degrees C)
      Tdeadband = 1.65
      Trlow = Tset - Tdeadband
      Trhigh = Tset + Tdeadband
*
* Ambient conditions
      gsolar = (0.12/3600.)*flarea* rad(simper)*0.3
      Ta = Tamb(simper)
      IF(house .EQ. 1) THEN
*****           write(15,*)'within TIMES, simper =',simper
      END IF
*temp      gapp = 0.910
*temp      gpeo = 0.480
*temp      qbt =  1.345
*temp      gains = gapp + gpeo + gsolar
*
      thetlow = Trlow - Ta
      thethi = Trhigh - Ta
      c1on = qhtg + gainscon + gsolar
      thetinfon = c1on/UA
      Trinfon = thetinfon + Ta
      c2on = thetlow - thetinfon
      c1off = gainscon + gsolar
      thetinfoff = c1off/UA
      Trinfoff = thetinfoff + Ta
      c2off = thethi - thetinfoff
      Tbalance = Tset - c1off/UA
*
*************************************************************
* Charging and discharging times ton and toff as seconds      **
* Accounting for strange conditions                           **
*************************************************************
*
      IF (thetinfon .LE. thethi) THEN
        ton = 999999.9
```

```
      toff = 0.0
    ELSE IF (thetinfoff .GE. thetlow) THEN
      ton = 0.0
      toff = 999999.9
    ELSE
      ton = -(c/UA)*alog((thethi -thetinfon)/c2on)
      toff = -(c/UA)*alog((thetlow -thetinfoff)/c2off)
    END IF
*
******************************************************************
************ ENERGY RATE CONTROL SIMULATION ****************
******************************************************************
*
    IF (house .EQ. 1) THEN
      ERC = (UA*(Tset - Ta) - gainscon)/(0.846307*0.293)
      linrat = ton/(ton + toff)
      linuse = linrat*hpfs
      WRITE(13,*) simper, linuse, ERC
    END IF
*
**************************************************************
* Initialize furnace and internal temp conditions for hour #1
**************************************************************
*
    IF (simper .EQ. 1) THEN
      Tstart = Tset
      checkst = Float(house)/Float(Nsims)
      IF (checkst .LT. fracton) THEN
        heater = 1
      ELSE
        heater = 0
      END IF
    ELSE
      Tstart = Tend
    END IF
*
**************************************************************
****  Allow for sudden click offs or ons caused by sudden      *****
****  thermostat set point changes                             *****
**************************************************************
*
    IF (Tstart .GT. Trhigh) THEN
      heater = 0
    ELSE IF (Tstart .LT. Trlow) THEN
      heater = 1
    END IF
*
**************************************************************
****  Define condition at beginning of the hour         *************
```

```
***************************************************************
*
    IF (heater .EQ. 0) THEN
      Tstop = Trlow
      Tinf = Trinfoff
      tnext1 = ton
      tnext2 = toff
    ELSE
      Tstop = Trhigh
      Tinf = Trinfon
      tnext1 = toff
      tnext2 = ton
    END IF
*
***************************************************************
*** time (sec) for internal temperature to reach first limit        **
***************************************************************
*
    IF ((heater .EQ. 1) .AND. (Tinf .LE. Tstop)) THEN
      time = 60.*float(szsimper)
    ELSE IF ((heater .EQ. 0) .AND. (Tinf .GE. Tstop)) THEN
      time = 60.*float(szsimper)
    ELSE
      time = -(c/UA)*alog((Tstop - Tinf)/(Tstart - Tinf))
    END IF
    RETURN
    END
*
*********************************************************************
******************2222222222222222222222222222**********************
****************                                 *******************
********        Subroutine to add each furnaces draw to the ensemble's use        *
**************                                 ********************
******************2222222222222222222222222222**********************
*********************************************************************
*
    SUBROUTINE ADD
    IMPLICIT NONE
    COMMON/BLOCK12/qhtg,time,tnext1,tnext2,heater
    COMMON/BLOCK127/simper,szsimper
    COMMON/BLOCK2/endtime,j
    COMMON/BLOCK23/Qsum(10000)
    INTEGER j,simper,check,heater,szsimper
    INTEGER k1, k2, k3
    INTEGER min,min1,minf,mind1,mind2,mind3
    REAL totmin,reltotmin,totminold
    REAL add1,add2
    REAL time,tnext1,tnext2,Qsum,qhtg,endtime
*
```

```
*******************************************************
** Add contribution of house #house's heater              *
** output (MJ) for each simulation time period to Qsum     *
*                                                       *
* min1,minf - 1st/last absolute minutes of hour - integers   *
* mind1,mind2- 1st/last absolute full minutes of cycle -integers *
* totmin    - absolute minutes into hour - reals           *
* reltotmin - relative minutes into hour - reals           *
* k1, k2    - integers control addition of times to cycle  *
* k3        - controls heaters on/off for each part of cycle *
*******************************************************
*************** k1 = 0,1,0,1,... ***************************
*************** k2 = 0,0,1,0,1,... *************************
*************** k3 = 0,1,0,1  or  k3 = 1,0,1,0 ****************
*************** reltotmin = time,time+tnext,time+tnext1+tnext2 *
*******************************************************
*
      min1 = szsimper*(simper - 1) + 1
      minf= szsimper*simper
      mind1 = min1
      IF (simper .EQ. 1) THEN
        totminold = 0.
      END IF
      totmin = min1 + time/60. - 1.0
*
      DO 100 j = 1,30
        k1 = (1 + (-1)**J)/2
        IF ((k1 .NE. 1) .AND. (j .NE. 1)) THEN
          k2 = 1
        ELSE
          k2 = 0
        END IF
        IF (heater .EQ. 0) THEN
          k3 = k1
        ELSE
          k3 = 1 - k1
        END IF
*
        totmin = totmin + (k1*tnext1 + k2*tnext2)/60.
        reltotmin = totmin - float(szsimper)*(simper-1)
        check = int(reltotmin/float(szsimper))
*
        IF (check .GT. 0) THEN
          mind2 = minf
        ELSE
          mind2 = int(totmin)
          mind3 = mind2 + 1
        END IF
        IF (mind3 .EQ. 1) THEN
```

```
        GOTO 80
      END IF
*
************************************************************
***     ADD use to full minutes within furnace half cycle        ******
************************************************************
*
      DO 50 min = mind1,mind2
        Qsum(min) = Qsum(min) + qhtg*k3
50      Continue
*
      IF (check .GT. 0) THEN
        endtime = (minf - totminold)*60.
        totminold = minf
        GOTO 120
      END IF
80      CONTINUE
*
**************************************************************
***     ADD use to last partial minute within furnace half cycle          *
**************************************************************
*
      add1 = qhtg*k3*(totmin-mind2)
      add2 = qhtg*(1-k3)*(mind3-totmin)
      Qsum(mind3) = Qsum(mind3) + add1 + add2
      mind1 = mind3 + 1
      totminold = totmin
100   CONTINUE
120   heater = k3
    RETURN
    END
*
*********************************************************************
*****************3333333333333333333333333*********************
****************                                  *******************
**********              Subroutine to write results to data files          ************
****************                                  *******************
*****************3333333333333333333333333*********************
*********************************************************************
*
    SUBROUTINE WRITER
    IMPLICIT NONE
    COMMON/BLOCK1346/Nsims
    COMMON/BLOCK3/Qsumax,Nmins,ibig
    COMMON/BLOCK23/Qsum(10000)
    COMMON/BLOCK34/Qnorm(800,1),DFper(800)
    COMMON/BLOCK346/lperiod
    COMMON/BLOCK35/avgeff
    INTEGER lperiod,Nsims,Nmins,ibig,nper,check2,l
```

```
      REAL avgeff,meandraw,totmean,Qnormsum,Qavg,Qsumax
      REAL DFper,Qnorm,Qsum,Qnormsumt,Qavg2
*
**********************************************************
** Write avg Qhtg (ft^3/hr) and use on 1 min and
** period min. basis to data file after last simulation
** period=minutes in eval period,nper = # of eval period
** DFper is average normalized draw over period
** use for period is DFper(per)*totmean*period/60 [=] ft^3
**********************************************************
*
      totmean = (Qsumax/.293)/Nsims
      meandraw = totmean/avgeff
      Write(11,*)'Avg gas draw',meandraw,'ft^3/hr'
      Write(12,*)'Avg gas draw',meandraw,'ft^3/hr'
      Write(15,*)'Avg gas draw',meandraw,'ft^3/hr'
*
      write(15,*) 'lperiod =',lperiod
      Qnormsum = 0.0
      Qnormsumt = 0.0
      nper = 1
*
      write(15,*),'Nmins,Nsims,Qsumax = ',Nmins,Nsims,Qsumax
      DO 250 l = 1,Nmins
        Qnorm(l,ibig) = Qsum(l)/Qsumax
*         Write(11,*) l,Qnorm(l,ibig)
*         Qavg = (Qsum(l)/.293)/Nsims
        Qavg = Qnorm(l,ibig)*meandraw
*         Write(11,*) l,Qavg
*       write(15,*),'l,lperiod,Qnorm(l,1),',l,lperiod,Qnorm(l,1)
        Qnormsum = Qnormsum + Qnorm(l,ibig)
        Qnormsumt = Qnormsumt + Qnorm(l,ibig)
        check2 = int(l/lperiod)
***         write(15,*),'ok2'
        IF (check2 .EQ. nper) THEN
          DFper(nper) = Qnormsum/lperiod
          Qavg2 = DFper(nper)*meandraw
*           WRITE(12,*) nper,DFper(nper)
          WRITE(12,*) nper,Qavg2
          Qnormsum = 0.0
          nper = nper + 1
        END IF
****          write(15,*),'ok3'
250   Continue
      Qnormsumt = Qnormsumt/Nmins
      WRITE(15,*)'Qnormsumt =',Qnormsumt
*       CLOSE(11)
      write(15,*),'ok4'
      CLOSE(12)
```

```
      RETURN
      END
*
**********************************************************************
**44444444444444444444444444444444444444444444444444444444444444444**
**********          Subroutine to calculate statistics of results          **************
**********************************************************************
*     Subroutine stats
*     Implicit none
*     COMMON/BLOCK1346/Nsims
*     COMMON/BLOCK34/period,Qnorm(800,1),DFper(800)
*     COMMON/BLOCK34/Qnorm(800,1),DFper(800)
*     COMMON/BLOCK346/period
*     INTEGER nper,i,check3,mstd,Nsims
*     REAL sumdev,Qnorm,mean,std(800)
*
*  calculate and write standard deviation on nstd hrs basis
*
*     sumdev = 0.0
*     nper = 1
*     Write(2,*) Nsims
*     DO 300 i = 1,Nmins
*       sumdev = sumdev + (Qnorm(i) - DFper(nper))**2
*       check3 = int(i/period)
*       IF (check3 .EQ. nper) THEN
*         std(nper) = sqrt(sumdev/period)
*         write(2,*) std(nper)
*         sumdev = 0.0
*         nper = nper + 1
*       END IF
*300  Continue
*     close(2)
*     RETURN
*     END
*
**********************************************************************
*****************5555555555555555555555555*********************
****************                                        ******************
**********          Subroutine to determine constant gains          ************
****************                                        ******************
*****************5555555555555555555555555*********************
**********************************************************************
*
      SUBROUTINE GAINER
      IMPLICIT NONE
      COMMON/BLOCK015/gainscon,rad(800),flarea
      COMMON/BLOCK05/UAAvg,TspAvg,TsbAvg
      COMMON/BLOCK35/avgeff
      COMMON/BLOCK5/IntAvg,Nsimpers
```

```
      COMMON/BLOCK567/checksb
      INTEGER Nsimpers,simper,checksb
      REAL UAAvg,gsolAvg,IntAvg,avgeff,gainscon
      REAL TspAvg,TsbAvg,TrAvg,flarea,rad,UseH2O,base
*
*temp     UseH2O = 0.478
      base = 1.133
      IF (checksb .EQ. 1) THEN
        TrAvg = (8.*TsbAvg + TspAvg*16.)/24.
      ELSE
        TrAvg = TspAvg
      END IF
      gsolAvg = 0.0
      DO 20 simper = 1,Nsimpers
        gsolAvg = gsolAvg + (0.12/3600.)*flarea* rad(simper)*0.3
 20   CONTINUE
      gsolavg = gsolavg/Float(Nsimpers)
      print*,'IntAvg =',IntAvg
      print*,'avgeff =',avgeff
      print*,'TrAvg =',TrAvg
      print*,'UAAvg =',UAAvg
      print*,'within gainer gsolavg=',gsolAvg
***      gsolAvg = gsolAvg/Float(Nsimpers)
      gainscon = UAAvg*(TrAvg+17.777)-gsolAvg-(IntAvg-base)*avgeff
      RETURN
      END
*
************************************************************************
******************6666666666666666666666666**********************
****************                                   *******************
**********          Subroutine to put comments in output files       ************
****************                                   *******************
******************6666666666666666666666666**********************
************************************************************************
*
      SUBROUTINE COMMENTS
      IMPLICIT NONE
      COMMON/BLOCK1346/Nsims
      COMMON/BLOCK346/lperiod
      COMMON/BLOCK567/checksb
      COMMON/BLOCK6/dumtemp,TambF,dumday,Nhours
      INTEGER Nsims,checksb,dumtemp,dumday,Nhours,lperiod
      REAL TambF
*
      WRITE(13,*)'************************************************'
      WRITE(12,*)'************************************************'
      WRITE(13,*)'Tambient and set back controlled at 15 min'
      WRITE(12,*)'Tambient and set back controlled at 15 min'
      WRITE(13,*)' # of simulated houses =',Nsims
```

```
WRITE(12,*)' # of simulated houses =',Nsims
WRITE(13,*)' # of hours of simulation =',Nhours
WRITE(12,*)' # of hours of simulation =',Nhours
IF (dumtemp .EQ. 0) THEN
  WRITE(13,*)' Temperature is constant at',TambF
  WRITE(12,*)' Temperature is constant at',TambF
ELSE
  IF (dumday .EQ. 1) THEN
    WRITE(13,*)' Temperature is actual for 12-18-89'
    WRITE(12,*)' Temperature is actual for 12-18-89'
  ELSE IF (dumday .EQ. 2) THEN
    WRITE(13,*)' Temperature is actual for 12-20-89'
    WRITE(12,*)' Temperature is actual for 12-20-89'
  ELSE IF (dumday .EQ. 3) THEN
    WRITE(13,*)' Temperature is actual for 12-21-89'
    WRITE(12,*)' Temperature is actual for 12-21-89'
  ELSE IF (dumday .EQ. 4) THEN
    WRITE(13,*)' Temperature is actual for 2-26-90'
    WRITE(12,*)' Temperature is actual for 2-26-90'
  ELSE IF (dumday .EQ. 5) THEN
    WRITE(13,*)' Temperature is actual for 3-1-90'
    WRITE(12,*)' Temperature is actual for 3-1-90'
  ELSE IF (dumday .EQ. 6) THEN
    WRITE(13,*)' Temperature is actual for 3-2-90'
    WRITE(12,*)' Temperature is actual for 3-2-90'
  ELSE IF (dumday .EQ. 7) THEN
    WRITE(13,*)' Temperature is actual for 1-5-91'
    WRITE(12,*)' Temperature is actual for 1-5-91'
  ELSE IF (dumday .EQ. 8) THEN
    WRITE(13,*)' Temperature is actual for 1-8-91'
    WRITE(12,*)' Temperature is actual for 1-8-91'
  ELSE IF (dumday .EQ. 9) THEN
    WRITE(13,*)' Temperature is actual for 1-9-91'
    WRITE(12,*)' Temperature is actual for 1-9-91'
  END IF
END IF
IF (checksb .NE. 0) THEN
  WRITE(13,*)' NIGHT SETBACK DIST',checksb,'IS INCLUDED'
  WRITE(12,*)' NIGHT SETBACK DIST',checksb,'IS INCLUDED'
ELSE
  WRITE(13,*)' NIGHT SETBACK IS NOT INCLUDED'
  WRITE(12,*)' NIGHT SETBACK IS NOT INCLUDED'
END IF
WRITE(13,*)' Energy Rate Control Results'
WRITE(12,*)' Temp Level Control for "timestep" =',lperiod
WRITE(13,*)'**************************************************'
WRITE(12,*)'**************************************************'
WRITE(15,*)'house    c      UA    qhtg   Tsp    Tsb'
WRITE(15,*)' -    kJ/C   kW/C    kW     C      C'
```

```
      RETURN
      END
*
*****************************************************************
*****************7777777777777777777777777*********************
****************                                  ******************
**********        Subroutine to set thermostat set point         ************
****************                                  ******************
*****************7777777777777777777777777*********************
*****************************************************************
*
      SUBROUTINE SETPOINT
      IMPLICIT NONE
      COMMON/BLOCK127/simper,szsimper
      COMMON/BLOCK1a7/Tset
      COMMON/BLOCK567/checksb
      COMMON/BLOCK7/checkset,Tsp,Tsb
      INTEGER checksb,simper,szsimper,simperday
      REAL checkset,Tset,Tsb,Tsp
*
*******     write(15,*)'simper=',simper
      IF(simper .LE. 24) THEN
        simperday = simper + 18*60/szsimper
      ELSE
        simperday = simper - 6*60/szsimper
      END IF
*****     write(15,*)'simperday = ',simperday
*******************************************************
      IF(checksb .EQ. 1) THEN
*******************************************************
        IF((simperday.LT.29).OR.(simperday.GE.93))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
**********************************************************
      ELSE IF(checksb .EQ. 2) THEN
**********************************************************
        IF (checkset .LE. 0.333) THEN
          IF((simperday.LT.25).OR.(simperday.GT.88))THEN
            Tset = Tsb
          ELSE
            Tset = Tsp
          END IF
        ELSE IF((checkset.GT.0.333).AND.(checkset.LE.0.666))THEN
          IF((simperday.LT.29).OR.(simperday.GT.92))THEN
            Tset = Tsb
          ELSE
            Tset = Tsp
```

```
    END IF
  ELSE IF(checkset.GT.0.666)THEN
    IF((simperday.LT.33).OR.(simperday.GT.96))THEN
      Tset = Tsb
    ELSE
      Tset = Tsp
    END IF
  END IF
************************************************************
  ELSE IF(checksb .EQ. 3) THEN
************************************************************
  IF (checkset .LE. 0.05882) THEN
        IF((simperday.LT.24).OR.(simperday.GE.88))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
  ELSE IF((checkset.GT.0.05882).AND.(checkset.LE.0.29412))THEN
        IF((simperday.LT.25).OR.(simperday.GE.89))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
  ELSE IF((checkset.GT.0.29412).AND.(checkset.LE.0.35294))THEN
        IF((simperday.LT.26).OR.(simperday.GE.90))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
  ELSE IF((checkset.GT.0.35294).AND.(checkset.LE.0.47059))THEN
        IF((simperday.LT.27).OR.(simperday.GE.91))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
  ELSE IF((checkset.GT.0.47059).AND.(checkset.LE.0.52941))THEN
        IF((simperday.LT.28).OR.(simperday.GE.92))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
  ELSE IF((checkset.GT.0.52941).AND.(checkset.LE.0.76471))THEN
        IF((simperday.LT.29).OR.(simperday.GE.93))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
  ELSE IF((checkset.GT.0.76471).AND.(checkset.LE.0.82353))THEN
        IF((simperday.LT.30).OR.(simperday.GE.94))THEN
```

```
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
      ELSE IF((checkset.GT.0.82353).AND.(checkset.LE.0.94118))THEN
        IF((simperday.LT.31).OR.(simperday.GE.95))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
      ELSE IF(checkset.GT.0.94118)THEN
        IF((simperday.LT.32).OR.(simperday.GE.96))THEN
          Tset = Tsb
        ELSE
          Tset = Tsp
        END IF
      END IF
*************************************************************
    ELSE
*************************************************************
      Tset = Tsp
    END IF
    RETURN
    END
```

APPENDIX B

MONITORED HOUSE PARAMETERS DATA FILE

Wisconsin Gas Company
Residential Audit Data
September 21, 1990

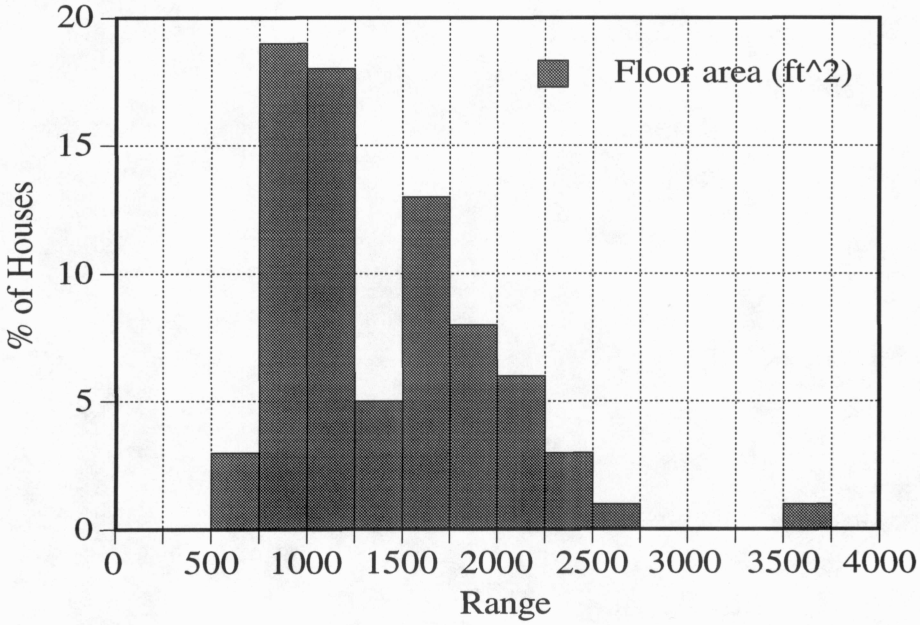
MET NUM	ACCT	Design Cooling Load kbtu/hr	Design Heating Load kbtu/hr	Total Floor Area sq.ft.	Overall Wall R-Value (F-sq.ft/Btuh	Wall Net Area (sq.ft.)	Overall Glazing R-Value (F-sq.ft/Btuh	Glazing Total Area (sq.ft.)	Overall Roof R-Value (F-sq.ft/Btuh	Roof Total Area (sq.ft.)	Furn/Boi Input Size kbtu/hr
1	1113176551	56	50	2300	25.8	1696	2.03	480	47.5	1150	60
2	2847468951	47	77	1470	12.9	940	2.03	516	13.5	1470	75
4	2330522782	51	50	2140	25.8	1666	2.03	510	47.5	1070	75
5	1489964676	27	39	940	4.4	866	2.03	190	17.5	940	63
6	1489964481	32	61	940	4.4	676	2.03	380	327.7	940	63
7	2283154862	-	-	-	-	-	-	-	-	-	0
8	3080502142	49	69	1580	8.9	1224	2.03	600	24.5	790	66
9	1661517633	33	49	1160	8.9	1256	2.03	280	25.5	580	100
10	1409163563	45	64	1800	8.9	1652	2.03	300	21.5	900	100
11	1986569163	43	62	1800	13.1	1580	2.03	340	24.5	900	74
12	1516626502	31	43	1010	9.1	756	2.03	300	17.5	1010	95
13	1483141372	48	69	1520	17.4	1224	2.03	600	24.5	760	66
14	2.6E+10	25	42	880	7.1	743	2.03	265	327.7	880	80
15	2576459412	26	35	880	9.1	743	2.03	265	21.5	880	150
16	2974464125	24	45	940	12.9	817	2.03	175	21.5	940	82
18	2023428601	51	90	1800	4.1	1660	2.03	420	15.5	900	124
19	1486999313	32	47	1120	16.9	735	2.03	385	327.7	1120	130
20	1486999312	32	34	1120	17.1	752	2.03	368	24.5	1120	125
21	2160801683	-	-	-	-	-	-	-	-	-	-
23	2755779544	52	69	1980	8.9	1556	2.03	460	21.5	990	160
26	1192613121	32	63	1300	17.1	1343	2.03	265	24.5	1300	130
27	2943290452	31	35	1010	8.9	756	2.03	300	21.5	1010	100
29	2539094283	51	72	1640	9.1	1878	2.03	490	9.5	820	88
35	2022556382	22	39	780	12.9	773	2.03	235	42.5	780	80
53	1580121404	26	37	1010	18.8	771	2.03	205	24.5	1010	80
57	1975210404	25	58	760	2.2	682	2.03	230	327.7	760	80
58	1975210597	39	69	760	2.2	682	2.03	230	2.6	760	100
69	1806502537	31	50	1150	8.9	837	2.03	315	327.7	1150	125
70	2367932439	-	-	-	-	-	-	-	-	-	-
80	2367932439	-	-	-	-	-	-	-	-	-	-
82	2179162253	-	-	-	-	-	-	-	-	-	-
			41.32	902							86

	Act. Peak Day Usage (Cu.Ft.)	Peak Day Deviation from regressio	Furnace Full load segments Peak Day	Furnace Full load duration peak day	Calculated 5 min consumptio cuft/5min	Difference between Sim-Actual therms/day
1	739	-54.4	55	18	4.59	0.8
2	1324	23.9	186	38	5.83	-0.99
4	974	105.9	113	6	5.83	-1.29
5	1369	122.4	232	6	5.00	-3.89
6	412	103.6	1	0	5.00	6.76
7	944	54.6	223	12	0.00	
8	1237	-13.9	143	3	5.08	-6.76
9	1048	129.3	56	33	6.67	-0.4
10	1262	-167.7	31	9	6.67	0.16
11	834	10.8	76	23	5.12	1
12	1274	137.4	84	2	6.33	-0.57
13	1659	29.7	189	14	5.08	-1.13
14	1141	-80.1	15	3	6.25	-1.25
15	1403	388.0	112	5	7.50	-1.13
16	1130	152.6	17	5	5.47	-0.82
18	1860	356.9	56	17	8.27	2.38
19	1395	272.2	4	1	9.53	-0.12
20	1190	73.4	88	3	9.17	-1.89
21					0.00	
	2014	400.1	54	11	10.67	6
	1370	29.2	123	14	8.99	2.98
	1820	429.0	156	7	6.67	-1.37
	1848	232.8	174	12	6.83	-1.3
	1798	462.4	132	16	5.33	-2.93
	732	61.6	2	1	6.33	-0.21
	1775	396.4	223	49	5.67	-0.03
			25		6.50	3.77
	1370	36.0	13	5	6.25	0.15
	838	148.2	230	33	0.00	
	1149	165.5	288	26	0.00	
	1080	-161.7	288	288	0.00	

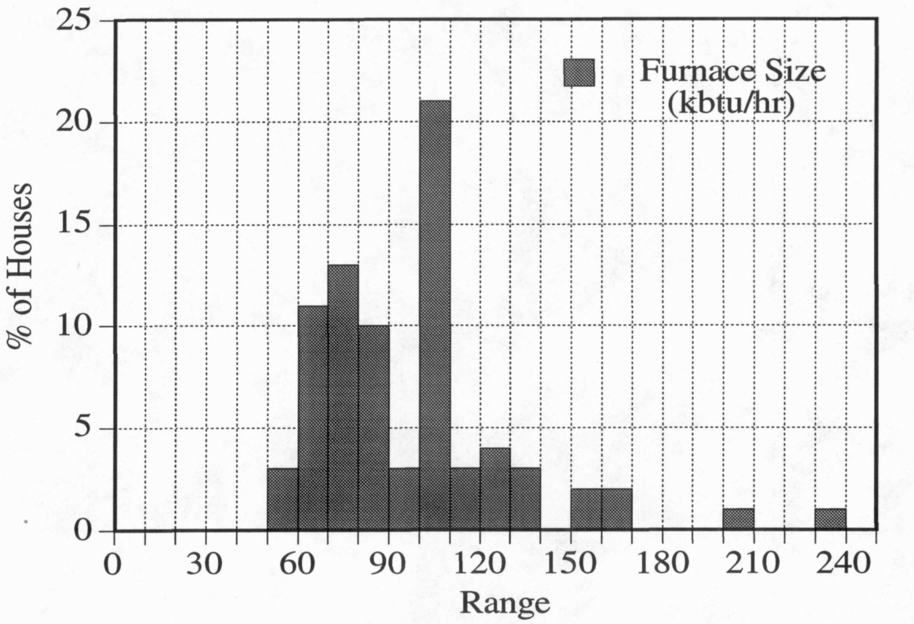
Furn/Boiler Steady-State Efficiency (%)	Furn/boil Size*eff /Design Load	Winter ACH	Htg. Interim Bin Infil.	Thermo-stat Setting F	Setback Setting F	numbe people in house	Heated or Unheated Basemen	Baseload Therms per Month	Slope	Interc.	Annual Heating Usage (Therms
91.7	110	0.60	1.50	66	66	5	Y	27.5	-0.393	29.2	845
93.3	91	1.31	0.68	70	64	4	N	20.0	-0.7	47.3	900
93.3	140	0.65	0.34	68	68	3	N	20.0	-0.443	31.8	478
95.2	154	0.91	0.00	68	65	1	N	24.4	-0.638	45.7	438
95.2	98	1.42	2.50	74	70	2	N	38.2	-0.18	11.1	1284
0.0	-	-	-				Y		-0.406	33.1	
92.4	88	1.33	3.20	72	72	2	Y	22.4	-0.603	46.2	1676
80.0	163	1.15	0.60	68	60	2	Y	22.1	-0.473	33.6	615
80.0	125	0.97	0.51	70	68	3	Y	49.5	-0.762	52.1	1094
83.0	99	0.99	0.52	70	62	4	N	28.5	-0.399	30.4	708
80.0	177	1.25	1.60	68	68	2	N	30.1	-0.559	41.9	935
92.4	88	1.36	1.70	75	74	5	Y	28.1	-0.919	58.9	1305
93.7	178	1.06	5.50	70	60	2	N	17.7	-0.608	44.9	1248
60.0	257	1.06	0.54	70	60	2	N	20.0	-0.554	36.9	543
80.0	146	1.10	2.00	70	55	2	N	20.0	-0.531	35.5	781
80.0	110	1.10	0.59	74	70	2	Y	16.7	-0.788	54.9	1753
88.0	243	1.29	2.00	70	70	3	Y	18.1	-0.623	40.7	1027
88.0	324	1.04	2.20	68	68	2	Y	25.3	-0.581	40.8	718
-	-	-	-				N				
80.0	186	1.04	1.60	65	60	4	Y	35.1	-0.883	58.6	1174
83.0	171	1.18	2.20	73	70	1	Y	34.4	-0.668	49.3	2069
80.0	229	1.01	3.50	72	72	4	N	38.9	-0.72	50.9	1230
93.2	114	1.29	1.60	68	68	3	Y	30.9	-0.856	58.9	1231
80.0	149	1.31	1.40	70	62	1	N	24.4	-0.782	48	658
95.0	205	0.65	0.34	70	70	3	Y	32.8	-0.327	24.7	422
85.0	117	1.31	0.68	70	65	3	N	49.2	-0.685	50.7	1232
78.0	113	1.06	0.00	70	65	3	N	29.1	-0.497	34.4	1276
60.0	150	1.19	0.62	68	68	3	N	20.0	-0.694	48.8	1119
-	-	-	-				Y		-0.343	25.4	
-	-	-	-				Y		-0.47	36.4	
-	-	-	-				Y		-0.605	45.8	
64.41579	141.71	0.88		69.87							

APPENDIX C

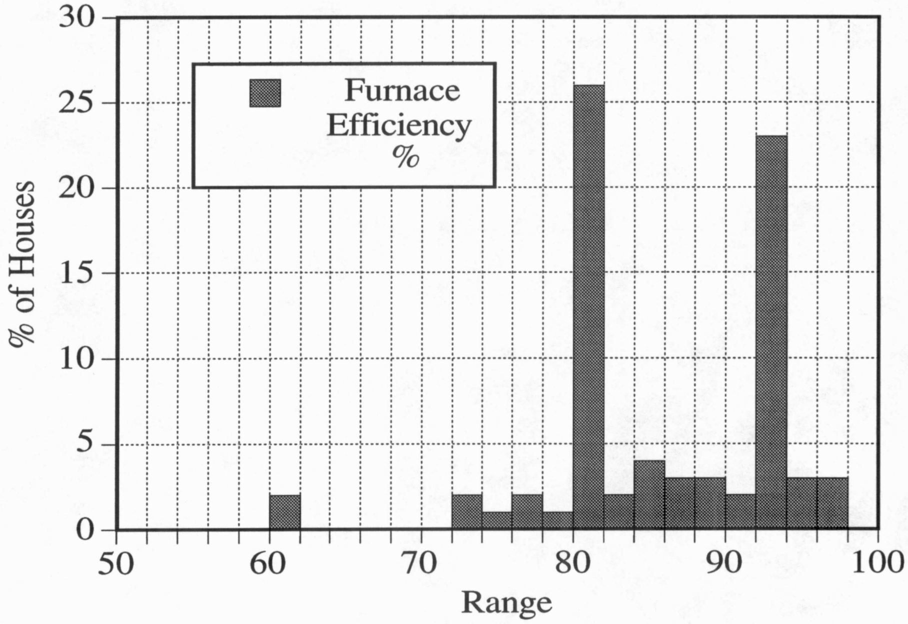
DISTRIBUTIONS OF HOUSE PARAMETERS



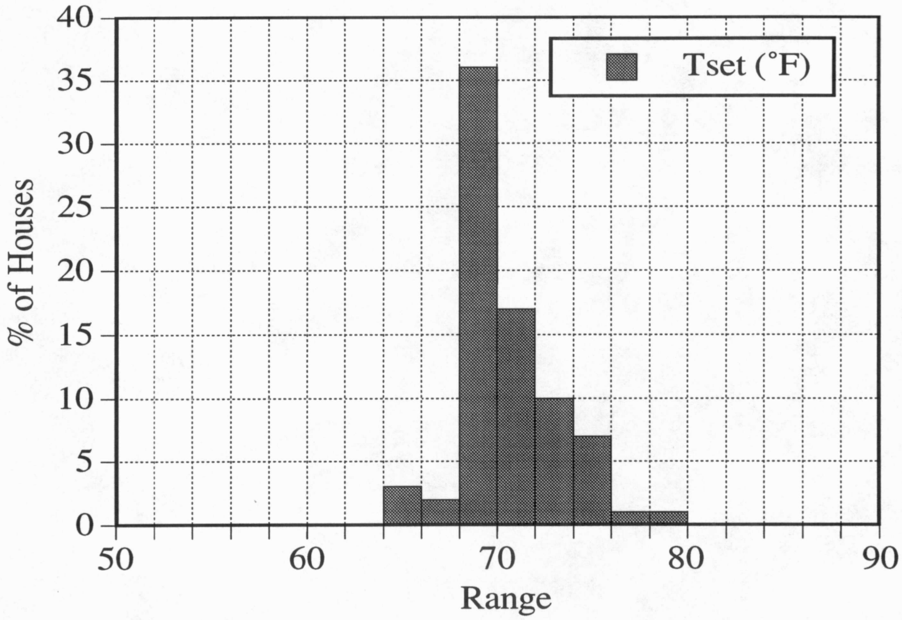
House Floor Area



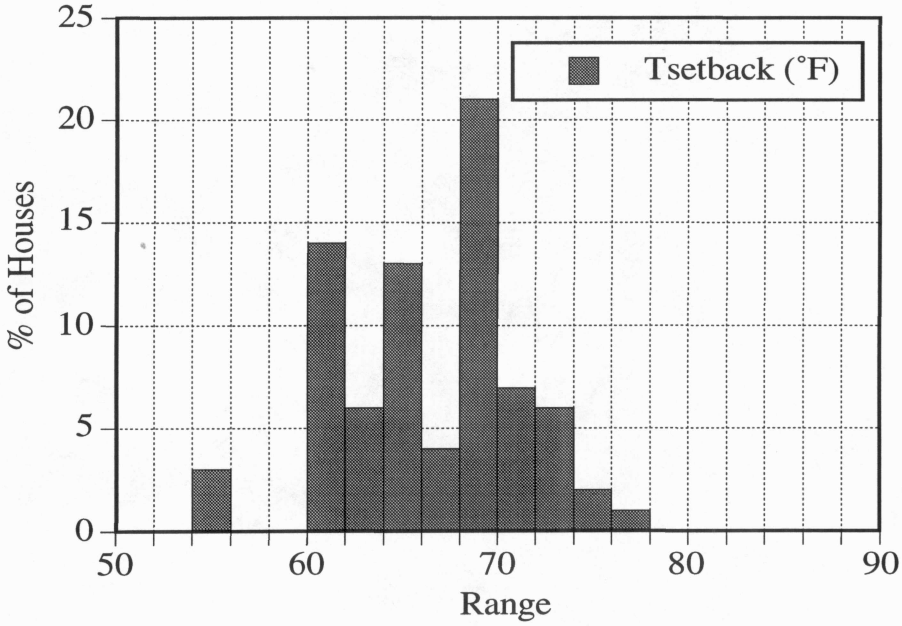
Furnace Size



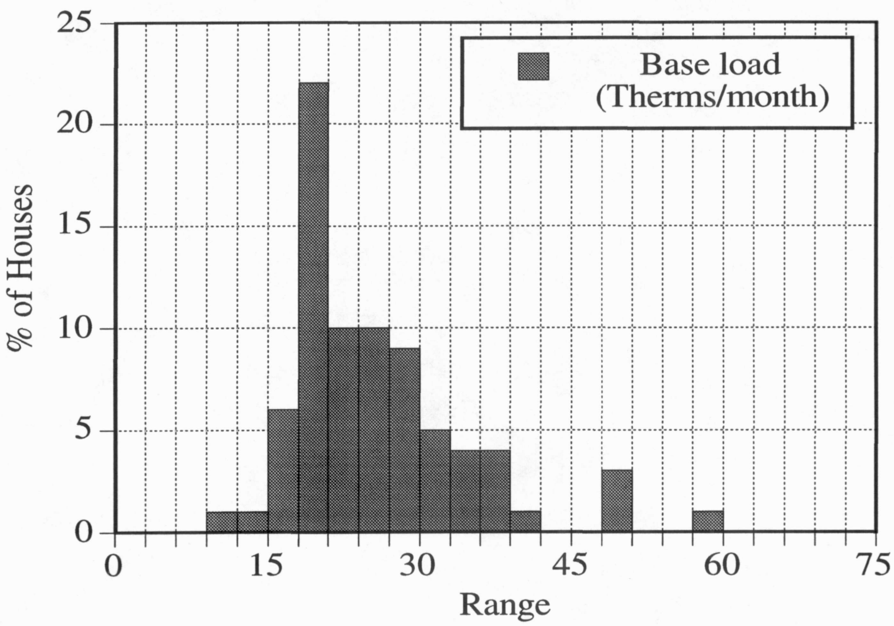
Furnace Efficiency



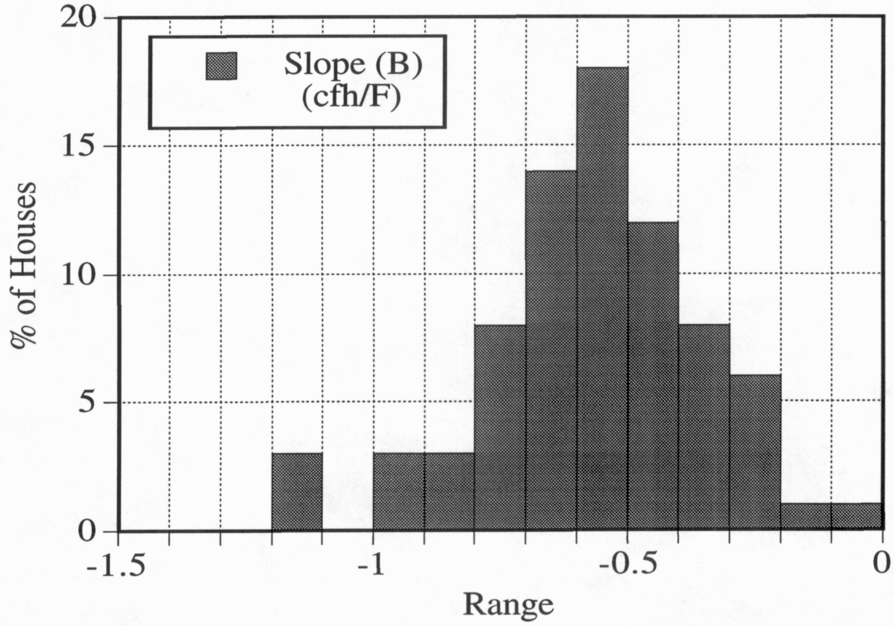
Daytime Thermostat Set Point



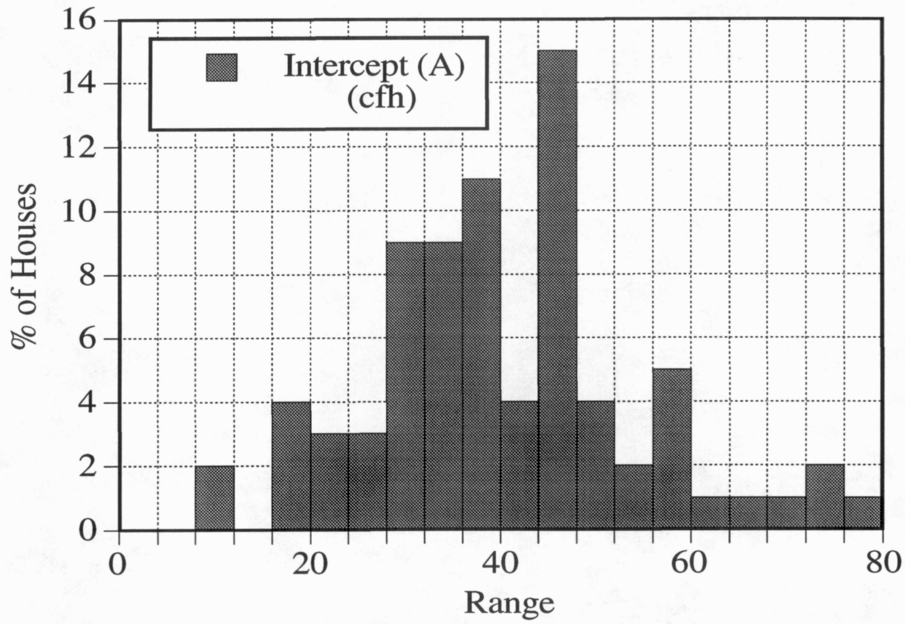
Nightime Thermostat Set Point



Base Load



Slope from WGC survey



Intercept from WGC survey

APPENDIX D

AIR CONDITIONING EES DECK

```
{Simulation of Residential Air Conditioning using
Energy Rate Control}

FUNCTION LATINF(Volumeflow,Wambient,Winternal)
DUM = 3000*Volumeflow*(Wambient - Winternal)
IF (DUM < 0) THEN
LATINF = 0
ELSE
LATINF = DUM
ENDIF
END

UA = .51*.5274*1000     {W/C}
Tset = (70-32)*5/9     {C}
Ta = TaTMY*10     {C}

{ alpha is }
alpha = 0.9

{It = incident solar radiation horizontal}
It = ITMY /3.6     {KJ/m^2 over previous hour to W/m^2}
```

```
ACH = 0.3
spvol = Volume(AirH2O,T=Ta,P=101,R=RHTMY)     {m^3/kg}
floorarea = 1300  {ft^2}
height = 8             {m}
Vol = (floorarea/10.764) * height     {m^3}
Vdot = Vol*ACH*1000/3600             {l/s}
wR = HumRat(AirH2O,T=Tset,P=101,R=0.40)
wa =HumRat(AirH2O,T=Ta,P=101,R=RHTMY)

h = 4   {Btu/hr-ft^2-F} {external heat transfer coefficient from John}
hsi = 1/0.044     {W/m^2-C   from p.69 Stoecker Table4-4 air resistance}

{Sol - air temperature  (C) }
Tsa = Ta + alpha*It/hsi

{QL = UA*(Tsa - Tset) + ACH*Vol/spvol*(wa - wR)*ifg}
Ql = UA*(Tsa - Tset) + 1.23*Vdot*(Ta - Tset) + LATINF(Vdot,wa,wR)
Elect1 = Ql/1
Elect2.5 = Ql/2.5
Elect3.5 = Ql/3.5
```

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