DEVELOPMENT OF AN IMPROVED DEGREE-DAY CONCEPT BY ANALYSIS OF HISTORICAL WEATHER DATA FOR PREDICTING ENERGY REQUIREMENTS OF BUILDINGS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

English Letters and Symbols

A	surface area, ft^2
A_d	door area, ft^2
A_g	glass area, ft^2
A_r	roof area, ft^2
A_{rj}	surface area of the representative building, ft^2
A_w	wall area, ft^2
a	slope of Equation (8.4)
b	intercept of Equation (8.4)
C_1, C_2, C_3, C_4	constants used in Equations (6.7) and (6.14)
C_1 through C_{15}	constants used in Equation (7.15)
CBLDG	building parameter for cooling, Equation (7.21)
CDD	improved cooling degree-day, °F-day
CL	cooling demand, Btu
CLD	design cooling load, Btu/day
C_p	specific heat capacity of air, Btu/lbm-°F
CU	cooling unit, Equation (7.17)
DD	conventional degree-day, °F-day
DT	daily temperature range, °F
DW	humidity ratio difference of indoor and outdoor air, lbm of water/lbm of air
$\overline{DW}$	daily average humidity ratio difference of indoor and outdoor air, lbm of water/lbm of air

E_b	boiler output, Btu
E_{bmax}	maximum boiler output, Btu
EER	energy efficiency ratio, Btu/watt-hr
EC	seasonal cooling energy consumption, watt-hr
EH	seasonal heating energy consumption, watt-hr
FA	net floor area, ft^2
$\overline{FA}$	average net floor area, ft^2
FRACS	fraction of solar insolation
FRACT	fraction of temperature
h	heat transfer coefficient at the outer surface, Btu/hr-ft^2-°f
H_1, H_2, H_3, H_4	coefficients used in Equations (6.13) and (6.15)
H_1 through H_{15}	coefficients used in Equation (7.16)
H	height, ft
HBLDG	building parameter for heating, Equation (7.22)
HDD	improved heating degree-day, °F-day
HLD	design heating load, Btu/day
HR	number of hours of occurrence of 5°F temperature bins, hr
HU	heating unit, Equation (7.18)
I_{fg}	latent heat of vaporization of water, Btu/lbm of water
K	constant of proportionality, Equation (8.9), watt-hr/Btu
k	constant of proportionality, Equation (6.4), Btu/°F-day
L	length, ft
MAX	variable to choose maximum of two values
N	number of buldings
$\overline{NA}$	average normalized area, Equation (5.1)
q_s	sensible heat gain, Btuh
q_ℓ	latent heat gain, Btuh

Q	total seasonal cooling done, Btu
$\overline{R}$	daily average solar insolation, Btu/hr-ft^2
R_{max}	maximum daily solar insolation, Btu/hr-ft^2
S_c	shading coefficient of glass
SCE	seasonal cooling efficiency
SEER	seasonal energy efficiency ratio, Btu/watt-hr
SHE	seasonal heating efficiency
T	dry bulb temperature, °F
T_b	base temperature, °F
T_{base}	base temperature, °F
T_d	design temperature, °F
T_{max}	maximum daily temperature, °F
T_{min}	minimum daily temperature, °F
$\overline{T}$	average daily temperature, °F
U_g	heat transfer coefficient of glass, Btu/hr-ft^2-°F
U_r	heat transfer coefficient of roof, Btu/hr-ft^2-°F
U_w	heat transfer coefficient of wall, Btu/hr-ft^2-°F
VI	ventilation and infiltration, ft^3/min
W_{max}	maximum humidity ratio, lbm of water/lbm of air
x	normalized temperature, Equation (8.6)
y	load ratio, Equation (8.5)

Greek Letter Symbols

α	absorptance of the surface for solar radiation
β	constant of proportionality, Equation (6.10), Btu/°F-day
η	boiler efficiency
ΔT	temperature difference, °F

Subscripts

A	test procedure A
B	test procedure B
b	base
base	base
bmax	maximum boiler
C	test procedure C
D	test procedure D
d	design
d	door
eq	equivalent
g	glass
i	building index
j	surface index
ℓ	latent
max	maximum
min	minimum
r	roof
res	residential
s	sensible
w	wall

CHAPTER I

INTRODUCTION

According to a well quoted report of the Stanford Research Institute (1), energy requirements for residential and commercial buildings (space heating and cooling) amounts to approximately 20 percent of the total energy consumed in the United States. It is often necessary to estimate these energy requirements and fuel consumptions of HVAC systems for both short and long term operation. These quantities can be much more difficult to calculate than design heat loss and gain or required system capacity, since they involve the integration over the period in question of the influence of many factors which may vary greatly with time. Comparison of energy requirements before and after implementation of an energy conservation program is also essential in determining the effectiveness of the program. For these and other reasons it is important to be able to estimate the energy requirements of buildings.

Application of the digital computer to calculate energy requirements has become routine. Use of a computer to perform energy analysis calculations began over a decade ago, and this application has gained popularity as fuel prices increase and as developments in the field bring this technology within the reach of the design engineer. Building energy analysis on the computer has typically been accomplished by performing an hour-by-hour (usually for a year) simulation of building zones and building energy systems. While modern building energy simulation programs are extremely useful, they are cumbersome to use and require detailed information about the building. "Hand checking" of the many calculations performed in an hour-by-hour analysis program is also difficult. For these reasons a much simpler procedure for estimating annual energy usage in buildings is desirable. This discussion does not imply in any sense that existing techniques for the comprehensive analysis of building energy requirements and costs are unacceptable; instead, a need for a simple but reasonably accurate technique to complement these more complex analytic aids is the basis of concern. The need for development of these techniques for estimating energy usage of commercial structures is of great importance, because a vast majority of the literature in this area has concentrated on residential dwellings. A simplified procedure in estimating energy requirements of commercial structures may find two successful applications:

1. As an aid in design, allowing an early estimate of the impact of design decisions and building uses on energy consumption.

2. As a diagnostic tool, facilitating the identification of insufficiencies in existing buildings.

The heating degree-day has been in steady use for over 40 years by utility and fuel suppliers as a measure to predict the energy demand of the average population of structures. The building design profession also uses it to estimate monthly and annual heating requirements. Traditionally, degree-days for both heating and cooling are calculated at a base temperature of 65°F. Mathematically, a conventional degree-day is expressed by the following:

$$\text{Heating:}\quad DD = \text{Max}\left\{\left(65°\text{F} - \frac{T_{max} + T_{min}}{2}\right),\ 0\right\}$$

$$\text{Cooling:}\quad DD = \text{Max}\left\{\left(\frac{T_{max} + T_{min}}{2} - 65°F\right),\ 0\right\}$$

where T_{max} and T_{min} are daily maximum and minimum temperatures, and the statistic $1/2\ (T_{max} + T_{min})$ is called the midrange of the daily temperature. The variable MAX indicates that positive quantities will result for DD and resulting negative values will be set to zero. Theoretically, degree-day base temperature should equal the building's balance point temperature, defined as the temperature above or below which the heating or cooling system is not needed, respectively. The balance temperature of a building, which determines the degree-day base to be used, is a complex function of thermostat settings, interior heat release, solar gains, and insulation levels. Ideally, the balance point temperature is an exterior temperature at which heat losses through the shell of the building, at the specified interior temperature, exactly matches its internal gains with no contribution from the heating and cooling system. This relationship is complicated by the sun, however, which can augment interior gains through transparent surfaces, and which can increase the effective temperature at the exterior surface of the building shell. The 65°F base traditionally used for both heating and cooling was obtained from extensive analysis of light residentials (2). This value may well have been appropriate for a poorly insulated building with 72°F heating and cooling thermostat settings, but this value may be considerably different for buildings of different types and structures. An investigation was undertaken in this study to determine the base temperature of a class of structures from an analysis of thermal response of building samples.

Simple statistical analysis can be a useful tool for developing, testing, and monitoring policy programs designed to reduce the building demand for energy. Such analyses may also be useful for monitoring the effects of changing demographic patterns or the effects of an acute temporary energy shortage on building demand. The most simple, statistical experiment would consist of measuring total energy demand at a monthly level on a sample of building units before and after the implementation of a conservation program. The before and after demands would be compared in order to see whether the program had been effective in reducing demand. Unfortunately, the anlaysis is complicated by the fact that the fuel required for space conditioning is a major portion of the building demand for energy, and the weather data distribution over a month is a major determinant of this portion of the demand. Since weather is not controllable, some attempt must be made to adjust the monthly demand for the coolness or warmth of the month, prior to making any comparison. It is crucial that the adjustment of demand for weather be as accurate as possible; otherwise, an error introduced by a faulty adjustment may distort the assessment of the effects of the program.

The conventional degree-day is the simplest method of extrapolating climate to yearly or monthly heating and cooling requirements. It is a function of atmospheric temperature only, so that significant effects of sun, humidity, and wind on heating and cooling are considered only indirectly. Although this method has shown satisfactory results for residential heating, utilizing weather data averaged over a long period, its extension for cooling computation has been limited and erratic.

A feasibility study of ways to replace or improve the present degree-day procedure has been underway at Oklahoma State University for the past few years. This study is based on an effort to develop an improved procedure to predict accurately the adjustment of demand for changes in climate. One of the difficulties with the degree-day procedure is the need for an efficiency parameter which adequately represents the system performance over the period of time under consideration. In the present study a simplified procedure for estimating an efficiency parameter for a system performance is discussed.

Objectives

The main objective of this study was to develop a procedure which accounts for all significant environmental parameters for a particular class of structures on a year-round basis; there is no intent to replace existing methods which compute energy requirements on an hourly basis using a dynamic model, such as the transfer function method. Rather, the results would be used to process and analyze actual energy consumption data so that actual usage trends and patterns of consumption can be determined. Furthermore, the results would be utilized to estimate energy requirements in cases where detailed simulations are not possible or feasible. The major objective of this study can be broken down into the following categories:

1. Identifying the significant environmental parameters.
2. Developing a procedure for structuring a hypothetical representative building which typifies the general behavior of the class of structures under consideration.
3. Developing a procedure for calculating heating and cooling degree-days for estimating energy requirements of the representative building.
4. Developing a simplified analytical procedure for estimating energy requirements of commercial structures.

5. Recommending a simplified procedure for estimating a seasonal energy efficiency parameter for predicting energy consumption.

The problem analysis included the following phases:

1. Significant environmental parameters were identified. This was achieved by analyzing the sensitivity of the thermal response of buildings to perturbations in climate (see Chapter IV).

2. A procedure for selecting a hypothetical representative building was established and a representative building was structured. This was achieved by analysis of a sample of buildings from the population under consideration (see Chapter V).

3. A procedure was developed for predicting energy requirements of the representative building utilizing the newly developed degree-day concept. This was achieved by regression analysis of the actual weather data and the corresponding simulated demand for the representative building (see Chapter VI).

4. An analytical expression for estimating energy requirements of buildings was developed. This was achieved by regression analysis of the combined actual weather and building data and simulated demand for a variety of buildings (see Chapter VII).

5. A simplified procedure for converting energy demand to energy consumption was discussed. This was achieved by utilizing seasonal energy efficiency ratio concepts (see Chapter VIII).

CHAPTER II

LITERATURE SURVEY

The heating degree-day has long been in use as an index of the fuel consumption of a heating plant, whether it be residential or commercial, although it applies to residential. The weather bureau includes this term in practically all of its monthly weather reports and in some annual summaries. The heating degree-day can also be used to check the operating efficiency of a heating plant from season to season and to estimate the probable fuel or energy requirements of a heating plant. When it is used for the latter purpose, a 10- or 20-year average of the annual degree-days for the locality must be used to get reliable results.

In an extensive survey of the literature, no standard practice was found concerning the correlation of cooling energy or fuel consumption with some index similar to that for heating, as the degree-day. It has been stated that if a cooling degree-day determined at some base mean daily temperature were used, it would be highly erratic because of the latent heat that has to be extracted from the air and the heat load of the occupants, lights, and appliances not related to the outside air temperatures.

The conventional degree-day method is the simplest method used for extrapolating climate to yearly or monthly heating and cooling requirements. The American Gas Association (2) determined from records in the heating of residences that the gas consumption varied directly as the degree-days, or as the difference between 65°F and the mean outdoor temperature. In other words, on a day when the mean temperature was 20 degrees below 65°F, twice as much gas was consumed as on a day when the temperature was 10 degrees below 65°F. Studies made by the National District Heating Association (3) of the metered steam consumption of 163 buildings located in 22 cities (and served with steam from a district heating company) substantiated the approximate correctness of the 65°F base chosen by the gas industry. From these developments researchers utilized the fuel consumption per degree-day ratio (for a sufficiently long period) to compare and determine the relative operating efficiencies. Such results should be used with some reservation as discussed in Reference (4), since it is possible to have wide variations (e.g., between early and late winter periods).

Since the early days of the development of the degree-day method, researchers have constantly been concentrating on refining and improving this method. An example of this is discussed in a study by Harris and Anderson (5) where they discuss the development of a degree-day correction factor. From their analyses they concluded that the corrected degree-day approach to estimating seasonal energy consumption of residential heating equipment provides a logical procedure for applying correction factors to the conventional degree-day operation to compensate for normal extraneous heat inputs to the house, and for the maintenance of an indoor temperature other than 70°F. Use of air temperature tables in estimating energy requirements are discussed in a paper by Singman and Cohen (6), who utilized air temperature tables published by the Department of Water and Power of the City of Los Angeles, derived from 10-year records of hourly dry bulb temperatures. This paper describes the use of heating and cooling degree-hours, defined to be the sum of all products of the difference between each temperature, and selected base temperature, times the expected number of hours during which such temperature occurs within a given time period. A cooling energy factor was introduced by Anders (7) in a study to develop a procedure for selecting the equipment and utility systems that serves two purposes: (1) provides a basis of comparison for all the various types of equipment and forms of fuel and energy available, and (2) can be simplified for use by the 15 post office regions. This paper describes the use of cooling energy factors and explains how this factor reflects the amount of cooling effect that can be obtained from outside air which assists the refrigeration machine in rejection of heat from the building. The procedure in this paper utilizes calculations and tabulations of the monthly heating and cooling energies, and normal electric energy demand and consumption, as the basic data for comparison of various systems and energies.

The most accurate way to calculate the energy units of heating and cooling requirements for a structure over a period of time is to correlate the hourly weather duration and the heat flow associated with various weather (8). But this weather and heat flow information must be modified to give due consideration to internal heat generated in the building. This internal heat modification incorporated into the weather and building data approach represents a major departure from the degree-day methods on heating that have been used for many years, and that have more recently been considered for cooling. An interesting study by Umlang (9) describes a method which employs weather data tables arranged so that they serve as multipliers which determine the heating or cooling energy requirements for any building for which the heat load characteristics are known. The major drawback of this technique is that the work involved in preparing these temperature tables for different areas is rather tedious. As the theory was developed by stages, no systematic approach to preparation of these tables is possible.

An investigation utilizing 11 normally occupied residences in six cities was reported in Reference (10). A method for predicting the operating cost of residential cooling equipment was developed and confirmed by test results in this paper. The analysis of the results of this paper shows that operating costs can be related to degree-days above 70°F. It was also concluded that the degree-day concept is preferable to the degree-hour concept frequently postulated for cooling.

The concept of using a cooling degree-day as an index of air conditioning energy consumption was traced back to 1953 (11). A study by Pappas and O'Brien of Southern Research Institute revealed that the use of a cooling degree-day (based on 65°F as an index of cooling requirements) appears to give a reasonable correlation with the energy consumption of cooling plants. Temperature bases of 75°F and 80°F showed practically no correlation with cooling energy consumption. They concluded that a 65°F base for the cooling degree day is not the complete answer for estimating energy or fuel consumption to compare seasonal operating efficiency; however, it does appear to be a step in the right direction if it is adopted and practiced. Studies of monitored buildings in recent years have revealed base temperatures significantly different from the 65°F base traditionally used. Analysis of data from the Twin River project by Myer and Benjamini (12) of Princeton University led them to their development of "modified degree-days." Their study stated that modified degree-days differ from conventional degree-days in two ways: (1) the

65°F base temperature in degree-days is replaced by a reference temperature parameter which is fitted to the data, and (2) the distribution of temperatures over a typical day is taken into consideration for modified degree-days. Their data exploration shows that the addition of a variable reference temperature parameter is decidedly the most important difference between the "modified" and conventional measure. Another form of the modified degree-day is discussed by McQuiston and Parker (13). This method accounts for the adjustment of the use of a 65°F base temperature, and the decrease in efficiency of a fuel-fired furnace and heat pumps under partial load, by use of interim and part load correction factors, respectively.

The influence of degree-day base temperature on building energy prediction is studied by Arens and Nall (14). The companion paper to this one (15) describes how to adjust the annual heating and cooling requirements predicted by TRY (test reference year) data. Their result is based on the relationship between heating and cooling requirements and heating and cooling degree-days to a base appropriate to a particular test house. The test house was designed, however, to be typical of most current residential constructions. The conclusions of these studies are that a combination of the TRY tape analysis and energy calculations demonstrate a new test of the effectiveness of degree-days to different bases for predictions of annual heating and cooling requirements. Results both from monitored buildings and from computer studies indicate that the traditional 65°F base for degree-day calculations does not accurately reflect the actual balance point temperature of occupied residential buildings. Variations of temperature distributions in different climate areas may result in significant errors in predictions when an inappropriate base temperature is used for the degree-day calculation. Energy conservation efforts based on these predictions may be inappropriate, resulting in increased energy usage and operating costs.

Among the cited references, some were based in part on studies which are closely related to the present study. Selection of a hypothetical representative building for simulation studies of energy requirements were discussed in References (16, 17, 18). Studies by Armstrong and May (19) of the Newcastle-Upon-Tyne Polytechnique, and Jones and Sepsy (20) of Ohio State University, are also among these studies. In the study by Jones and Sepsy, a building located on the campus of Ohio State University was instrumented and monitored to verify the simulation methods. The purpose of their study was to develop computer simulation methods for predicting heating and cooling load profiles using weather, structural, and architectural data as input, and predicting energy consumption of the system. Detailed field measurements on a test building were compared with the simulated results. Their conclusion from this study is that the general agreement between simulated and measured data, during periods where the equipment and controls were operating as assumed in the model, were satisfactory. The major items which caused uncertainty were difficult to predict or control; these include the relationship between the assumed thermodynamic equilibrium space temperature and the set point of the space thermostats, and the percent of internal shading at the windows. Their current studies, utilizing this instrumented building, are directed towards determining the effects of various changes in system operations and control modes to identify various energy conservation methods.

The ASHRAE Task Group on Energy Requirements, for heating and cooling of buildings, has worked on the development of a procedure for hour-by-hour computer-based methods of calculating building cooling and heating loads and yearly energy usage (21, 22). They developed a procedure for determining the weather data for input into the final calculation method. They also researched existing computer programs which had the same function (calculation of yearly building energy usage), compared with one another and with measured test results. From their analyses they developed a model for generating a Test Reference Year (TRY) to calculate energy requirements of buildings. The ASHRAE procedures for load and energy calculations were tested by the best means that the Task Group were able to devise, and the correlation was close enough that, when properly applied, predicted the energy requirements of a structure, dependent on the input parameters. They also demonstrated how an accurate prediction of energy requirements can be made by existing energy analysis programs provided that (1) the program includes simulations for the systems under consideration, and (2) the input closely reflects the actual operation of the building.

Emerging literature dealing with the analysis of energy data primarily reports studies which are "macro," both in time and sample frame, in the sense that the data indicate the monthly demand for energy for a diverse aggregate of energy consumption units. Analysis of the monthly energy bills for all of the residential consumers served by one or more utility companies would be a typical framework. These analyses proceed by ignoring, or statistically adjusting, the diversity of the units under analysis.

A study of a single homogeneous community in central New Jersey, where a set of almost identical owner-occupied town houses are located, were reported by Mayer (23). On the negative side, analysis of a single homogeneous community prohibits one from making statistical references about the totality of constructions, or even making claims about a wide variety of construction types. On the positive side, analysis of a large homogeneous sample gives one a great deal of confidence in making statements about the behavior of units similar to those under analysis. Furthermore, analysis of similar units gives a strong indication of both the variation in energy consumption patterns and the effects of numerous variables on the level and pattern of energy demand.

In the survey of literature cited, there seemed to be a great deal of homogeneity in the sense that energy consumptions were directly related to a climatic index in various forms of a degree-day, which in almost all cases had no climatic parameter other than the atmospheric temperature.

CHAPTER III

DESCRIPTION OF THE METHODS OF SOLUTION

This chapter outlines the general procedure to accomplish the objectives of this study. Discussions are made to demonstrate the needs for the analyses that are discussed in the chapters that follow.

From the survey of literature discussed in the previous chapter, the need for a simplified procedure to estimate energy requirements of commercial structures was apparent. The vast majority of literature surveyed deals with procedures for estimating the energy requirements of residential dwellings. These procedures normally relate energy consumption to climatic indices, which are functions of atmospheric temperature only. This has been known to result in erratic estimation, as the effects of the other significant climatic parameters are neglected. The present study differs from these in that energy requirements are related to a climatic index which accounts for all significant environmental variables.

As mentioned in the previous chapter, the concept of selecting a hypothetical representative building for simulation studies of energy requirements has been a common practice (16, 17, 18). This concept generally is used to avoid extensive analyses of a large number of structures which require a great deal of computation, time, and effort. Instead, a representative building from the class of structures under consideration can be selected and efforts can be directed to an analysis of this building. The results of these analyses can be generalized and extended to other structures in the same category.

In the present study, a hypothetical building was modeled to represent the thermal behavior of heavy institutional buildings. This building was selected from the architectural plans of a sample of institutional buildings. A detailed procedure in modeling a representative building, which typifies the behavior of the class of structures under study, is discussed in Chapter V.

It was discussed earlier that this study differed from most others in that the effects of additional environmental parameters were considered in estimating energy requirements. For this purpose, the parameters were identified (Chapter IV) and a representative building was structured (Chapter V). From simulation studies of the representative building, an improved degree-day concept, which is a function of the significant environmental parameters, was developed (Chapter VI). Detailed discussion of the formulation and development of this concept, along with its feasibilities and applications, are discussed in Chapter VI. The method described in Chapter VI assumes that the heating and cooling demands of a building are directly related to the corresponding degree-days. Moreover, these degree-days are functions of significant weather parameters. That is:

$$CL = f(CDD) \tag{3.1}$$

$$HL = g(HDD) \tag{3.2}$$

where

CL = cooling demand;

HL = heating demand;

CDD = cooling degree-day;

HDD = heating degree-day;

and

$$\text{CDD} = f(\text{weather parameters}) \tag{3.3}$$

$$\text{HDD} = g(\text{weather parameters}) \tag{3.4}$$

The functional relationships of the above equations, along with the methodology utilized in obtaining these relationships, are discussed in detail in Chapter VI.

It is important to realize that the analysis of the results from the representative building was instrumental in the development of an improved degree-day concept. This concept was utilized to estimate the demand of the representative building.

The procedure was then generalized to develop a method for estimating energy requirements of the commercial structures. This developed procedure accounts for variations in the shape and envelope characteristics of any building within the category of heavy structures. More specifically, the procedure was developed for estimating energy requirements of buildings which may be categorized as heavy structures (6 to 8 inch heavy concrete exterior walls, 6 inch concrete floor slab, and approximately 130 lb of building material per square foot of floor area). The estimating technique was developed for buildings whose total glass area ranges between 1/4 to 3/4 of their total wall area. The interior shading devices which were utilized in these formulations had shading coefficients which ranged between 0.25 to 1.00 (Table X). Various glass materials which were utilized in these developments covered the range of the transparent material typically used in commercial structures. The occupancy of these buildings was in the range of approximately 200 to 300 square feet of net floor area per person. The internal loads generated by lights amounted to approximately 1.5 to 3.0 watts per square foot of net floor area. Ventilation and infiltration rates were in the range of five cubic feet per minute per person. Computational experiments which were conducted to develop these techniques involved the analysis of simulated heating and cooling demand of these buildings with continuous occupancy (seven days per week), and with the heating and cooling equipment operating under steady state conditions. It is emphasized that these developments are for estimating energy requirements for space heating and cooling, and the power input to lights, appliances, and other components should be estimated separately.

The methodology in development of this generalized procedure is discussed in detail in Chapter VII. The procedure involves the assumption that heating and cooling demand of a building is a function of the product of two distinct variables. These variables represent the characteristic behavior of the building and weather parameters. That is:

$$CL = f_1(\text{building parameters}) \times f_2(\text{weather parameters}) \tag{3.5}$$

$$HL = g_1(\text{building parameters}) \times g_2(\text{weather parameters}) \tag{3.6}$$

where the weather variables are expected to be the functions of significant environmental parameters, and the building variables are expected to be the functions of the most significant building parameters. The functional forms of the above equations, along with the methodology utilized in obtaining those equations, are discussed in detail in Chapter VII.

One of the major difficulties with the degree-day procedures for estimating energy requirements is the need for an efficiency parameter which adequately presents the system performance over the period of time under consideration. In the present study, research was concentrated on the presentation of a procedure to determine a seasonal energy efficiency ratio which will adequately describe the system performance. Detailed discussion of this procedure is explained in Chapter VIII. Utilizing this efficiency parameter concept, energy consumption may be calculated from predicted demand obtained from Equations (3.5) and (3.6). That is:

$$EC = CL/SEER \tag{3.7}$$

$$EH = KHL/SHE \tag{3.8}$$

where

EC = cooling energy consumption;
EH = heating energy consumption;
CL = cooling demand;
HL = heating demand;
SEER = seasonal energy efficiency ratio;
SHE = seasonal heating efficiency; and
K = conversion factor.

One of the most important features of the present model is the capability of a systematic generation of weather tables for different locations. These tables can be generated through the use of an analytical expression developed in this study, and utilizing weather tapes. The values in these tables serve as multipliers to estimate heating and cooling demand when used in conjunction with the significant building parameters (Equations (3.5) and (3.6)). It is important to note that these significant building parameters are combined in a systematic manner to produce a constant value for the building under consideration. Therefore, the analysis will include determination of the product of two values (building and weather parameters) to estimate the demands of this building. Utilizing the concept of efficiency parameter, the energy consumption of the building can be calculated. A generated weather table using this procedure for different locations are presented in Appendix A of this study.

In summary, the following procedure was followed to accomplish the major goal of this study:

1. Significant environmental parameters were identified (Chapter IV).
2. A representative building was modeled (Chapter V).
3. An improved degree-day concept was developed (Chapter VI).
4. A simplified approach for predicting the demand of a building was developed (Chapter VII).
5. An efficiency parameter for estimating energy consumption was introduced (Chapter VIII).

CHAPTER IV

SENSITIVITY ANALYSIS OF THE THERMAL RESPONSE OF BUILDINGS TO PERTURBATIONS IN THE WEATHER PARAMETERS

This chapter analyzes the sensitivity of building structures to changes in weather conditions and identifies the significant environmental variables. Two different buildings from different classes of structures (i.e., heavy and light) were investigated. The cooling demand of the buildings were used to measure the effect of perturbations in environmental conditions. Computational tests were conducted to determine sensitivities to outdoor dry bulb temperature, solar flux, humidity, and combined ventilation and infiltration. Computational experiments were conducted utilizing actual climatic data (24) and employing an energy simulation program using the ASHRAE transfer function procedure (25). Results obtained from these analyses are discussed in the latter part of this chapter.

It should be apparent (due to interactions between the outside environmental variables, the structure, the inside space, and the occupant) that the role of climatalogical factors in predicting the thermal behavior of buildings cannot be assessed independently of the interacting elements. Changes in outside ambient air temperature certainly have fewer immediate effects on the demand of a massive structure than on a lightweight structure. However, this may not be a valid statement if the massive structure permits a large infiltration rate. The role of incident solar radiation is very important when irradiated surfaces are good absorbers, or when they transmit directly to the interior space. On the other hand, if the opaque surfaces are good reflectors and the transparent surfaces are shaded, or if air velocities over the surfaces are high and the air temperature low (compared to surface temperatures), the effect of incident solar radiation may not be significant. In general, environmental factors become less important in influencing energy requirements as the thermal resistance and capacitance of protective elements separating the human from the surroundings is made greater. The two buildings that were analyzed and are discussed in this chapter were selected to have identical shapes, size, volume, and occupancy, but with different boundary characteristics in that the thermal resistances and capacitances of the exterior walls of these buildings were different. Detailed discussion of the procedure involved in conducting the computational experiments is discussed for each building separately.

Heavy Construction

A sample building (Whitehurst Hall), located on the campus of Oklahoma State University, was chosen to investigate the sensitivity of the thermal response of a heavy building to perturbations in the weather. Whitehurst Hall is a four-story office building facing north with 57,366 square feet of net floor area. This building was chosen specifically because of the availability of extensive building envelope information and specifications from a previous study (i.e., shape, construction material, people and other internal heat generating loads, and schedule). Computational experiments were conducted to analyze the effects of varying climatalogical parameters on the cooling demand of this building. Basically, four variables were considered for this analysis, namely, atmospheric dry bulb temperature, solar insolation, humidity difference of indoor and outdoor space, and the combined effects of ventilation and infiltration. The computational experiments involved simulating cooling demand of this building for an average 24-hour day by employing a dynamic simulation model which required detailed building data and actual weather information on an hourly basis. The methodology involved to generate an average 24-hour day, utilizing actual weather data, is discussed in Reference (26). This procedure was employed in conducting the computational experiments. The concept of an average day was utilized, as this represents a variation of the climate over an entire month which has a great deal of influence on the outcome of the experiments. Each computation investigated the variation in cooling energy demand of this building as a result of perturbations in the variables under consideration. The range of values that was investigated for each variable covered both extremes of a typical situation. To investigate the sensitivities to humidity difference (denoted by DW) and ventilation and infiltration (denoted by VI), a daily average value of these quantities was put into the simulation program and was used to compute the demand. However, this procedure could not be followed for variations in temperature and solar insolation because there is no one-to-one correspondence of data. In other words, each computational experiment which required one input value of humidity, ventilation, and infiltration also required 24 hourly values of temperature and solar insolation data. It is apparent that profiles of temperature and solar insolation data should be used for calculating the cooling demand. One possibility would be to use temperature and solar insolation values which are randomly distributed over 24 hours for each computation. The application of this method to a problem of this magnitude, which is being analyzed in this context, would be very rigorous and time consuming, and the outcome probably will not provide any additional information than a simple systematic approach as was utilized in the present study.

The methodology used was based on generating temperature and solar insolation profiles similar in shape to those calculated for the average day. This was achieved by use of constants, which served as multipliers of weather data in the computer program, to generate distributions of identical shapes with different mean values. These multipliers were denoted by FRACT and FRACS, representing fractions of the actual temperature and solar insolation hourly data that were used in the simulation program. The values of these constants were chosen because they produced distributions of temperatures ranging from 80 percent to 120 percent of the actual temperature data (see Figure 1). The solar insolation multipliers also generated a distribution which ranged from 10 percent to 200 percent of the actual insolation data (see Figure 2). This approach greatly simplifies input information for computational purposes.

It is important to realize that the assumption that identical distributions are used in each computation can be justified for the following reasons. An average day is used to simulate the cooling demand and is a justification of this assumption. This day is calculated from an arithmetic averaging of the actual weather data over an entire month. Therefore, it contains the information in perturbations of the weather over an entire month. Hence the distribution of the temperature and solar insolations, which are calculated for this day, represent the typical

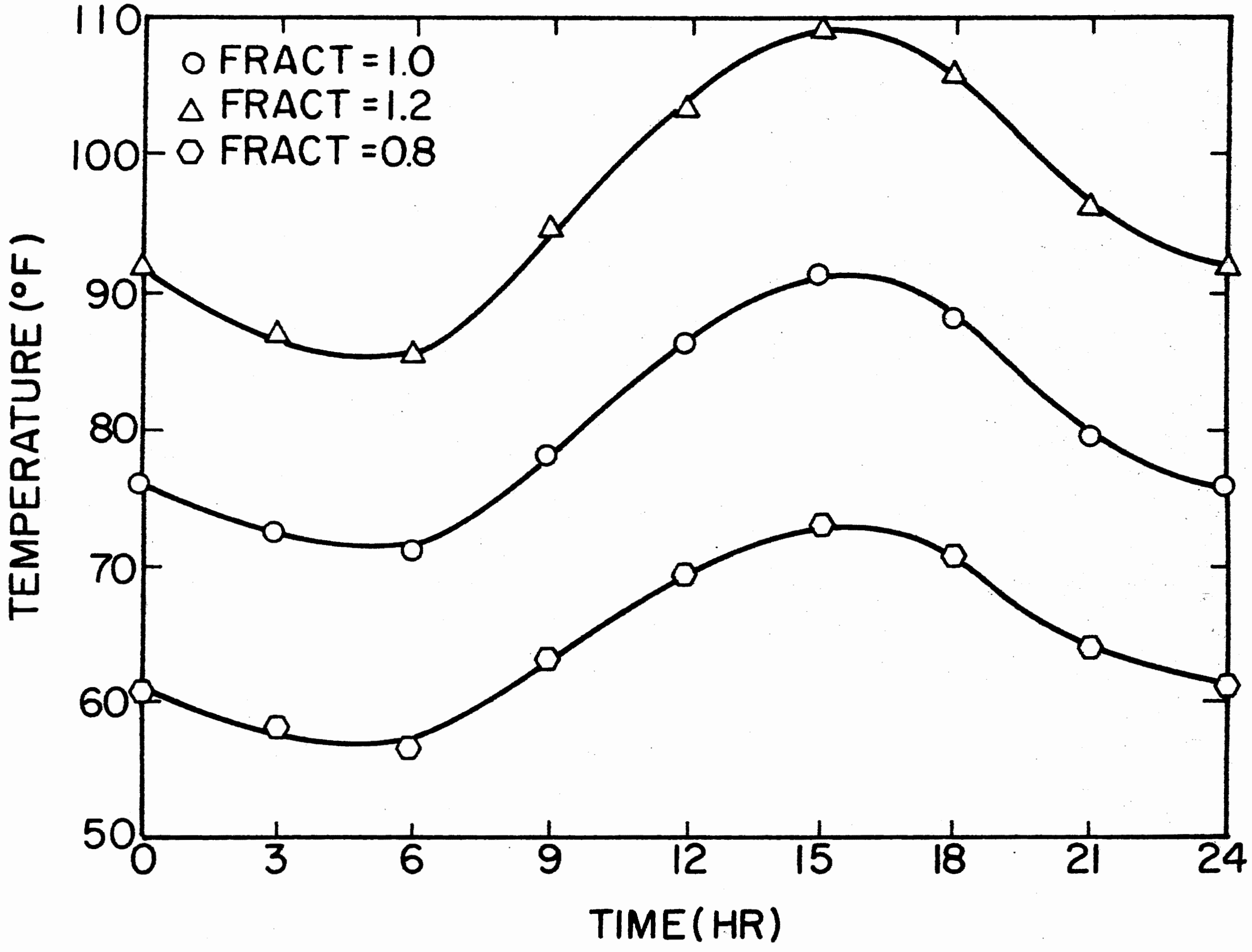

Figure 1. Temperature Profiles for the Average Day of August

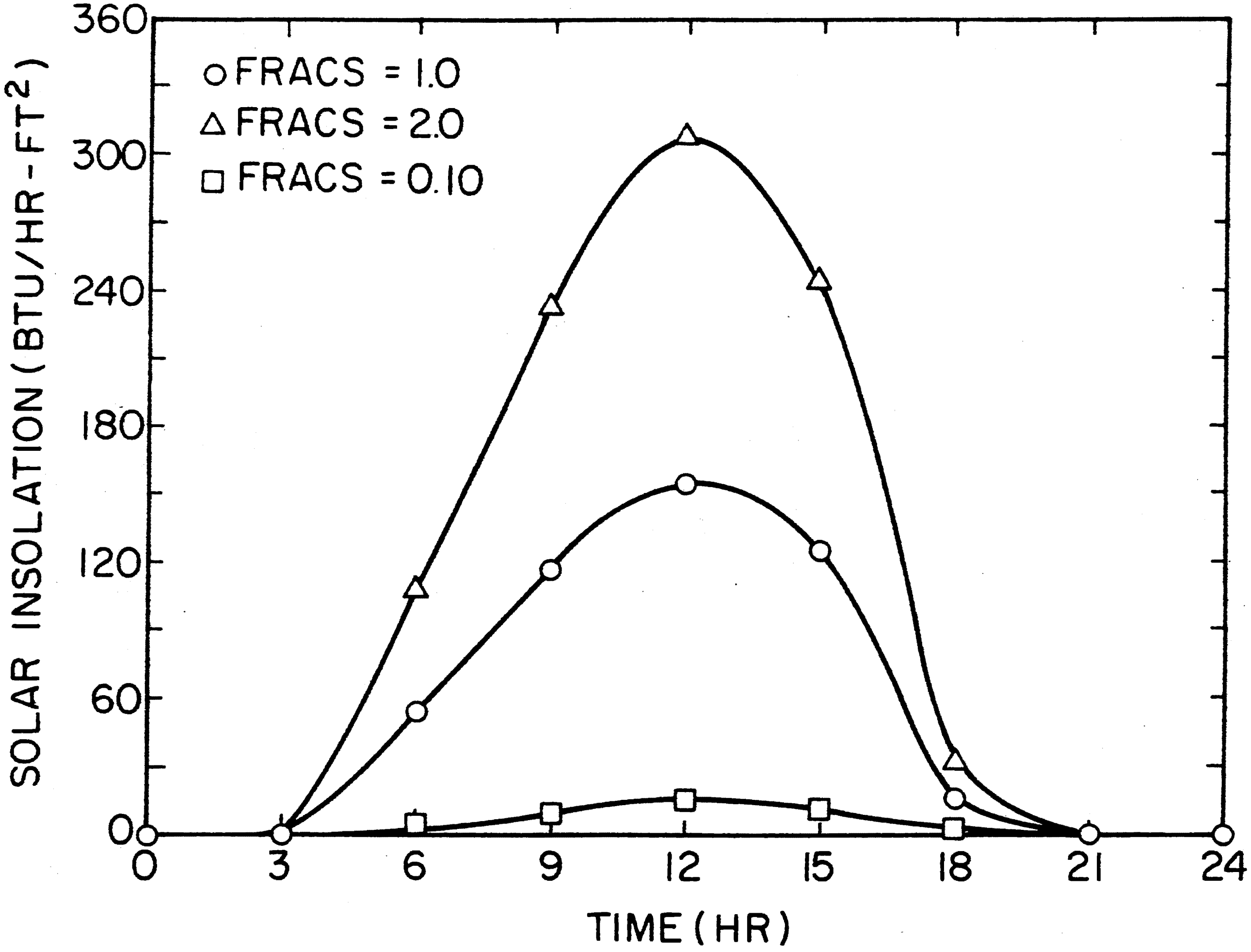

Figure 2. Solar Insolation Profiles for the Average Day of August

distribution for that month. This justifies the use of similar profiles (by use of multipliers) because they can also be regarded as typical variations in the weather.

The general procedure to conduct the computational experiments consists of constructing a two-dimensional table of values where the rows and columns denote the variables under consideration, and each entry of this table denotes the cooling demand. The matrix of values obtained from computational experiments made for Whitehurst Hall is tabulated in Table I. Major rows and columns of Table I, which represent the variables under analysis, are divided into several subrows and subcolumns to represent the actual magnitude of the variables used in the simulation program. As discussed earlier, where temperature and solar insolation are concerned, the values of multipliers represent a fraction of the actual recorded data which were used in the simulation program. After completion of the computational experiments, which led to development of Table I, an attempt was made to analyze the general outcome. Results obtained from these analyses are discussed in the latter part of this chapter. Graphical representation of the results obtained are displayed in Figures 5 through 8.

Light Construction

For the purpose of comparison and as a measure of dependability and reliability of the prevailing results, identical computational tests were conducted for a building from a different class of structures (i.e., light construction). This is a hypothetical building which was selected because of its identical shape, facade, and area to the heavy building which was discussed earlier. The envelope characteristics of this

TABLE I

SENSITIVITY ANALYSIS OF THE HEAVY CONSTRUCTION TO PERTURBATIONS IN THE CLIMATE

		FRACS					FRACT					DW x 10^2					VI			
		0.10	0.50	1.00	1.50	2.00	0.80	0.90	1.00	1.10	1.20	-0.80	-0.50	0.20	0.70	0.85	325	650	975	1300
FRACS	0.10	---	---	---	---	---	0.267	0.514	0.809	1.102	1.397	0.590	0.635	0.741	---	0.839	0.729	0.756	0.783	0.809
	0.50	---	---	---	---	---	0.447	0.718	1.013	1.306	1.600	0.794	0.839	0.945	---	1.043	0.933	0.960	0.987	1.013
	1.00	---	---	---	---	---	0.561	0.844	1.138	1.432	1.727	0.919	0.964	1.070	---	1.168	1.058	1.085	1.111	1.138
	1.50	---	---	---	---	---	0.634	0.922	1.216	1.510	1.804	0.997	1.042	1.148	---	1.246	1.136	1.163	1.189	1.216
	2.00	---	---	---	---	---	0.773	1.067	1.360	1.655	1.949	1.141	1.187	1.292	---	1.391	1.281	1.307	1.334	1.360
FRACT	0.80	0.267	0.447	0.561	0.634	0.773	---	---	---	---	---	0.330	0.375	0.481	0.567	0.587	0.525	0.537	0.549	0.561
	0.90	0.514	0.718	0.844	0.922	1.067	---	---	---	---	---	0.695	0.671	0.776	0.852	0.874	0.785	0.805	0.824	0.844
	1.00	0.809	1.013	1.138	1.216	1.360	---	---	---	---	---	0.919	0.964	1.070	1.146	1.168	1.058	1.085	1.111	1.138
	1.10	1.102	1.306	1.432	1.510	1.655	---	---	---	---	---	1.213	1.259	1.364	1.440	1.463	1.332	1.366	1.399	1.433
	1.20	1.397	1.600	1.727	1.804	1.949	---	---	---	---	---	1.508	1.553	1.659	1.734	1.757	1.606	1.646	1.687	1.727
DW x 10	-0.80	0.590	0.794	0.919	0.997	1.141	0.330	0.625	0.919	1.213	1.508	---	---	---	---	---	1.004	0.975	0.947	0.919
	-0.50	0.635	0.839	0.964	1.042	1.187	0.375	0.671	0.964	1.259	1.553	---	---	---	---	---	1.015	0.998	0.981	0.964
	0.20	0.741	0.945	1.070	1.148	1.292	0.481	0.776	1.070	1.364	1.659	---	---	---	---	---	1.041	1.051	1.061	1.070
	0.70	---	---	---	---	---	0.567	0.852	1.146	1.440	1.734	---	---	---	---	---	1.060	1.089	1.117	1.146
	0.85	0.839	1.043	1.168	1.246	1.391	0.587	0.874	1.168	1.463	1.757	---	---	---	---	---	1.066	1.100	1.134	1.168
VI	325	0.729	0.933	1.058	1.136	1.281	0.525	0.785	1.058	1.332	1.606	1.004	1.015	0.041	1.060	1.066	---	---	---	---
	650	0.756	0.960	1.085	1.163	1.307	0.537	0.805	1.085	1.366	1.646	0.975	0.998	1.051	1.089	1.100	---	---	---	---
	975	0.783	0.987	1.111	1.189	1.334	0.549	0.824	1.111	1.399	1.687	0.947	0.981	1.061	1.117	1.134	---	---	---	---
	1300	0.809	1.013	1.138	1.216	1.360	0.561	0.844	1.138	1.433	1.727	0.919	0.964	1.070	1.146	1.168	---	---	---	---

building were chosen because they placed this building within the light construction category, as suggested by ASHRAE (25).

Transfer function coefficients of the exterior surfaces for this construction were computed by employing a computer program TRANSF based on a method described in Reference (27). Computational experiments made for a heavy construction were replicated for this light building, and as discussed earlier, the results were tabulated and are shown in Table II. Graphic presentation of the outcome of this analysis is shown in Figures 9 through 12. Analysis and discussion of the prevailing results for this building are discussed, along with the results of the heavy construction in the next section of this study.

Analysis of the Results

As discussed earlier in this chapter, the general outcome of the sensitivity analysis of both heavy and light construction is tabulated in Tables I and II, respectively. There are a number of ways, preferred by most engineers and scientists, to graphically demonstrate this analysis. A graphic illustration of data has the advantage of providing insight into the physical behavior of the variables under analysis. As stated previously, one objective of this study was to identify significant environmental variables (see Chapter I). In order to accomplish this task, an attempt was made to illustrate the variations in the cooling demand of each building as a function of each variable. Figures 3 and 4 present typical variations in cooling demand as a function of climatic variables for heavy and light construction, respectively. Sharp variations in cooling demand are observed for variations in temperature and solar insolation values, moderate changes can be observed for changes in humidity, and no significant variations are detected for perturbations in ventilation and infiltration for both construction types. It is

TABLE II

SENSITIVITY ANALYSIS OF THE LIGHT CONSTRUCTION TO PERTURBATIONS IN THE CLIMATE

		FRACS					FRACT					$DW \times 10^2$					VI			
		0.10	0.50	1.00	1.50	2.00	0.80	0.90	1.00	1.10	1.20	-0.80	-0.50	0.20	0.70	0.85	325	650	975	1300
FRACS	0.10	---	---	---	---	---	0.383	0.554	0.772	1.024	1.276	0.553	0.598	0.704	0.779	0.802	0.693	0.719	0.745	0.772
	0.50	---	---	---	---	---	0.582	0.759	0.986	1.238	1.490	0.767	0.813	0.918	0.994	1.016	0.907	0.933	0.959	0.986
	1.00	---	---	---	---	---	0.732	0.917	1.151	1.403	1.655	0.932	0.977	1.083	1.158	1.181	1.071	1.098	1.124	1.151
	1.50	---	---	---	---	---	0.846	1.039	1.276	1.528	1.780	1.057	1.102	1.208	1.284	1.306	1.196	1.223	1.249	1.276
	2.00	---	---	---	---	---	1.018	1.215	1.455	1.707	1.958	1.236	1.282	1.387	1.463	1.485	1.376	1.402	1.429	1.455
FRACT	0.80	0.383	0.582	0.732	0.846	1.018	---	---	---	---	---	0.428	0.473	0.579	0.737	0.751	0.702	0.712	0.772	0.732
	0.90	0.554	0.759	0.917	1.039	1.215	---	---	---	---	---	0.680	0.725	0.831	0.923	0.942	0.866	0.883	0.900	0.917
	1.00	0.772	0.986	1.151	1.276	1.455	---	---	---	---	---	0.932	0.977	1.083	1.158	1.810	1.071	1.098	1.124	1.151
	1.10	1.024	1.238	1.403	1.528	1.707	---	---	---	---	---	1.184	1.229	1.335	1.410	1.433	1.303	1.336	1.369	1.403
	1.20	1.276	1.490	1.655	1.780	1.958	---	---	---	---	---	1.436	1.481	1.587	1.662	1.685	1.534	1.575	1.615	1.655
$DW \times 10^2$	-0.80	0.553	0.767	0.932	1.057	1.236	0.428	0.680	0.932	1.184	1.436	---	---	---	---	---	1.016	0.988	0.950	0.932
	-0.50	0.598	0.813	0.977	1.102	1.282	0.473	0.725	0.977	1.229	1.481	---	---	---	---	---	1.028	1.011	0.994	0.977
	0.20	0.704	0.918	1.083	1.208	1.387	0.579	0.831	1.083	1.335	1.587	---	---	---	---	---	1.054	1.064	1.073	1.083
	0.70	0.779	0.994	1.158	1.284	1.463	0.737	0.923	1.158	1.410	1.662	---	---	---	---	---	1.073	1.101	1.130	1.158
	0.85	0.802	1.016	1.181	1.306	1.485	0.751	0.942	1.810	1.433	1.685	---	---	---	---	---	1.079	1.113	1.469	1.181
VI	325	0.693	0.907	1.071	1.196	1.376	0.702	0.866	1.071	1.303	1.534	1.016	1.028	1.054	1.073	1.079	---	---	---	---
	650	0.719	0.933	1.098	1.223	1.402	0.712	0.883	1.098	1.336	1.575	0.988	1.011	1.064	1.101	1.113	---	---	---	---
	975	0.745	0.960	1.124	1.249	1.429	0.722	0.900	1.124	1.369	1.615	0.960	0.994	1.073	1.130	1.147	---	---	---	---
	1300	0.772	0.986	1.151	1.276	1.455	0.732	0.917	1.151	1.403	1.655	0.932	0.977	1.083	1.158	1.181	---	---	---	---

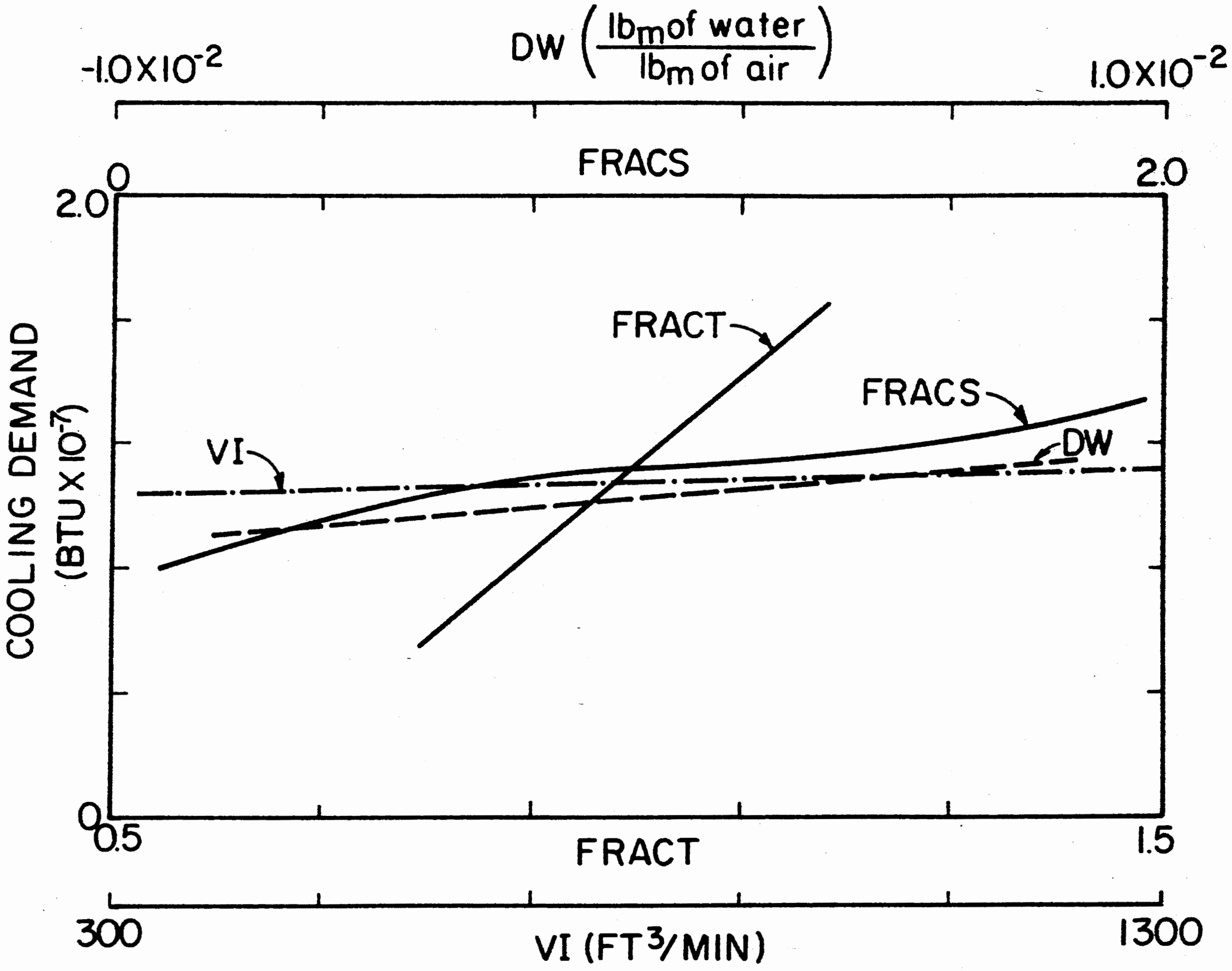

Figure 3. Typical Variations in Cooling Demand of the Heavy Construction

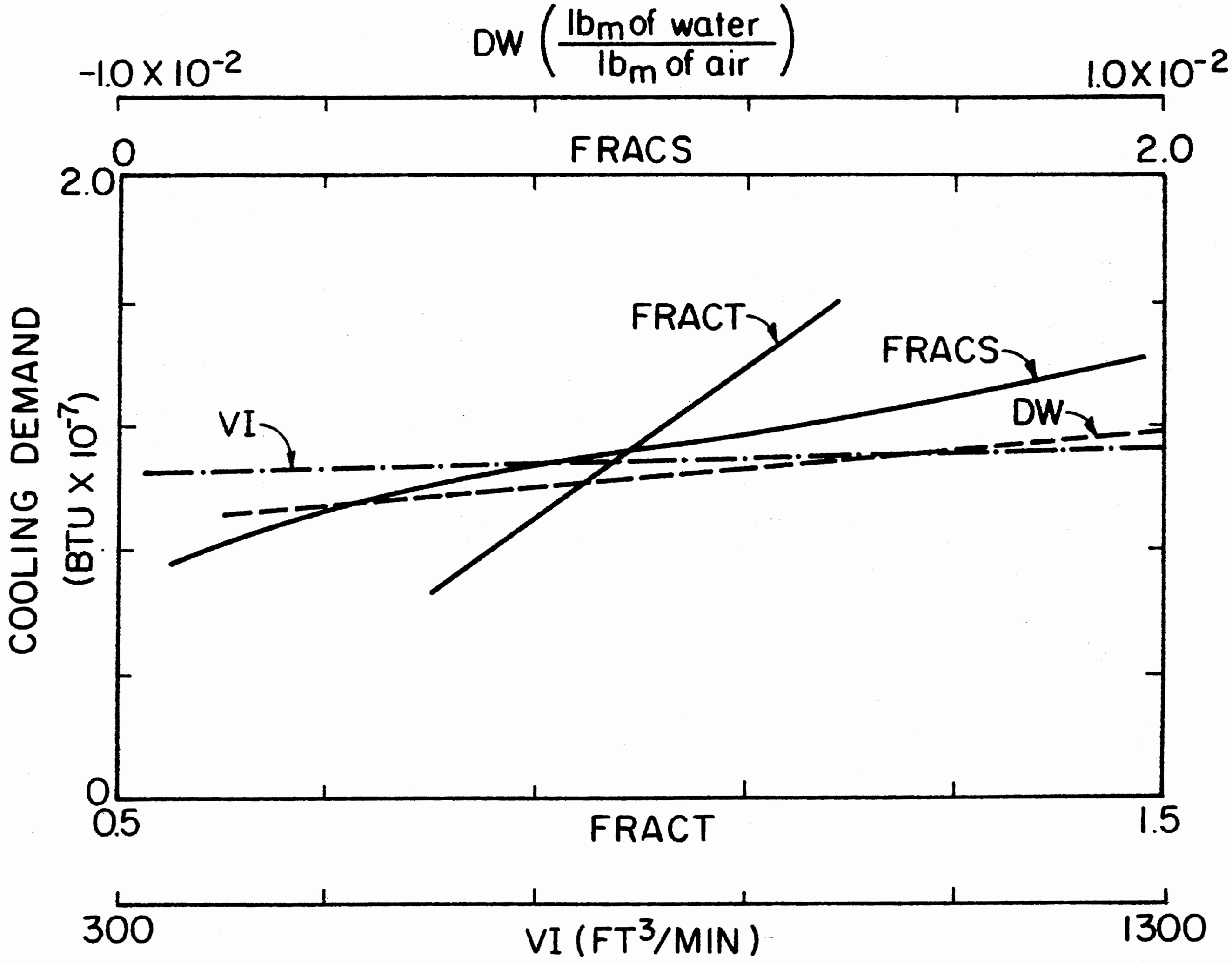

Figure 4. Typical Variations in Cooling Demand of the Light Construction

important to notice that the pattern of variations in both cases is almost identical, which serves as a measure of reliability and dependability of the computational experiments. This will be discussed in further detail in the remainder of this chapter.

Basically, four series of plots were made for each construction to illustrate variations in cooling demand as a function of each variable. Each series consists of three plots which demonstrate the effects of parametric values of each variable. These plots are discussed in order. Illustrations for the heavy construction are considered first. Series of plots are illustrated in Figure 5(a), (b), (c) and demonstrate variations in the cooling demand of the heavy construction as a function of solar insolation. It is evident that each series of plots consists of three illustrations, as seen in Figure 5. Figure 5(a) represents variations for different parametric values of temperature. Figure 5(b) is representative of variations in parametric values of humidity ratio difference. Figure 5(c) demonstrates variations in parametric values of ventilation and infiltration. This analogy was consistently utilized in a graphic representation of the results of this section. The pattern of variations in all three plots of Figure 5 demonstrate an evident increase in cooling demand for increasing values of solar insolation. Quantitative analysis of these illustrations is demonstrated in tabular form in Table III and will be discussed in detail in the latter part of this chapter. Figure 6(a), (b), and (c) illustrates variations in cooling demand as a function of temperature for different parametric values of solar insolation (Figure 6(a)), humidity ratio difference of indoor and outdoor (6(b)), and ventilation and infiltration (6(c)). Again, it is evident in all of these plots that cooling demand of this building increase sharply as the

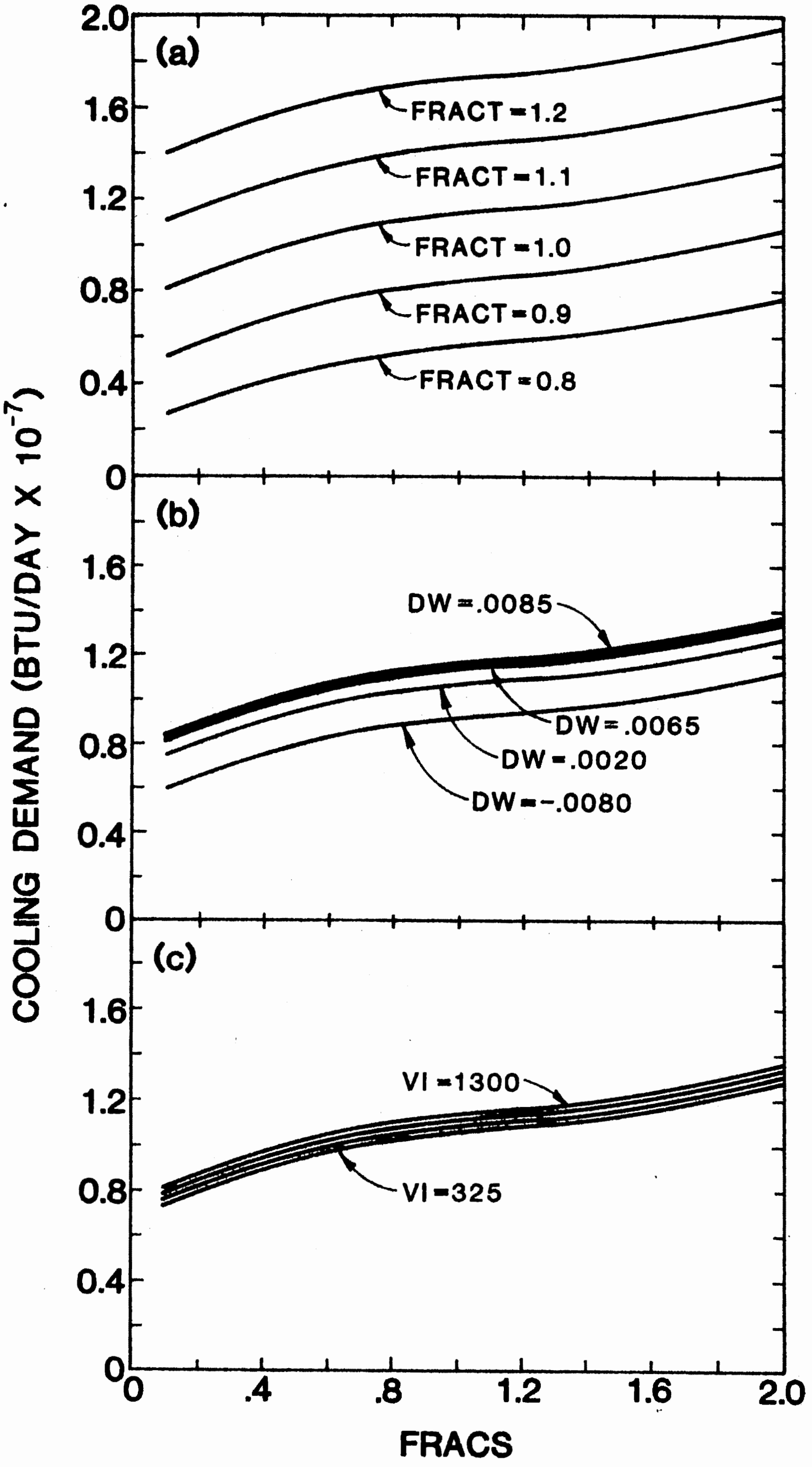

Figure 5. Cooling Demand of the Heavy Construction Versus Solar Insolation

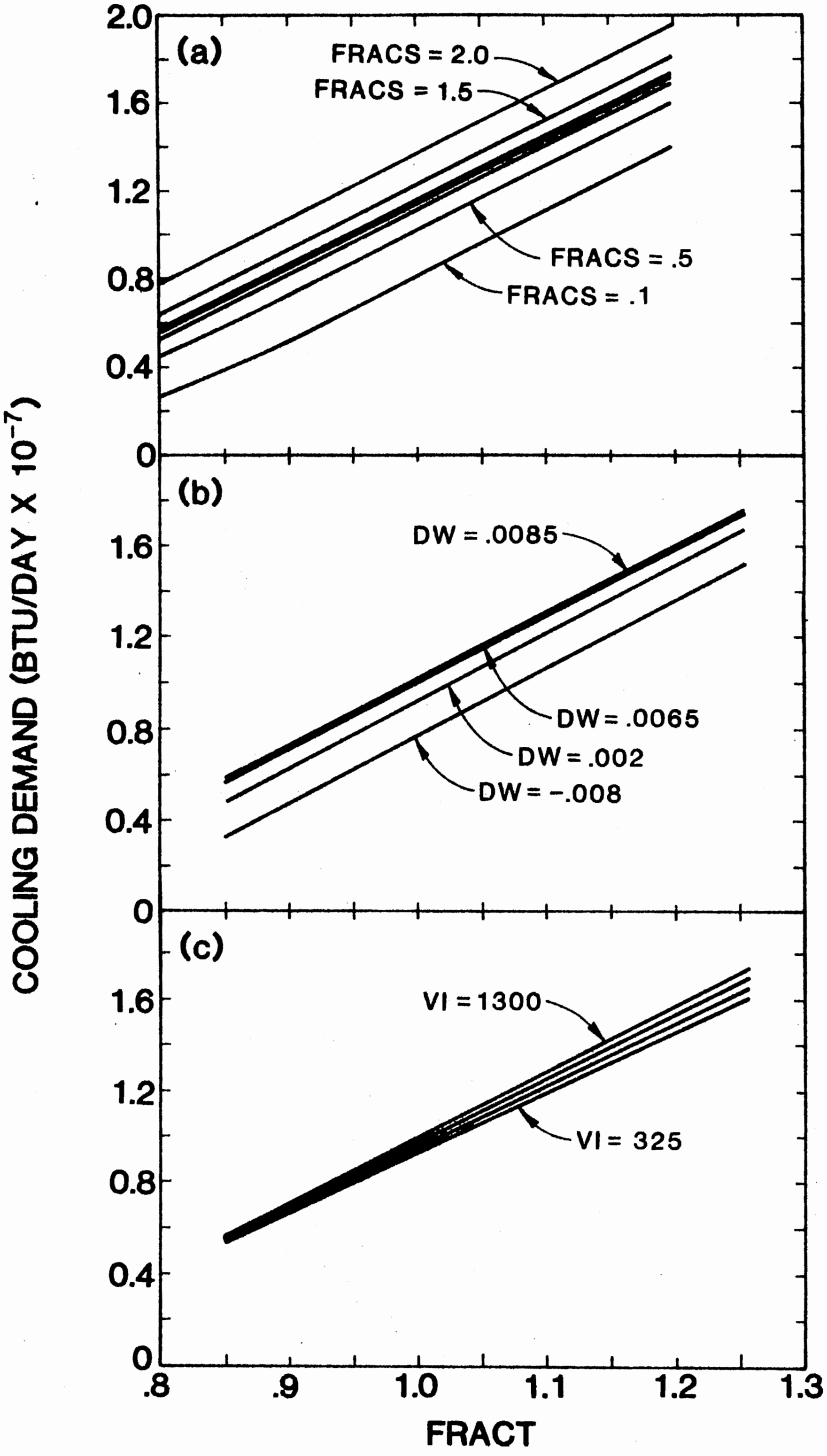

Figure 6. Cooling Demand of the Heavy Construction Versus Temperature

atmospheric temperature is increased. A series of plots illustrate the effects of variations in humidity ratio differences on the cooling demand of the building (Figure 7). A moderate increase in the value of cooling demand is observed for increasing values of humidity ratio difference in all plots. It is interesting to note the crossing pattern, which is observed for parametric values of ventilation and infiltration in Figure 7(c), because outdoor air is less humid than indoor conditions (i.e., DW is negative). Therefore, when ventilation and infiltration are introduced at a given rate, the latent component of heat generation, as a result of differences in the humidity ratio (DW) of incoming and outgoing air, acts as a detriment to the cooling component. This is best described by the following equations:

$$q_s = 1.10\ (VI)(\Delta T)$$

$$q_\ell = 4840\ (VI)(DW)$$

where

q_s = sensible heat gain as a result of temperature difference (Btuh);

q_ℓ = latent heat gain due to a difference in humidity ratio of incoming and outgoing air (Btuh);

VI = ventilation and infiltration (ft^3/min);

DW = difference in humidity of outdoor and indoor (lbm of water/ lbm of air); and

ΔT = difference in outdoor and indoor temperature (°F).

It is evident from the above that as DW becomes negative, it forces the latent heat gain to become a negative quantity. This causes the total heat gain, due to ventilation and infiltration (i.e., sensible plus latent), to become either a smaller positive quantity or a negative

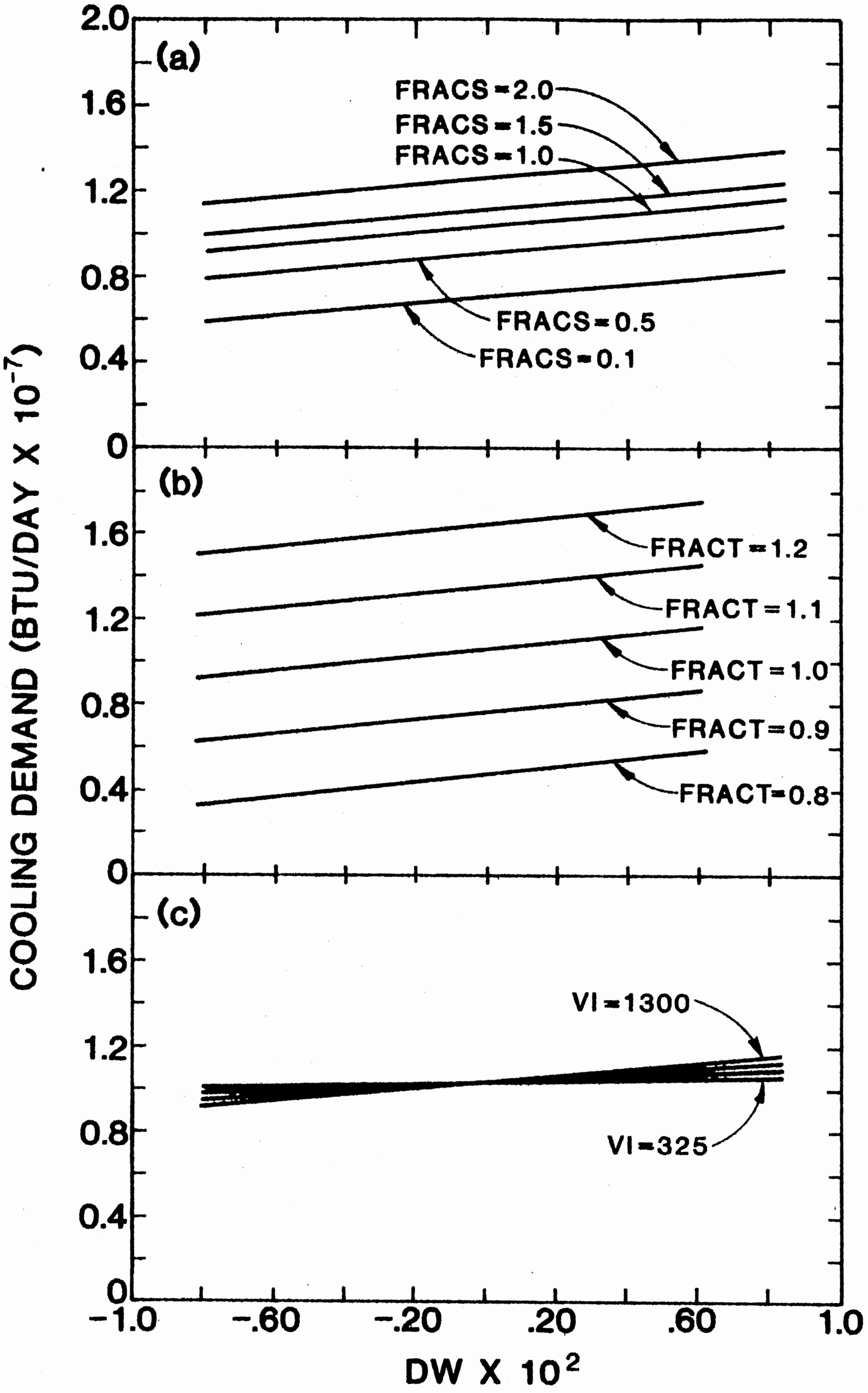

Figure 7. Cooling Demand of the Heavy Construction Versus Humidity Ratio Difference of Indoor and Outdoor Air

quantity, depending on the magnitudes of sensible and latent heat gains, respectively. It is also evident from the above equation that as VI increases, latent heat gain and cooling demand will also increase for positive values of DW. The exact opposite of this is true for negative values of DW. This is evident in the plot of Figure 7(c), where the crossing point occurs at point DW = 0, which is consistent with theoretical expectations.

The last series of plots for the heavy construction are shown in Figure 8. This figure illustrates variations in the cooling demand of this building as a function of changes in ventilation and infiltration. It is obvious that no significant changes in the cooling demand can be observed in any one of these plots. From the graphic presentations up to this point, one can observe that variations in the cooling demand are strongly affected by perturbations in solar insolation and temperature, moderately changed by variations in humidity, and no significant variations are detected for changes in ventilation and infiltration.

As discussed earlier, replicate series of figures were plotted for variations in the cooling demand of the light construction as a function of each variable. These plots are shown in Figures 9 through 12. It is interesting to note that identical behaviors and patterns, which were discussed for the heavy construction, can be observed for the light construction as well. Figure 9 illustrates the effects of perturbation in solar insolation on the cooling demand of this building. Strong effects can be observed in all three plots of this figure. The variations in cooling demand caused by perturbations in temperature are illustrated in Figure 10. A sharp increase in values of the cooling demand (for increasing values of temperature) is observed in all three plots of this figure.

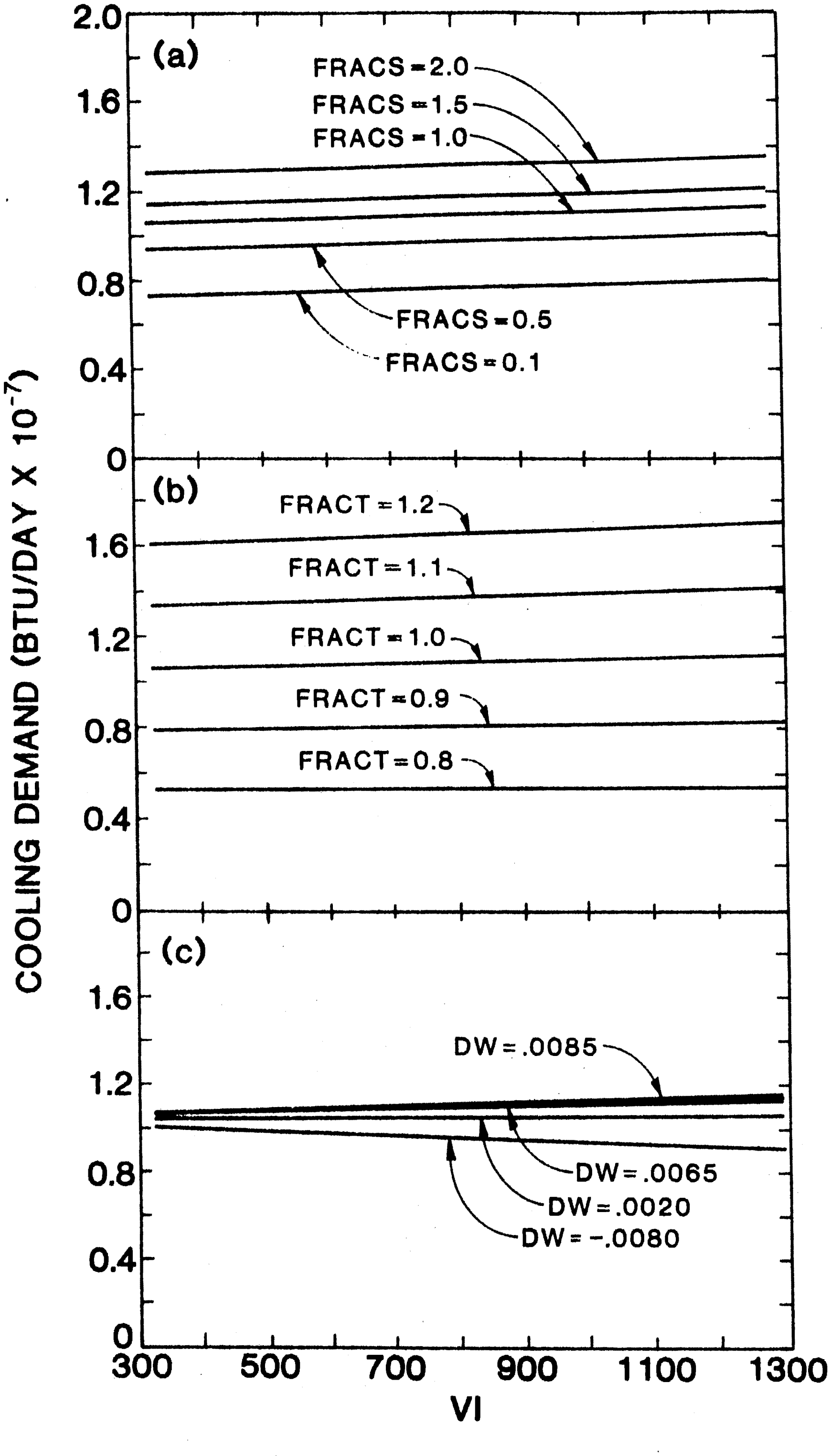

Figure 8. Cooling Demand of the Heavy Construction Versus Ventilation and Infiltration

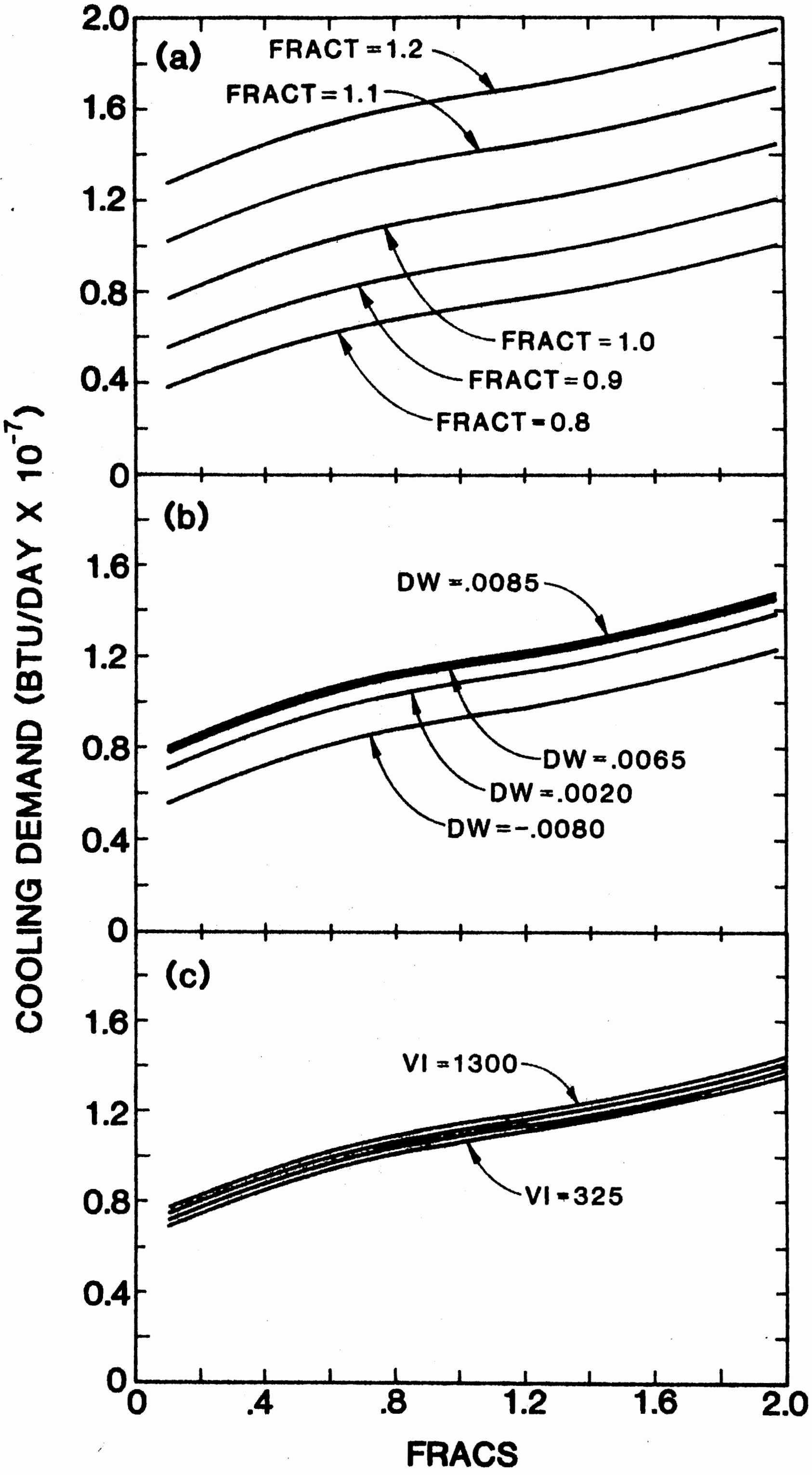

Figure 9. Cooling Demand of the Light Construction Versus Solar Insolation

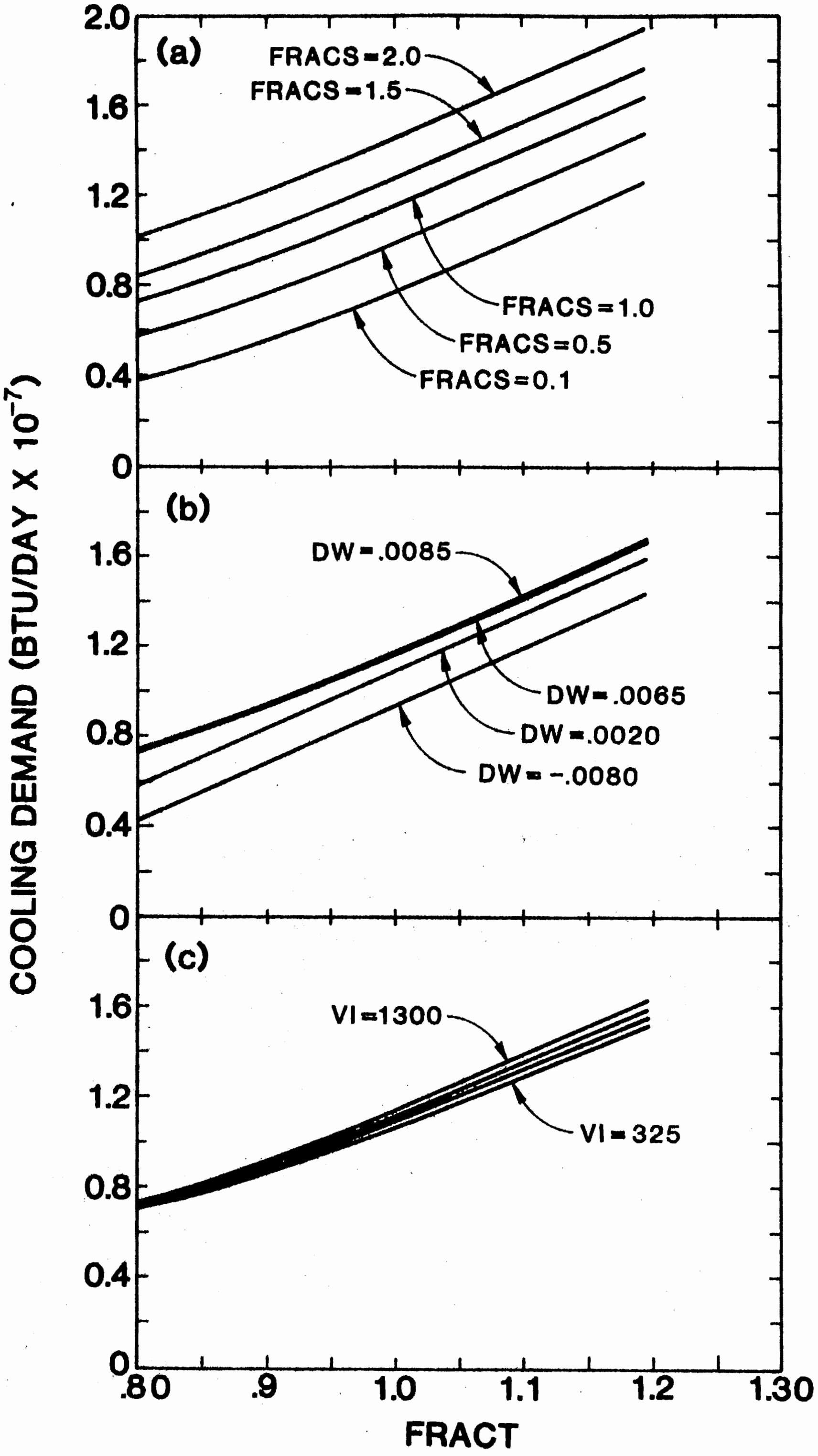

Figure 10. Cooling Demand of the Light Construction Versus Temperature

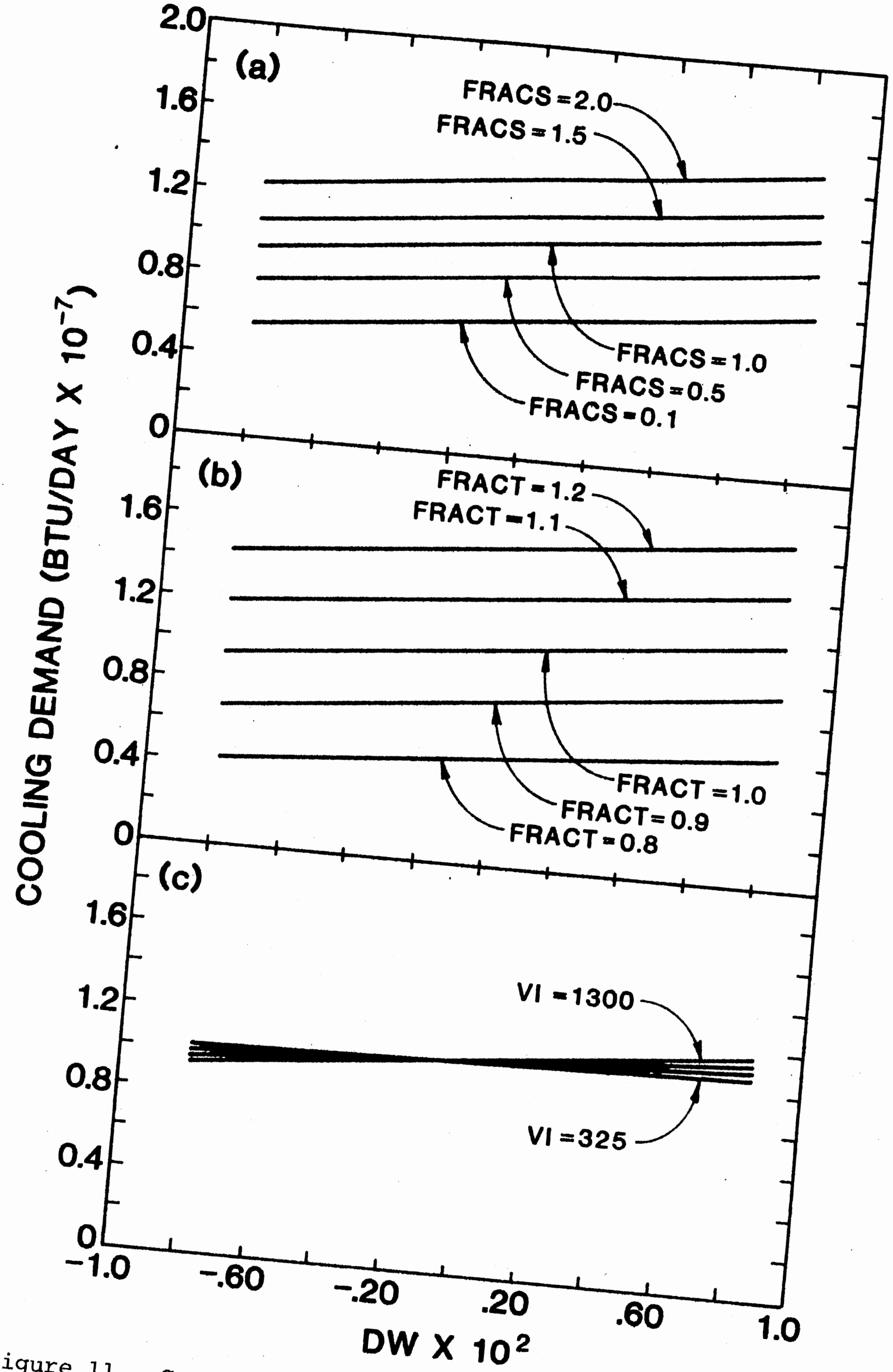

Figure 11. Cooling Demand of the Light Construction Versus Humidity Ratio Difference of Indoor and Outdoor Air

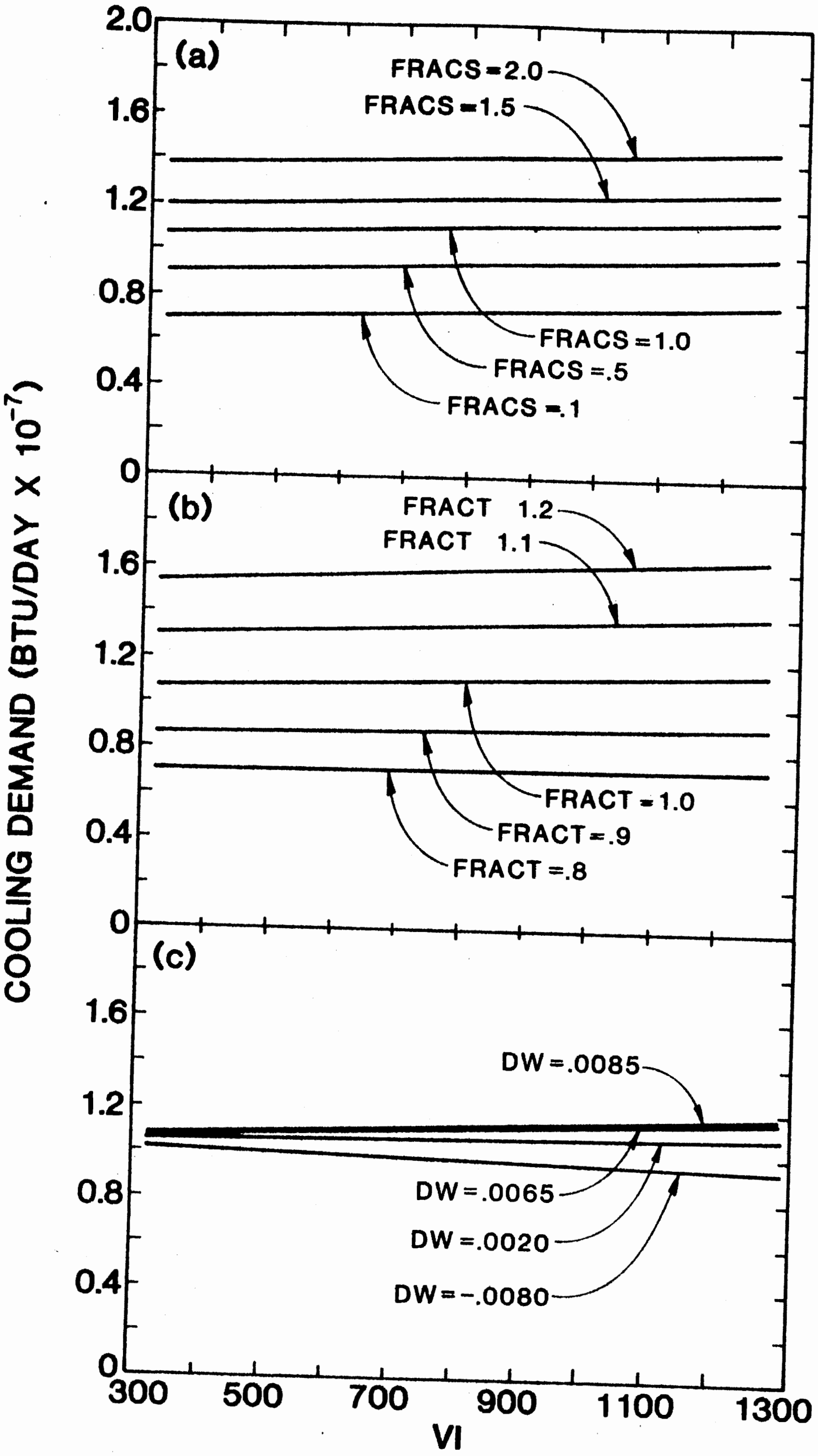

Figure 12. Cooling Demand of the Light Construction Versus Ventilation and Infiltration

The effects of variations in humidity, ventilation, and infiltration on cooling demand of the light construction are illustrated in Figures 11 and 12, respectively. Moderate or no significant effects in cooling demand are observed for humidity, ventilation, and infiltration, respectively.

Quantitative analyses of the results obtained, based on the study in this chapter, and represented by series of plots in Figures 5 through 12, are summarized in Tables III and IV for heavy and light construction, respectively. These tables summarize maximum deviations in cooling demand as a result of variations in each variable and the corresponding parameters. Maximum deviations listed in Tables III and IV served as criteria for determining the importance of the influence of environmental variables on sensitivity of the thermal response of buildings. A criterion was chosen with parameters which attributed to deviations below 10 percent; these were considered insignificant. This means that the climatic variables, the perturbations of which caused maximum deviations of above 10 percent in cooling demand, are considered the most influential. Analysis of the results of these tables demonstrate that temperature and solar insolation are the most dominant variables. This was also observed earlier in the graphic presentation of the results. It is also evident that sensitivity of the thermal response of both buildings is moderately affected by variations in humidity ratio difference of indoor and outdoor air. Deviations of about 10 percent and smaller, resulting from changes in ventilation and infiltration rates for both buildings, also suggest the insignificance of this variable compared to the effects of others that were considered.

In conclusion, it can be stated that quantitative generalizations

TABLE III

SUMMARY OF RESULTS OF HEAVY CONSTRUCTION

Variable	Parameter	Cooling Demand (BTU x 10^{-7}) MAX	MIN	Percent Deviation
FRACT	FRACS	1.39690	0.26703	80.88
	DW	1.50780	0.32978	78.13
	VI	1.72680	0.56104	67.51
FRACS	FRACT	0.77307	0.26703	65.46
	DW	1.14140	0.59029	48.28
	VI	1.28070	0.72955	43.03
DW	FRACT	0.58670	0.32978	43.79
	FRACS	0.83945	0.59029	29.68
	VI	1.16830	0.91915	21.32
VI	FRACT	1.72680	1.60640	6.97
	FRACS	0.80925	0.72955	9.85
	DW	1.16830	1.06600	8.75

TABLE IV

SUMMARY OF RESULTS OF LIGHT CONSTRUCTION

Variable	Parameter	Cooling Demand (BTU x 10^{-7}) MAX	MIN	Percent Deviation
FRACT	FRACS	1.27580	0.38298	69.98
	DW	1.43590	0.42776	70.21
	VI	1.65480	0.73202	55.76
FRACS	FRACT	1.01800	0.38298	62.38
	DW	1.23630	0.55275	55.29
	VI	1.37560	0.69304	49.62
DW	FRACT	0.75089	0.42776	43.03
	FRACS	0.80191	0.55275	31.10
	VI	1.81000	0.93182	21.10
VI	FRACT	1.65480	1.53450	7.27
	FRACS	0.77171	0.69304	10.19
	DW	1.18100	1.07860	8.67

regarding the influence of climate on the thermal behavior of a structure is not a simple task to achieve. This study shows how many interactions between the climatic variables, the structure, and the interior space should be taken into account, and a quantitative assessment of the resulting thermal response for a particular structure subjected to a particular climate can be made.

CHAPTER V

MODELING A REPRESENTATIVE BUILDING

This chapter discusses the technique utilized in selecting a hypothetical building to be representative of the class of structures under investigation. This analysis is one requirement of the objectives of this study (see Chapter I).

The practice of selecting a hypothetical representative building for simulation studies of energy requirements is a common practice among researchers (16, 17, 18). The general practice is to proceed with the analytical developments of this building and, based on these advancements, draw parallels to the actual conditions. The major interest of this study was concerned with the class of structures that may be categorized as heavy construction. Analyzing the individual thermal behavior of numerous construction types would require a tremendous amount of effort and computation time; therefore, a modeling method must be employed which will closely approximate the general response and behavior of these buildings. At this point an effort was concentrated on analyzing the behavior of a sample of institutional type buildings, which may be generally classified as heavy construction with average fenestration, with medium to high internal loads. General University buildings on the campus of Oklahoma State University were chosen for the investigation. A hypothetical representative building which typifies the thermal response of these buildings was modeled. The steps followed in structuring the hypothetical representative building are described below:

1. The buildings under consideration were categorized in two groups and a representative building for each category was found. These categories included buildings whose north-south axis constituted their dominant length, and buildings whose east-west axis constituted their dominant length.

2. After studying the architectural plans, general information about each individual building was obtained. This information included the building shape and facade, construction material used, and different surface types (walls, glass, doors).

3. The exterior surface areas of each building were normalized, based on the net floor area of the corresponding building. These normalized quantities were summed over the total number of buildings, and average values for these quantities were computed from the following equation:

$$\overline{(NA)}_j = \frac{\sum_{i=1}^{N} (A_i/FA_i)}{N} \; ; \; j = 1, 2, 3, 4 \qquad (5.1)$$

where

$\overline{NA}$ = average normalized area;

A = surface area (wall, glass, door);

FA = net floor area;

N = number of buildings;

i = building index (i = 1, 2, . . . N); and

j = surface index (1 = north, 2 = south, 3 = east, 4 = west).

4. An average net floor area was also calculated for these buildings by using the following equation:

$$\overline{FA} = \frac{\sum_{i=1}^{N} (FA)_i}{N} \tag{5.2}$$

where

$\overline{FA}$ = average floor area;

N = number of buildings; and

i = building index ($i = 1, 2, \ldots, N$).

By definition, the representative building is an average building which is modeled from analyses of the buildings that were investigated. Thus different surface areas of this building can be computed from the product of a corresponding normalized area and the average net floor area, that is:

$$A_{rj} = (\overline{NA})_j \times \overline{FA} \tag{5.3}$$

where A_r is the surface area of the representative building (wall, glass, door).

This procedure was utilized to calculate the dimensions of different surfaces for the representative building of each category.

Types of construction materials used for the exterior walls of the representative buildings were determined from a survey of the materials used for each building. Internal loads, occupancy, and building schedule were also determined from an analysis of each individual building. A computer program TRANSF was employed for calculating the transfer function coefficients of the exterior shell of both representative buildings. Tables V and VI summarize pertinent information from the representative buildings in each category.

Theoretically, the representative building typifies the thermal response of the buildings which it represents. This analogy is followed

TABLE V

REPRESENTATIVE BUILDING FOR NORTH-SOUTH FACING BUILDINGS

North Wall				South Wall				East Wall				West Wall			
A_w (ft2)		A_g (ft2)	A_d (ft2)	A_w (ft2)		A_g (ft2)	A_d (ft2)	A_w (ft2)		A_g (ft2)	A_d (ft2)	A_w (ft2)		A_g (ft2)	A_d (ft2)
L (ft)	H (ft)			L (ft)	H (ft)			L (ft)	H (ft)			L (ft)	H (ft)		
264.225	60			264.225	60			119.58	60			119.58	60		
15853.5		3709.5	193	15853.5		3103	185	7175.1		1096	126	7175.1		1021	43

Roofs

North		South		East		West		Horizontal	
L (ft)	H (ft)	L (ft)	H (ft)	L (ft)	H (ft)	L (ft)	H (ft)	L (ft)	H (ft)
264.225	29.35	264.225	29.35	119.58	27.21	119.58	27.21	234.225	89.58

Building: Representative for north-south facing buildings

FA = 109812 ft^2

Volume = 1895761.5 ft^3

Nomenclature:

A_w = total wall area

A_g = window area

A_d = door area

L = length

H = height

TABLE VI

REPRESENTATIVE BUILDING FOR EAST-WEST FACING BUILDINGS

North Wall				South Wall				East Wall				West Wall			
A_w (ft^2)		A_g (ft^2)	A_d (ft^2)	A_w (ft^2)		A_g (ft^2)	A_d (ft^2)	A_w (ft^2)		A_g (ft^2)	A_d (ft^2)	A_w (ft^2)		A_g (ft^2)	A_d (ft^2)
L (ft)	H (ft)			L (ft)	H (ft)			L (ft)	H (ft)			L (ft)	H (ft)		
84.6	60			84.6	60			222.57	60			222.57	60		
5076		1012	11.5	5076		1001	0	13354		2377	170	13354		2115	260

Roofs

North		South		East		West		Horizontal	
L (ft)	H (ft)	L (ft)	H (ft)	L (ft)	H (ft)	L (ft)	H (ft)	L (ft)	H (ft)
84.6	25.60	84.60	25.60	222.57	29.02	222.57	29.02	192.57	54.60

Building: Representative for east-west facing buildings

FA = 63787.5 ft^2

Volume = 1129765.3 ft^3

Nomenclature:

A_w = total wall area

A_g = window area

A_d = door area

L = length

H = height

in the next chapter (see Chapter VI), where an analytical model for expressing heating and cooling degree-days was developed from a simulation study of the thermal response of the representative building.

CHAPTER VI

DEVELOPMENT OF AN IMPROVED HEATING AND COOLING DEGREE-DAY CONCEPT

This chapter discusses the methodology for development of an analytical procedure for expressing heating and cooling degree-days in terms of the significant environment variables, which were identified earlier in Chapter IV. These degree-day quantities were employed to develop a procedure for estimating the heating and cooling demand of the representative building.

An effective way to calculate the heating and cooling demand of a building is to study the building thermal performance by using accurate computer simulations. In order for such studies to be conducted on the computer, however, the computer program to be used should be very comprehensive, and should indicate the proper response to the change in many parameters which are pertinent to energy usage. The intent of this chapter and the chapters to follow is to provide a simplified procedure for estimating heating and cooling demand which may be acceptable for many engineering practices. The procedure developed is based on the detailed computer simulation of thermal performance of buildings, which takes into account all of the variables previously identified that affect the building characteristics. Appendix B displays the listing of the computer program which was utilized throughout this study to perform an hour-by-hour dynamic simulation of thermal performance of buildings. The analysis was concentrated strongly on heavy construction for which a representative building was modeled in the preceding chapter. The procedure was then extended to study the thermal performance of a light residential dwelling to determine the possibilities of implementing this methodology to other classes of structures. These analyses are described below.

Prediction Model for the Representative Building

For this section an analytical model was developed for predicting heating and cooling demand of the representative building. The analysis is discussed under two different categories (i.e., cooling and heating). An expression for degree-days and, consequently, a prediction equation for demand of each category was developed.

Cooling

The procedure begins with the conventional degree-day method and proceeds with improving and modifying this technique, based on previous findings of this study, to achieve the final formula.

First, the conventional degree-day is described by

$$DD = (\bar{T} - 65)\,\frac{N}{24} \qquad (6.1)$$

where

DD = conventional degree-day (°F day);

$\bar{T}$ = average temperature $(T_{max} + T_{min}/2)$ (°F); and

N = period for which $\bar{T}$ is calculated (hr).

Theoretically, building demands over a period of time are directly proportional to degree-days accumulated during that period. That is,

$$CL = f(DD) \qquad (6.2)$$

and for the purpose of this study the conventional means are replaced by the following improved procedure:

$$CL = f(CDD) \tag{6.3}$$

Therefore,

$$CL = kCDD \tag{6.4}$$

where CDD is defined by

$$CDD = (T_{eq} - T_{base}) \frac{N}{24} \tag{6.5}$$

and

CL = cooling demand (Btu);

CDD = cooling degree-day (°F-day);

k = constant of proportionality (Btu/°F-day);

T_{eq} = equivalent ambient temperature (°F); and

T_{base} = balance or base temperature of the building (°F)

where, in the above formula, it is evident that equivalent and base temperatures are utilized in places of average and 65°F temperatures, which are typically used in the conventional procedure. Theoretically, the equivalent ambient temperature is a function of predominant ambient parameters which were identified in Chapter IV. Moreover, this is a fictitious temperature, and is defined to be the temperature of outdoor air, which in the absence of any radiation exchanges and latent effects, and with no variation in the temperature distribution, will result in the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, humidity, and temperature distribution effects. Furthermore, it can be postulated that this temperature can be expressed in following form:

$$T_{eq} = C_1\overline{T} + C_2 DT + C_3 \frac{\alpha}{h} \overline{R} + C_4 \frac{I_{fg}}{C_p} \overline{DW} \tag{6.6}$$

where

$\overline{T}$ = average daily temperature (°F);

DT = daily temperature range $(T_{max} - T_{min})$ (°F);

$\overline{R}$ = daily average solar insolation (Btu/hr-ft^2);

$\overline{DW}$ = daily average humidity ratio difference between indoor and outdoor air (lbm of water/lbm of day air);

α = absorptance of the surface for solar radiation;

h = coefficient of heat transfer by long wave radiation and convection at the outer surface (Btu/hr-ft^2-°F);

I_{fg} = latent heat of vaporization of water (Btu/lbm water);

C_p = specific heat sapacity of air (Btu/lbm air, °F); and

C_1, C_2, C_3, C_4 = constants.

The parameters α, h, I_{fg}, and C_p were employed to maintain the dimensional consistency of the above equation. It easily can be observed that the equivalent ambient temperature is a function of predominant climatic variables as identified previously. It should also be noted that a new variable DT (daily temperature range) is added to this formulation. This variable is a climatic characteristic, which is normally suppressed by a daily average temperature in the conventional degree-day approach, although it could be very influential in estimating energy consumption. A day with an average temperature which is equal to building balance tempertuture but with a large daily range might require heating by night and cooling by day (accumulating energy requirements without accumulating either type of degree-day). Thus a building in this climate will appear to have a high energy demand in relation to its degree-day. This variable was included in the formulation of T_{eq} and CDD to adjust the estimated demand for variations in the daily temperature. Prior to making any estimate of the equivalent temperature for any climate, the coefficients of these climatic terms (C_1 through C_4) must be determined. Evaluation of these coefficients is described as follows: from the basic equations we have,

$$CL = kCDD \tag{6.4}$$

$$CDD = (T_{eq} - T_{base}) \frac{N}{24} \tag{6.5}$$

$$T_{eq} = C_1\overline{T} + C_2DT + C_3 \frac{\alpha}{h} \overline{R} + C_4 \frac{I_{fg}}{C_p} \overline{DW} \tag{6.6}$$

therefore, by direct substitution,

$$CL = k(C_1\overline{T} + C_2DT + C_3 \frac{\alpha}{h} \overline{R} + C_4 \frac{I_{fg}}{C_p} \overline{DW} - T_{base}) \frac{N}{24} \tag{6.7}$$

This expression relates cooling demand to climatic variables in the simplest manner. For a specified building and a particular climate, evaluation of cooling demand in the above equation will require knowledge of the coefficients k, C_1, C_2, C_3, C_4 and also the balance temperature T_{base} of this building. The method used to calculate these quantities required least squares fitting of the regression analysis of the simulated and weather data. These data were generated from simulating the cooling demand of the representative building using actual weather data over a specified period. The listing of the computer program which performs the regression analysis of data is presented in Appendix B. The results obtained from these calculations are discussed in detail in the latter part of this chapter, and the calculated coefficients are listed in Table VII.

TABLE VII

CONSTANTS OF EQUATIONS FOR PREDICTING HEATING AND COOLING DEMANDS

Representative				Residential			
Constant	Cooling	Constant	Heating	Constant	Cooling	Constant	Heating
C_1	1.00000	H_1	1.00000	C_1	1.00000	H_1	1.00000
C_2	-0.07745	H_2	-0.13810	C_2	-0.15300	H_2	0.00806
C_3	0.25587	H_3	0.42129	C_3	0.24450	H_3	0.25010
C_4	0.08145	H_4	-0.06755	C_4	0.15550	H_4	0.08942
k*	537440.16	β*	451299.93	k*	12607.88	β*	12511.28
T_{base}**	57.20	T_{base}**	57.20	T_{base}**	60.00	T_{base}**	60.00

*Units are Btu/day-°F.

**Units are °F.

Heating

This section describes a method developed for calculating heating degree-days, utilizing the same procedure and identical analogy that was used in the formula for cooling degree-days.

Based on the same analogy which was used previously for cooling, the formulation begins with a definition of the conventional heating degree-day:

$$DD = (65 - \overline{T}) \frac{N}{24} \tag{6.8}$$

Theoretically, heating demand is directly related to heating degree-days.

$$HL = f(HDD) \tag{6.9}$$

Therefore,

$$HL = \beta HDD \tag{6.10}$$

where

$$HDD = (T_{base} - T_{eq}) \frac{N}{24} \tag{6.11}$$

and

HL = heating demand (Btu);

HDD = heating degree-day (°F-day);

T_{eq} = equivalent ambient temperature (°F);

T_{base} = balance or base temperature of building (°F);

N = period for which HDD is calculated (hr); and

β = constant of proportionality (Btu/°F-day).

Without further elaboration, an equivalent ambient temperature can be expressed by the following formula, as it was discussed earlier.

$$T_{eq} = H_1\overline{T} + H_2DT + H_3\frac{\alpha}{h}\overline{R} + H_4\frac{I_{fg}}{C_p}\overline{DW} \tag{6.12}$$

This relationship expresses the equivalent ambient temperature as a function of climatic variables in a manner identical to the one that was discussed for cooling. The difference between heating and cooling equivalent temperatures is the coefficient of the climatic terms. When Equation (6.12) is substituted in Equation (6.11) and the result is replaced in Equation (6.10), the following relationship is obtained:

$$HL = [T_{base} - (H_1\overline{T} + H_2DT + H_3\frac{\alpha}{h}\overline{R} + H_4\frac{I_{fg}}{C_p}\overline{DW})]\frac{N}{24} \tag{6.13}$$

This relationship expresses the heating demand (HL) as a function of the predominant climatic parameters. As described for cooling, the evaluation of heating demand for a particular climate will require knowledge of the coefficients and the balance temperature in the above equation. Least squares fitting of the regression analysis of the simulated demand and weather data revealed the values of these quantities. These data were generated by simulating the heating demand of the representative building using actual weather data over a specified period. Detailed descriptions of the results which were obtained from these computations are made in the latter part of this chapter. Table VII displays the computed values of the constants that are necessary to compute heating and cooling demand of the representative building. It is important to note that the analysis in this chapter, up to this point, was mostly concentrated on a class of heavy construction, and specifically on a typical representative building of this class. Analytical models were developed to predict heating and cooling demand of this building. These analytical models were functions of improved heating and cooling degree-days, respectively. Although the major interest of this study is concerned with heavy structures, there is a great deal of interest in investigating the applicability of this procedure to other classes of structures (i.e., medium and light construction). It is reiterated that this study does not intend to work out the computations necessary for development of expressions that are applicable to these classes of structures; rather, its purpose is to investigate and determine whether the developed procedure can be implemented and extended to other building categories. This led to the analysis of a light residential dwelling which is described below.

Prediction Model for a Light Residential Building

This section describes an extension of the procedure, which was previously developed for the representative building, to analyze the thermal response of a light residential building. The building selected is a family dwelling located in Stillwater, Oklahoma, with an approximate net floor area of about 2170 square feet. The identical procedure, which was developed for predicting demand of the representative building, was followed to calculate the heating and cooling degree-days. These quantities were utilized to develop equations for estimating heating and cooling demand of this building. The analysis proceeded by simulating the heating and cooling demand of this residential building over a certain period and formulating an analytical expression using the values of demand and corresponding climate. The analytical expressions (heating and cooling) which were developed for this building were identical in form to those previously described for the representative building. That is,

$$CL_{res} = k(C_1\overline{T} + C_2 DT + C_3 \frac{\alpha}{h}\overline{R} + C_4 \frac{I_{fg}}{C_p}\overline{DW} - T_{base})\frac{N}{24} \qquad (6.14)$$

$$HL_{res} = \beta[T_{base} - (H_1\overline{T} + H_2 DT + H_3 \frac{\alpha}{h}\overline{R} + H_4 \frac{I_{fg}}{C_p}\overline{DW})]\frac{N}{24} \qquad (6.15)$$

where the subscript "res" denotes the calculations for a residential building. For simplicity and convenience, identical nomenclature is used for both buildings. The convention follows the use of "C" coefficients describing the cooling mode and "H" coefficients denoting the heating mode operations. It must be emphasized that although identical nomenclature is used for both buildings (representative and residential), the values of these constants are different for each case. Least squares fitting of the regression analysis of the heating and cooling demand, and the corresponding climatic data, revealed the values of these constants. Table VII presents the values of these constants for both the heating and cooling modes and for both buildings. The results obtained from these analyses are discussed in the following sections.

Analysis and Discussion of the Results

The results obtained from the analyses described in the previous sections of this chapter are described in detail below. These analyses are discussed in two distinct parts for the representative and residential types of construction, respectively. For each case comparisons are made between the simulated and predicted results to verify the validity of the developed procedure. Comparisons are also made between the predictions of the developed model and the conventional degree-day procedure in an attempt to demonstrate the advantages of the present study. The results are illustrated by both tabular and graphic means in the remainder of this chapter.

Results of the Representative Building

As discussed in the introductory part of this chapter, the purpose of the analysis included development of an improved procedure to determine heating and cooling degree-days, which will help to compute heating and cooling demand, respectively. The procedure included determining a functional relationship which expresses the demand of this building as a function of the predominant climatic parameters. Furthermore, these significant climatic variables are combined in a manner which forms a degree-day type of function. The basic functional form of these variables was discussed earlier and are repeated below:

$$CL = kCDD \tag{6.4}$$

$$CDD = (C_1\overline{T} + C_2DT + C_3\frac{\alpha}{h}\overline{R} + C_4\frac{I_{fg}}{C_p}\overline{DW} - T_{base})\frac{N}{24} \tag{6.14}$$

$$HL = \beta HDD$$

$$HDD = [T_{base} - (H_1\overline{T} + H_2DT + H_3\frac{\alpha}{h}\overline{R} + H_4\frac{I_{fg}}{C_p}\overline{DW})]\frac{N}{24} \tag{6.15}$$

The regression analysis procedure resulted in the evaluation of coefficients and constants in the above equations. These values are listed in Table VII and when substituted in the above equations, result in the following:

$$CL = 537440.16*CDD \tag{6.16}$$

$$CDD = [\overline{T} - 0.0770\ T + 0.256\frac{\alpha}{h}\overline{R} + 0.081\frac{I_{fg}}{C_p}\overline{DW}] - 57.2 \tag{6.17}$$

$$HL = 451299.93*HDD \tag{6.18}$$

$$HDD = 57.2 - [\overline{T} + 0.138\ DT + 0.421\ \frac{\alpha}{h}\ \overline{R} - 0.067\ \frac{I_{fg}}{C_p}\ \overline{DW}] \tag{6.19}$$

Notice that the demand is expressed as linear functions of degree-days, which are consistent with the theoretical assumptions and empirical results. It should also be noted that the variable N (the period for which degree-days are calculated) does not appear in the final formula. This is because daily averages of the climatic variables are used in these developments with the exception of the daily range (DT), which is a daily characteristic, so that in reality N has a value of 24 hours and is cancelled with the constant value of 24 in the denominator of these formulas. In simpler terms one may state that these are degree-days and, as the name implies, they represent deviations of a variable (temperature, in this particular case) from a fixed quantity for a day (i.e, N = 24 hrs), as compared to the possible degree-hours which represent these differences for an hour (i.e., N = 1 hr). These equations are helpful in estimating and predicting heating and cooling demand via simple calculations, rather than using dynamic simulation models which require extensive and elaborate building data and hourly climatic conditions. Utilization of these equations requires daily climatic conditions and a calculator to perform an accumulative sum of the calculated demand.

As a check of the validity and reliability of the developed procedure, an attempt was made to compare simulated and predicted demands. The comparison method involved simulating heating and cooling demand using a computer simulation model and actual weather data, then comparing these values with those computed from the predicting equations. For clarity these evaluations are graphically illustrated in Figures 13 and 14

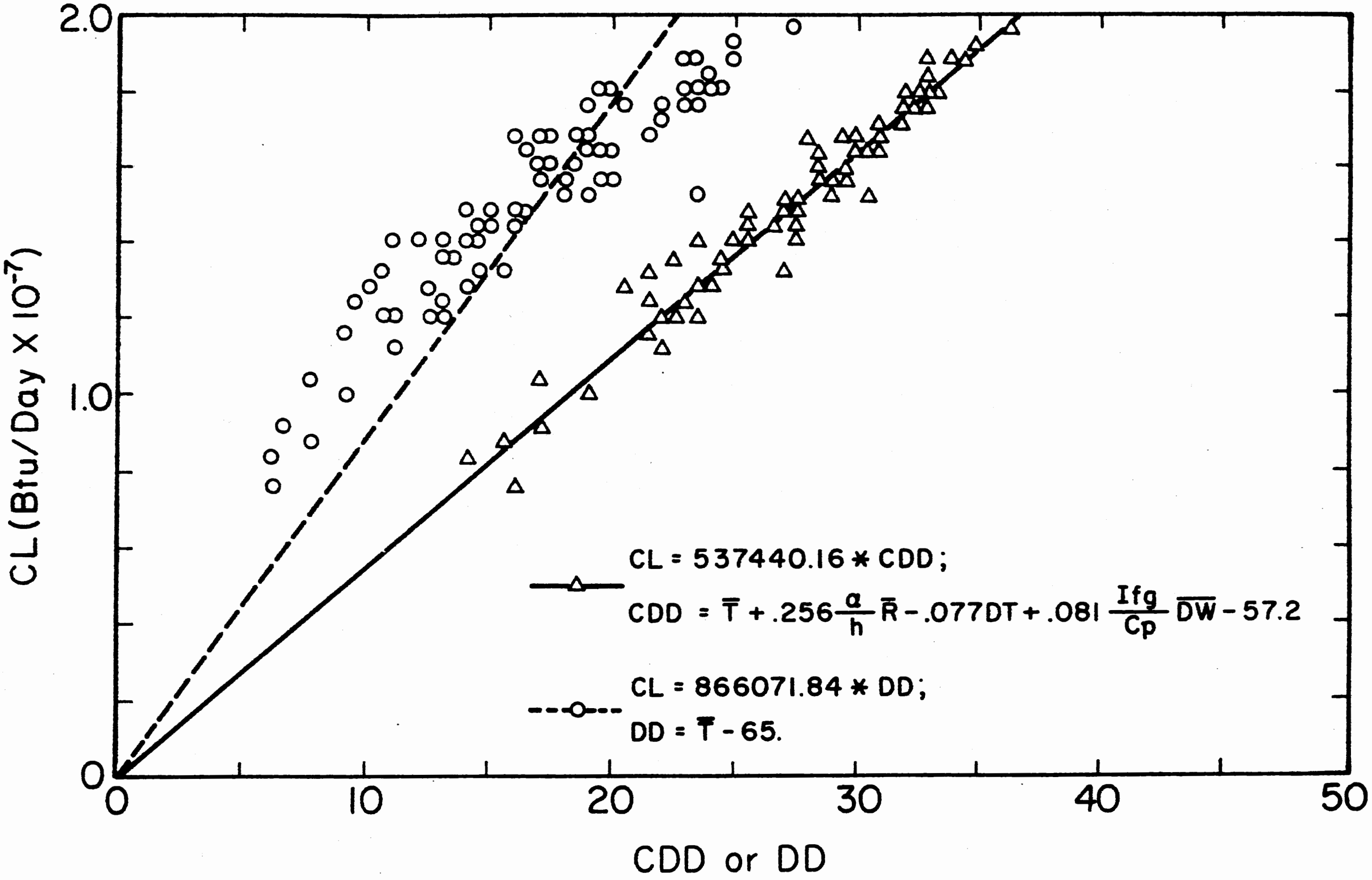

Figure 13. Daily Cooling Demand of the Representative Building Versus CDD or DD

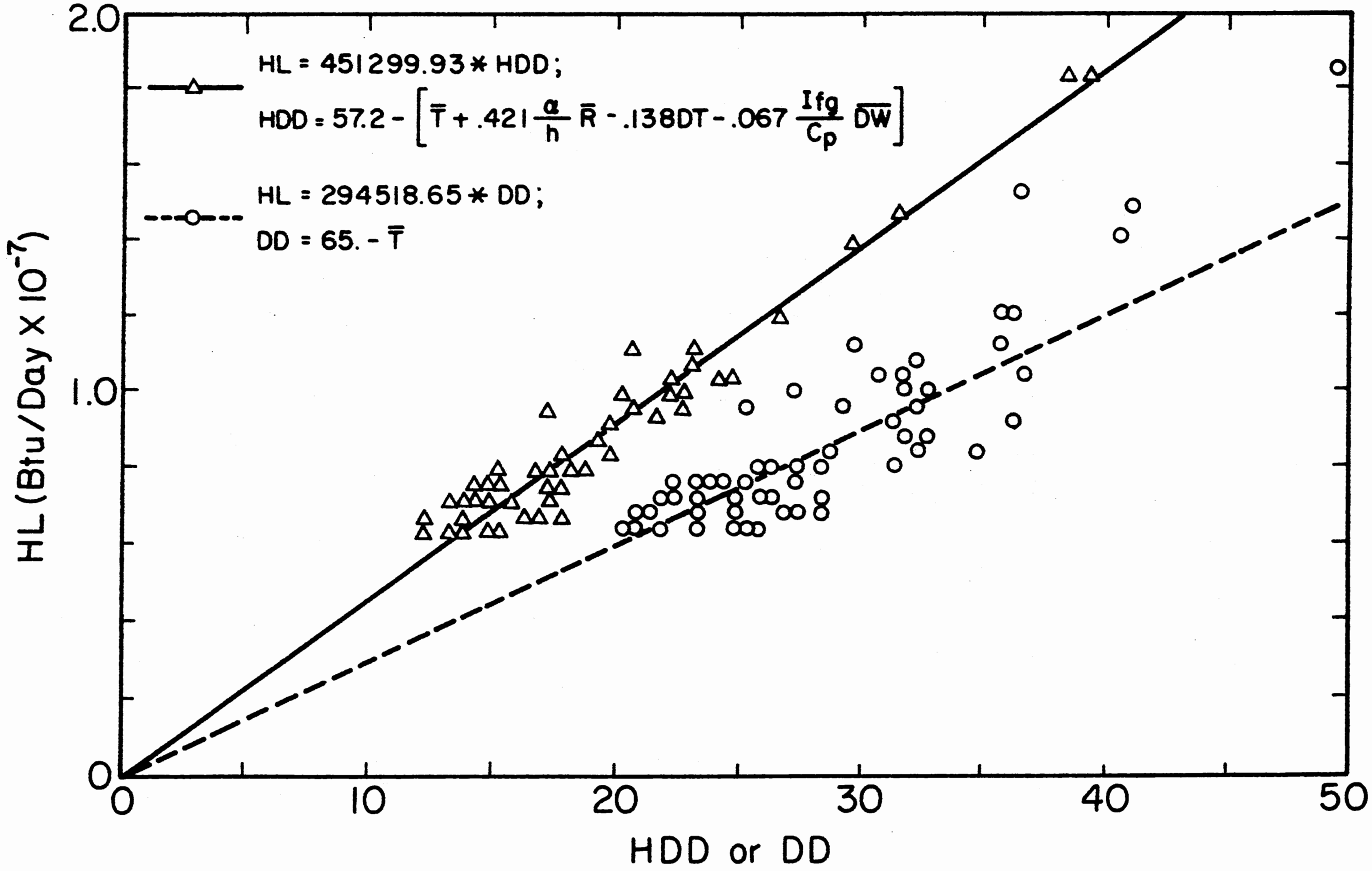

Figure 14. Daily Heating Demand of the Representative Building Versus HDD or DD

for cooling and heating, respectively. These figures demonstrate the deviations between the computer simulated values and those computed from the predicting equations. At this point we are concerned only with one set of data points which are demonstrated by triangles. The purpose of illustrating the other set of data points on the same plots will be discussed shortly. Figure 13 represents the variations in cooling demand as a function of cooling degree-days. The data points demonstrate the simulation values, and the solid line describes the prediction equation. It is obvious that the prediction function closely describes the behavior of simulated data, and the approximation is quite satisfactory. By comparing the simulated and predicted values, the analysis of the results obtained demonstrated that the maximum deviation is below 15 percent and the average error is about 3 percent. This is very reasonable, considering the fact that daily values are being compared, and smaller deviations are expected when monthly or seasonal values are considered (see Figure 15).

Figure 14 illustrates variations of the heating demand as a function of a heating degree-day. The scattered data illustrate the heating demand from the computer simulation, and the solid line represents the predicting relation. The functional relationship that describes the variation of heating demand as a function of heating degree-day is shown in this figure. It is emphasized again that variations are plotted for daily values and the deviations are satisfactory and within 15 percent, with an average error of about 5 percent. In an attempt to demonstrate how these deviations tend to become smaller for longer periods, monthly values of heating and cooling demand versus corresponding degree-days were plotted in Figure 15. This figure illustrates the extrapolation of the predicting equations in approximating the computer simulation of

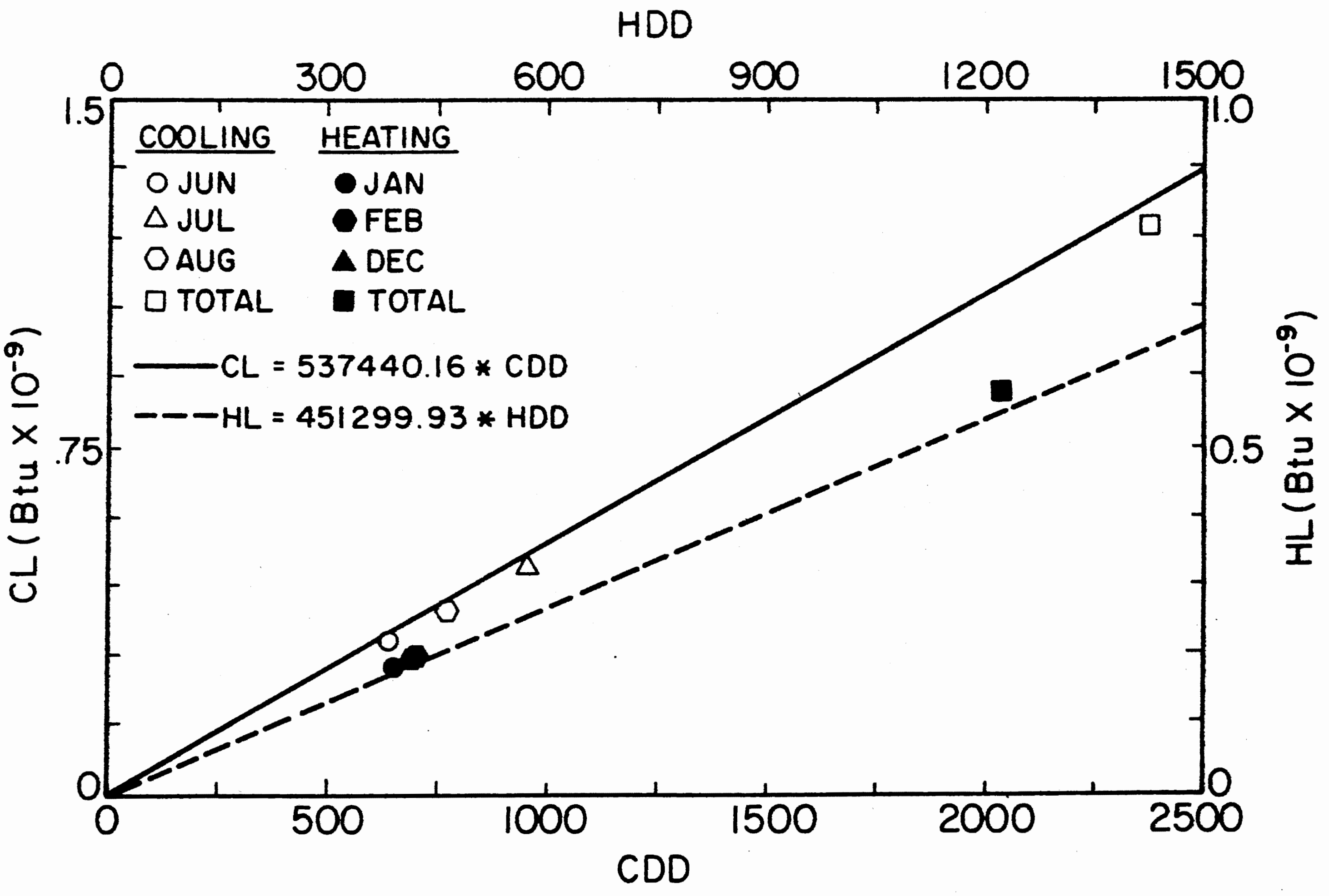

Figure 15. Monthly Demand of the Representative Building Versus CDD and HDD

monthly and seasonal demand. The simulated values are demonstrated by unshaded and shaded characters, representing cooling and heating demand, respectively. The solid and broken lines describe the functional relationships which were developed for perdicting cooling and heating demand. It is evident that these relationships, when extrapolated to cover longer periods of time, result in better agreements. Variations of the simulated values from the predicting functions are within ±5 percent.

These agreements insured the validity of the developed procedure. This led to further investigation of the performance of the present procedure as compared to the conventional method. This was achieved by comparing the predicted values (obtained from both the conventional degree-day procedure and the present model) with the computer simulated results. Heating and cooling results are graphically shown in Figures 13 and 14. In Figure 13, scattered data points (shown by circles) illustrate the variation of simulated cooling demand versus changes in the conventional degree-days. In this figure both sets of data points are simulated values and are not coincident due to the use of an abscissa, which is defined in two different ways (DD and CDD). It was discussed earlier that the simulation values and the corresponding weather data were fitted by an equation which is shown by a solid line in Figure 13. The same procedure was utilized to develop an analytical model which will predict heating and cooling demand by employing the conventional degree-day method. The simulation data and the corresponding degree-days calculated by the conventional method were fitted by the following equations:

$$\mathrm{CL} = k\mathrm{DD} \qquad (6.20)$$

where

$$DD = (\overline{T} - 65)\ \frac{N}{24} \tag{6.1}$$

and

$$HL = \beta DD \tag{6.21}$$

where

$$DD = (65 - \overline{T})\ \frac{N}{24} \tag{6.8}$$

Degree-days were calculated from weather data and were used with the simulation data in the regression analysis to reveal the value of k and β. The broken line that passes through the simulation data in Figure 13 represents the functional relationship which was obtained from this analysis.

In simpler terms the solid and broken lines of Figures 13 and 14 demonstrate the best fit equations that can be achieved by utilizing the techniques of the present model and the conventional procedure, respectively. Visual investigation of these figures reveals that the agreements between the predicted and simulated results are much closer to the present model than for the conventional procedure. It is interesting to note that there seems to be some uniformity between the general trends of the simulation data and the present model prediction equations (solid line)(Figures 13 and 14). There also appears to be a great deal of scatter and nonuniformity between the patterns of the simulated data and the predicted model of the conventional method (broken line).

Quantitative analysis of these results is made possible by tabular means in Table VIII. This table illustrates the simple statistical analysis of both regression equations. The quantitative results listed in Table VIII, as well as a graphic demonstration in Figures 13 and 14,

TABLE VIII

COMPARISON OF THE RESULTS OF THE PRESENT MODEL AND THE CONVENTIONAL DEGREE-DAY PROCEDURE

	Representative				Residential			
	Present Model		Conventional Degree-Day		Present Model		Conventional Degree-Day	
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
Percent Maximum Error	14.38	14.50	36.70	32.78	14.30	14.89	35.00	41.05
Percent RMS Deviation	4.60	8.50	15.34	13.54	4.20	6.20	15.97	12.58
Percent Average Error	3.15	6.02	12.34	10.99	3.20	4.70	13.61	9.67
Error Sum Squared	0.18272 x 10^4	0.65398 x 10^4	0.18818 x 10^5	0.11367 x 10^5	0.18410 x 10^4	0.29665 x 10^4	0.21180 x 10^5	0.11714 x 10^5

demonstrate the superiority of the present model as compared to conventional measures. Table VIII lists smaller values of maximum deviation, root mean square deviation of data from the fit, average error, and error sum of squares for the present model as compared to the conventional method. Some interesting observations were made during analyses of the results which are worth mentioning. First, it was stated earlier that climatic data used in development of this study were daily averaged values over a period of 24 hours. Most weather stations, however, report average daily temperatures that are midrange values of maximum and minimum daily temperatures. In an attempt to investigate the differences between these two techniques, no significant improvement was observed. This suggests that although the procedure was developed based on an averaging procedure over a 24-hour period, the midrange of maximum and minimum temperatures for a day can also be used without a significant loss in accuracy of the model. The applicability of this model covers climates where variations in daily range are not too severe in that the midrange and daily average temperatures are almost identical. Another interesting observation was made by comparing the results of the present model with the conventional method, where the base temperature was replaced with 55°F in the conventional model. This was done to account for changes in construction, development of new insulation techniques, and changes in life style, which have significant effects in reducing the balance temperature of buildings. This procedure caused a shift in the data points of Figures 13 and 14. Consequently, this changed the slope of the best fit line; however, no significant improvement was observed in the accuracy of the model. This gives further proof that the model presented in this study is feasible and cannot be improved upon by the conventional degree-day method.

The most unique feature of the present model (which cannot be described quantitatively and requires qualitative analysis) is that there seems to be a great deal of nonlinearity in the simulation data when plotted versus the conventional degree-day values (Figures 13 and 14). This causes large deviations between the simulated and the predicted values when a linear model is employed. However, this nonlinearity effect is eliminated when data are plotted versus the degree-day model which was developed in this study. This suggests that the addition of the other important climatic variables appears to smooth out the scatter in the data and eliminates the nonlinear effects. This can be considered a great improvement and a desirable characteristic of the present model.

Results of the Residential Building

It was previously mentioned that extension of the developed procedure to investigate the feasibility and generality of this model is desirable. The procedure was then extended to include the analysis of a residential structure, the results of which are discussed in this section. The general methods used to develop an analytical model for this building were discussed previously. The results obtained from these analyses are illustrated in Table VII and Figures 16, 17, and 18. These figures follow the same format that was utilized in the graphic illustration of the representative building. Figure 16 displays the plot of the cooling demand versus degree-days. These degree-days are evaluated based on two different techniques. Those demonstrated by CDD in these figures represent the present model procedure, and those shown by DD represent the conventional method. The agreements between predicted and simulated results are quite satisfactory. The solid and broken lines demonstrate the behavior of the cooling demand as predicted by the present model and the conventional method, respectively. The simulated results are shown by triangles and circles representing these variations with respect to CDD and DD, respectively. It is obvious that the present model predicts the simulated values much closer than the conventional method. Figure 17 displays the plot of the heating demand versus HDD and DD. The solid and broken lines represent the prediction equations for the present model and the conventional procedure. The agreements between the predicted and simulated values, as described by the present model, are quite satisfactory. It is also evident from Figures 16 and 17 that the present model (solid line) fits the simulation data much more closely than the conventional method (broken line). The agreements between the simulated and predicted values are within ±15 percent for both heating and cooling. It is re-emphasized that these deviations are plotted for daily results, and better agreement is expected for longer periods. Figure 18 demonstrates the extrapolation of the predicting equations for estimating the monthly and seasonal demand. In this figure shaded and unshaded characters represent the monthly and seasonal simulated demand for heating and cooling. The solid and broken lines demonstrate the functional forms of the predicting models for cooling and heating. It is evident that deviations between the simulated and predicted results are much smaller than those shown in Figures 16 and 17. This suggests that the present model is a better predictor when longer periods are considered. This generally is considered to be of more interest in common engineering practices. The

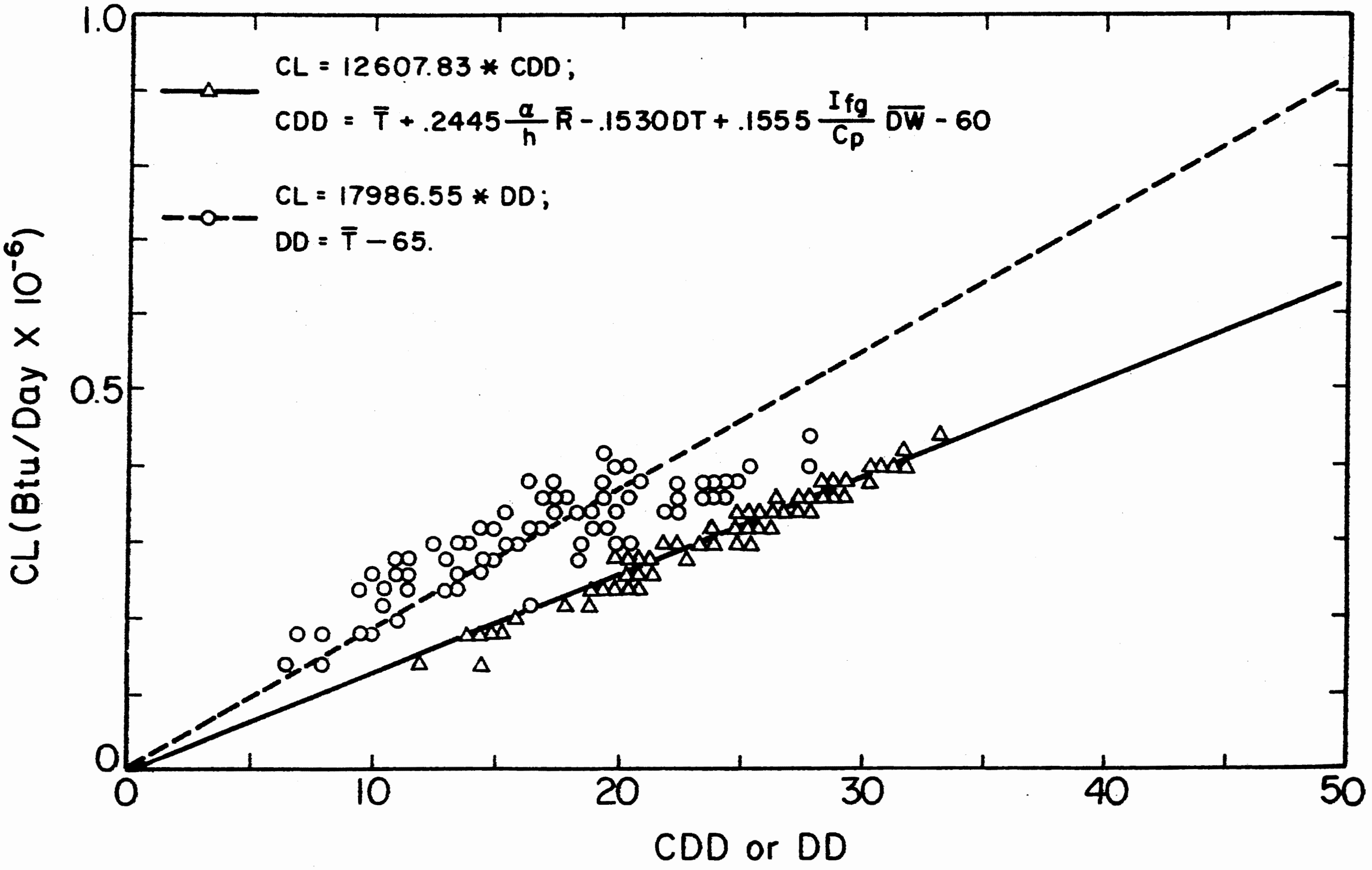

Figure 16. Daily Cooling Demand of the Residential Building Versus CDD or DD

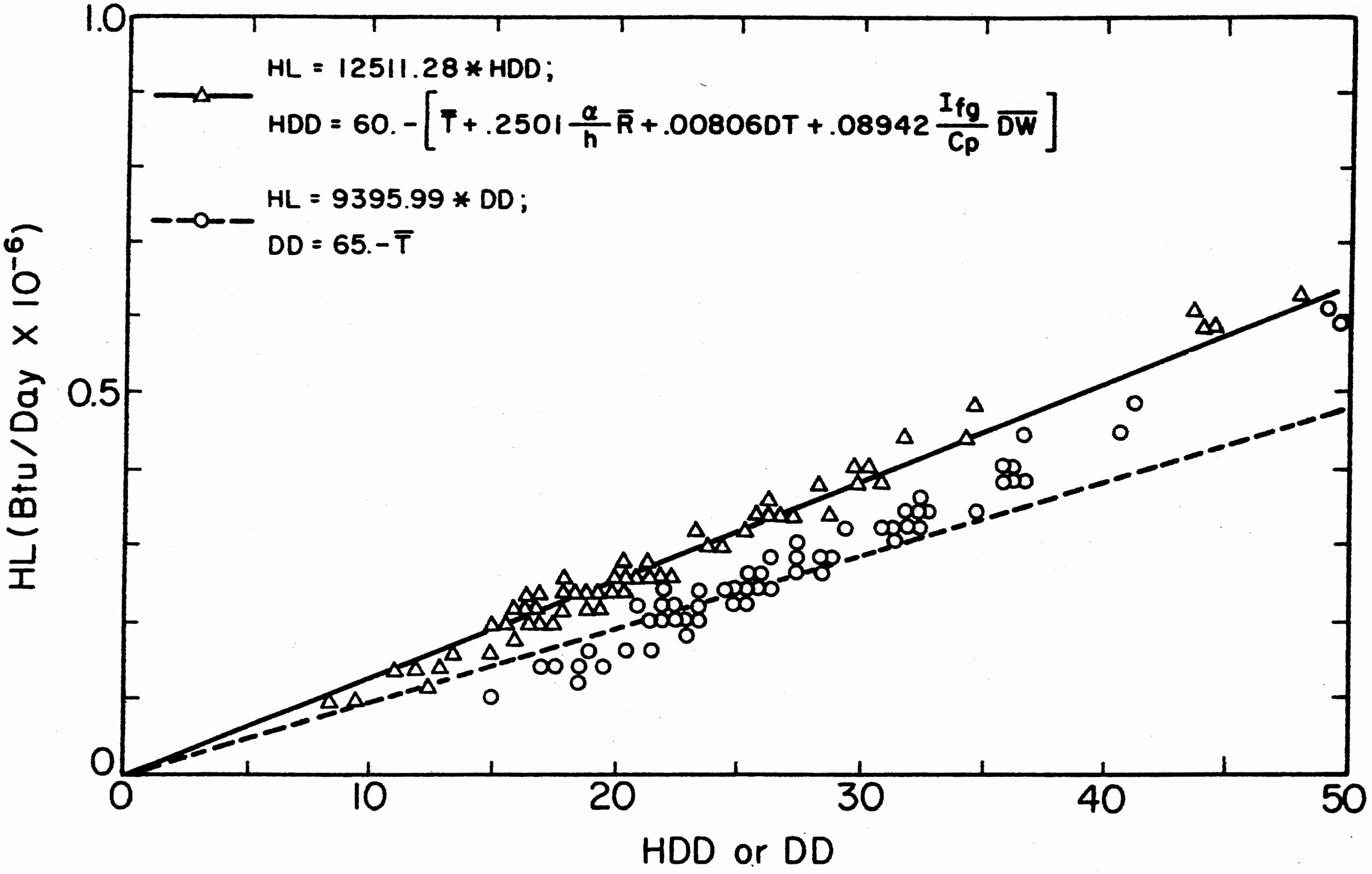

Figure 17. Daily Heating Demand of the Residential Building Versus HDD or DD

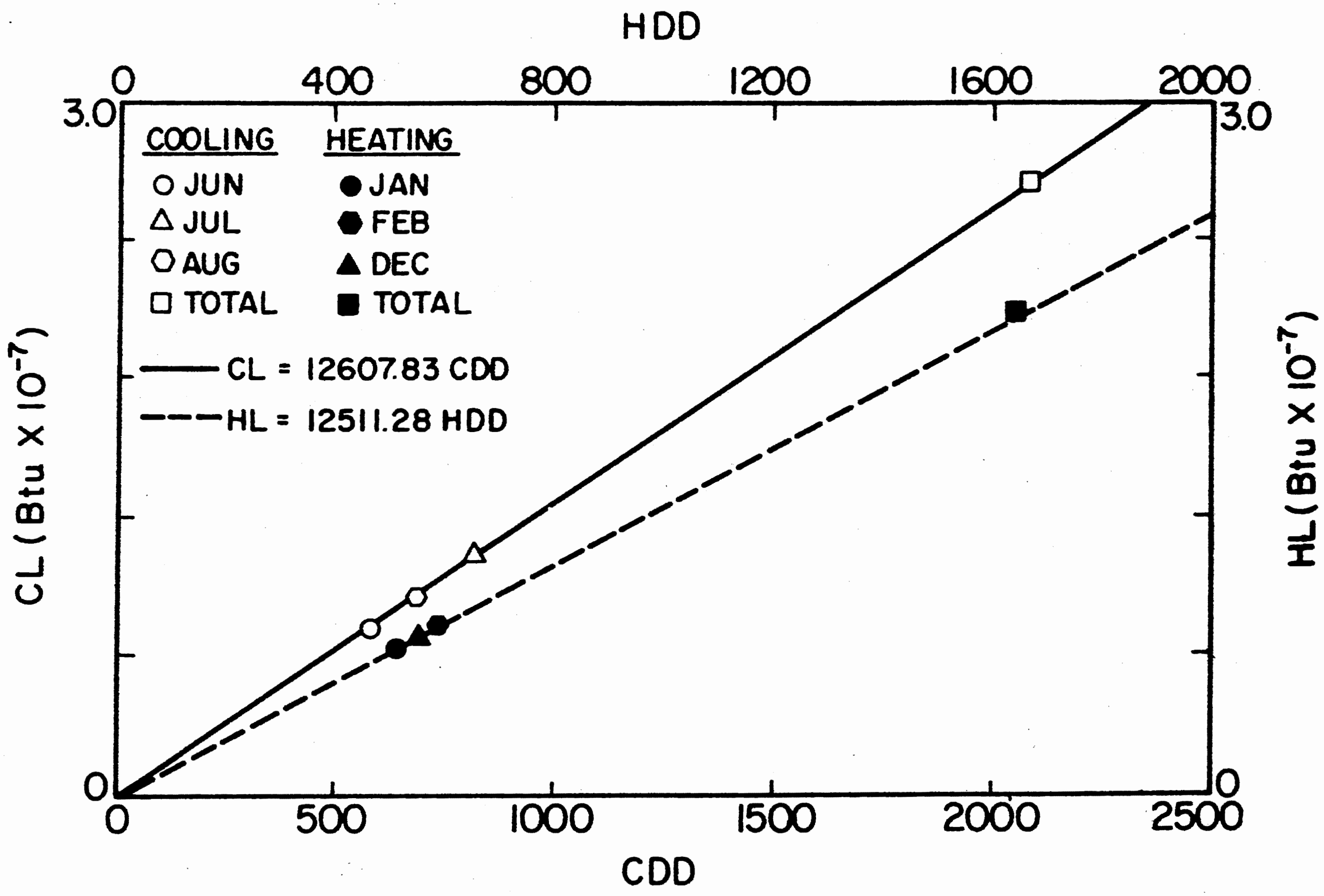

Figure 18. Monthly Demand of the Residential Building Versus CDD and HDD

estimates of seasonal or monthly demand are usually more desirable than the corresponding daily values.

A quantitative analysis of the results obtained for the residential building is tabulated in Table VIII. The values of the statistical quantities that are listed in this table demonstrate the improvement and preference of the present model over the conventional procedure.

In summary, an improved degree-day procedure was developed in this chapter. These heating and cooling degree-days were expressed as the function of important climatic variables, which were identified in Chapter IV. Furthermore, these quantities were utilized in the development of analytical expressions which were used to predict the demand. The procedure was first developed based on the analysis of the representative building. This procedure was then utilized to analyze a residential building. The results obtained proved the validity of this model, and suggested the usefulness of similar developments for other classes of structures. The total analysis of this chapter is a preliminary step in the development of a more general but elaborate procedure for predicting the energy consumption of buildings. This procedure is described in the following chapter.

CHAPTER VII

SIMPLIFIED PROCEDURE FOR ESTIMATING THE ENERGY DEMAND OF BUILDINGS

This chapter analyzes the methods utilized to develop a simplified procedure for estimating energy demand of commercial structures. This procedure is developed based on the improved degree-day concept discussed in the previous chapter. Transition from the model that was developed in the previous chapter to a more elaborate model in this section, and the need for making this transition, is discussed in the remainder of this chapter. The procedure was first developed using a linear predicting model which resulted in unsatisfactory evaluations. This technique was then utilized to develop a more sophisticated, nonlinear predicting model to estimate energy demand. The methods used to develop both of these techniques are discussed in the following sections.

Fundamental Necessities of a Simplified Energy Predicting Model

Fundamental necessities of a simplified procedure to estimate energy requirements of buildings (specifically for commercial structures) were discussed in detail in the introductory part of this study. Based on these discussions, an effort was made to develop a procedure to estimate demand of a representative building. Analytical formulas demonstrating demand of the representative building as functions of the improved degree-days (which are functions of the significant environmental parameters) were presented in Chapter VI. These formulas were as follows:

$$CL = k(C_1\overline{T} + C_2DT + C_3 \frac{\alpha}{h} \overline{R} + C_4 \frac{I_{fg}}{C_p} \overline{DW} - T_{base}) \frac{N}{24} \tag{6.7}$$

$$HL = \beta \left[T_{base} - (H_1\overline{T} + H_2DT + H_3 \frac{\alpha}{h} \overline{R} + H_4 \frac{I_{fg}}{C_p} \overline{DW})\right] \frac{N}{24} \tag{6.13}$$

These equations were shown to adequately predict the computer simulation results.

It is very important to realize that these equations (although they are a good predictor of the demand of the representative building) cannot be used to predict the demand of any building in general. There are several reasons for this which will be discussed in detail. First, by definition, the representative building is an average bulding which typifies the behavior of a construction group. Therefore, the prediction model of this building has the capability of predicting an average aggregate demand of these construction types. That is, no absolute data about individual buildings can be assessed from analysis of the results of the representative building. This implies that the representative building is a good predictor of the average aggregate demand of the construction which it typifies, but not a valid general predictor of an individual building. Second, it was discussed in Chapter VI that the regression analysis procedure was utilized to determine the value of the coefficients in Equations (6.7) and (6.13). These constants reflect the dynamic characteristics of the building that was analyzed. Therefore, they are characteristic functions of the representative building. These values will be different for other buldings; hence the results of the representative building cannot be generalized to analyze the dynamic response of other buildings. Therefore, these constants are utilized to describe the thermal behavior of the representative building via analytical expressions described by Equations (6.7) and (6.13). It is apparent that when the physical conditions are different (different buildings), the values of these constants will also be changed. Finally, it is apparent that Equations (6.7) and (6.13) are functions of weather parameters only, and are highly insensitive to building parameters. This means that these expressions will estimate the same values for a given weather condition regardless of the type of building under consideration. This obviously can lead to a highly erratic approximation when buildings with different envelope characteristics are analyzed.

Development of the analysis of the procedure described in the previous chapter was preceded by assuming a linear relationship between the demand and the weather parameters. These relationships were in the form demonstrated by Equations (6.7) and (6.13) and were strongly dependent on weather parameters but insensitive to any building variables.

The coefficients of the weather variables and the constants of proportionalities k and β were determined from regression analysis of the simulated demand and weather data. From discussions up to this point it is apparent that these proportionate constants should be related to some significant building variables. This means that the values of k and β should be back tracked and broken down to demonstrate the function of the fundamental building variables. It is also important to identify these building variables so that detailed building information will not be necessary to estimate the demand.

Mathematically, one can express these analogies by the following equations:

$$CL = f_1(\text{bldg}) \times f_2(\text{weather}) \tag{7.1}$$

$$HL = g_1(\text{bldg}) \times g_2(\text{weather}) \tag{7.2}$$

From Chapter VI,

$$CL = kf(\text{weather}) \tag{7.3}$$

$$HL = \beta g(\text{weather}) \tag{7.4}$$

Comparison of the forms of the above equations will yield:

$$k = f(\text{bldg}) \tag{7.5}$$

$$\beta = g(\text{bldg}) \tag{7.6}$$

It is emphasized again that building variables should be chosen so that not only should they reflect the fundamental characteristics of the buildings, but they should also be basic and simple to calculate.

It is postulated that:

$$k = f(A_w, A_g, A_r, U_w, U_g, U_r, S_c) \tag{7.7}$$

$$\beta = g(A_w, A_g, A_r, U_w, U_g, U_r, S_c) \tag{7.8}$$

where

A_w = total wall area (ft^2);

A_g = total glass area (ft^2);

A_r = roof area (ft^2);

U_w = overall heat transfer coefficient of wall (Btu/hr-ft^2-°F);

U_g = overall heat transfer coefficient of glass (Btu/hr-ft^2-°F);

U_r = overall heat transfer coefficient of roof (Btu/hr-ft^2-°F); and

S_c = shading coefficient of glass (dimensionless).

From the above equations the need to determine the functional relationships between k and β and the building variables is apparent. One possibility would be to use the values of k and β, which were obtained for the representative building, then use a linear model and regression analysis to obtain the coefficients of the building variables. That is:

$$k = C_1A_wU_w + C_2A_gU_g + C_3A_rU_r + C_4S_cU_gA_g \qquad (7.9)$$

$$\beta = h_1A_wU_w + h_2A_gU_g + h_3A_rU_r + h_4S_cU_gA_g \qquad (7.10)$$

where in the above equations the product of terms is used to establish dimensional consistency. The difficulty with this technique is that this problem is mathematically undetermined. Also, the information obtained from this type of analysis will not be basic or reliable, because the values of k and β are calculated for the representative building and do not contain general information about any other construction.

From the analogies discussed above, the need for investigating the thermal response of several different buildings becomes apparent. These investigations will supply the necessary information to express the values of k and β in terms of the basic building variables. The major problem is to determine the number of construction types which need to be analyzed in order to obtain enough information to develop a general procedure to estimate energy requirements. This problem was resolved by employing a fractional factorial technique using randomly selected test combinations. The application of this method to the problem involved in the present study is discussed in the next section.

Fractional Factorial Experiments Randomly Selected Test Combinations

The need for investigating several different buildings was discussed in the previous section. From Equations (7.7) and (7.8) of the previous section, the significant building variables were considered to be the surface areas (wall, glass, roof), heat transfer coefficients of each surface (wall, glass, roof), and the shading coefficient of glass. Basically, this amounts to seven different building variables. The problem analysis includes simulation studies of the number of buildings that could be structured using all possible combinations of these variables. This analysis can be simplified by considering several reasonable, general shapes and dimensions (length, width, height) for commercial structures. Specifying the dimensions of a building fixes the values of the variables A_w and A_r and in turn reduces the number of building variables to five. These variables are heat transfer coefficients of each surface (U_w, U_g, U_r), glass area (A_g), and shading coefficient of the glass (S_c). To simplify the analysis, a ratio of glass to wall was considered instead of the galss area. The analysis reduces to conduct a simulation study of the number of buildings that can be structured from all possible combinations of these five variables. These variables should cover the range of values which are typical for commercial structures. This analogy is complicated by the fact that if four levels of values are assumed for each variable, the analysis will require the simulation study of $(4)^5$ or 1024 buildings. The analysis of such a large number of structures is practically impossible. This would require utilization of a procedure which would extract adequate information on the effects of these variables more efficiently than the traditional method.

Randomly selected test combinations of the fractional factorial experiments method (28) were utilized for this purpose. This method required testing of approximately one percent of the full factorial experiments (1024). It is obvious that this method cannot produce as much information as a complete analysis of all 1024 buildings. But, adequate information can be obtained by compromising the absolute accuracy with economy and time. For the purpose of this study nine base buildings with different shapes, orientations, and dimensions were considered. The shapes and dimensions of these buildings were chosen so that they resembled a typical commercial structure. The values of the variables were also chosen so that they covered the typical range of values found in a commercial structure. The analysis included randomly distributing the values of these constants among the nine base buildings. The procedure involved selecting a set of nine consecutive numbers from the random number table. A number between 1 and 9 was assigned to each random number corresponding to its rank, if the random numbers were arranged in ascending order (Table IX). This created a set of random numbers between 1 and 9 (number of buildings). The values of the variables were assigned to these buildings (Table IX). The information obtained from this analysis was collected for each building and are tabulated in Table X. This table displays pertinent information about each building and the corresponding values of each variable. The simulation studies of the demand of these buildings, using actual weather data, provided the necessary information needed to develop a procedure to estimate energy requirements. Two different techniques were investigated and are discussed in this chapter.

Linear Model for Estimating Energy Demand of Buildings

A linear model for estimating energy demand of commercial structures was developed. This model was developed utilizing linear combinations of significant weather and building variables. From the previous discussion we have:

TABLE IX

FRACTIONAL FACTORIAL EXPERIMENT RANDOMLY SELECTED TEST COMBINATIONS

RANDOM No.	Bldg. No.	U Wall	RANDOM No.	Bldg. No.	$\frac{A_{glass}}{A_{wall}}$	RANDOM No.	Bldg. No.	U Glass		RANDOM No.	Bldg. No.	S_c	RANDOM No.	Bldg. No.	U Roof
								S	W						
31347	6	0.115	88977	7	0.25	11354	2	1.04	1.10	87056	7	0.25	10721	2	0.052
30240	5	0.115	15243	2	0.25	31312	3	1.04	1.10	90581	8	0.30	39755	6	0.052
23823	3	0.314	24335	4	0.25	69921	8	0.81	0.81	94271	9	0.40	31652	5	0.052
19051	2	0.314	61105	6	0.40	79888	9	0.81	0.81	42187	3	0.50	87662	8	0.106
44640	7	0.378	19087	3	0.40	06256	1	0.65	0.62	74950	6	0.55	83651	7	0.106
00812	1	0.378	42678	5	0.50	46065	4	0.65	0.62	15804	2	0.60	23790	4	0.158
97207	9	0.415	98086	9	0.50	52777	5	0.50	0.50	62783	5	0.75	18370	3	0.158
24767	4	0.415	94614	8	0.75	54563	6	0.50	0.50	49159	4	0.85	88318	9	0.206
48336	8	0.415	00582	1	0.75	59952	7	0.50	0.50	14676	1	1.00	00157	1	0.206

TABLE X

PERTINENT INFORMATION ABOUT BASE BUILDINGS

Bldg. Code	Bldg. No.	U_{wall}	U_{glass}	U_{roof}	$\frac{A_{glass}}{A_{wall}}$	S_c	A_{wall}	A_{roof}	A_{glass}
1	1	0.378	0.65	0.206	0.75	1.00	8160.	20800.	6120.0
2	2	0.314	1.04	0.052	0.25	0.60	16320.	20800.	4080.0
3	3	0.314	1.04	0.158	0.40	0.50	24480.	20800.	9792.0
4	4	0.415	0.65	0.158	0.25	0.85	32640.	20800.	8160.0
5	5	0.115	0.50	0.052	0.50	0.75	28800.	22500.	14400.0
6	6	0.115	0.50	0.052	0.40	0.55	6360.	13000.	2544.0
7	7	0.378	0.50	0.106	0.25	0.25	12720.	13000.	3180.0
8	8	0.415	0.81	0.106	0.75	0.30	19080.	13000.	14310.0
9	9	0.415	0.81	0.206	0.50	0.40	25440.	13000.	12720.0

$$CL = kf(\text{weather}) \tag{7.3}$$

and

$$k = f(\text{bldg}) \tag{7.5}$$

In Equation (7.5), if k is expressed in terms of the linear combination of the significant building variables, we have:

$$k = C_1U_wA_w + C_2U_gA_g + C_3U_rA_r + C_4S_cU_gA_g \tag{7.9}$$

or

$$k = C_1U_wA_w + (C_2 + C_4\ S_c)\ U_gA_g + C_3U_rA_r \tag{7.11}$$

If the weather variables are combined in a similar manner, we have:

$$f(\text{weather}) = C_5\overline{T} + C_6DT + C_7\frac{\alpha}{h}\overline{R} + C_8\frac{I_{fg}}{C_p}\overline{DW} - T_{base} \tag{7.12}$$

When Equations (7.11) and (7.12) are substituted into Equation (7.3), the following equation results:

$$CL = [C_1U_wA_w + (C_2 + C_4S_c)\ U_gA_g + C_3U_rA_r][C_5\overline{T} + C_6DT + C_7\frac{\alpha}{h}\overline{R} + C_8\frac{I_{fg}}{C_p}\overline{DW} - T_{base}] \tag{7.13}$$

By employing the same analogy, an identical expression for the heating portion is obtained.

$$HL = [H_1U_wA_w + (H_2 + H_4S_c)\ U_gA_g + H_3U_rA_r][T_{base} - (H_5\overline{T} + H_6DT + H_7\frac{\alpha}{h}\overline{R} + H_8\frac{I_{fg}}{C_p}\overline{DW})] \tag{7.14}$$

Equations (7.13) and (7.14) are utilized to estimate the energy requirements if the coefficients are determined. Calculating the values of these coefficients requires the following steps. First, the nine base buildings modeled (based on the analogy of the previous section) were used to simulate heating and cooling demand. The regression analysis of these simulated results and the corresponding weather data yielded the values of these constants. A list of the computer program which performs the necessary calculations to determine the values of these constants is displayed in Appendix B. Estimates of the energy requirements utilizing this method resulted in errors up to 60 percent. The general trends and patterns of the predicted values were largely different than the simulated results. It is therefore concluded that a simple model, expressed by Equations (7.13) and (7.14), is not sufficient for estimating the complex thermal behavior of commercial structures. However, development of this technique provides the necessary background and expertise for developing a more complex and nonlinear model, which will be discussed in the next section.

Nonlinear Model for Estimating Energy Demand of Buildings

As mentioned earlier, the adaptation of a linear predicting model resulted in unsatisfactory evaluations of the energy demand. This was expected due to the complexity of the problem under analysis. However, a linear model was developed for (1) the purpose of familiarization, and (2) gaining some experience in handling a more complex form of expression. Effort was concentrated on the development of a nonlinear model for estimating heating and cooling energy demand. The development procedure of this model is discussed separately for cooling and heating.

Cooling

Based on the knowledge that was gained from the analysis of the linear predicting model, it is postulated that the cooling demand in a normalized form can be expressed by the following equation:

$$\frac{CL}{CLD} = C_1 \left\{ 1 + (C_2 + C_3 S_c) \left[\frac{U_g A_g}{U_w A_w}\right]^{C_4} + C_5 \left[\frac{U_r A_r}{U_w A_w}\right]^{C_6} \right\} \left\{ C_7 \left[\frac{\overline{T}}{T_{max}}\right]^{C_8} + C_9 \left[\frac{DT}{T_{max}}\right]^{C_{10}} + C_{11} \left[\frac{\overline{R}}{R_{max}}\right]^{C_{12}} + C_{13} \left[\frac{\overline{DW}}{W_{max}}\right] + C_{14} \left[\frac{T_{base}}{T_{max}}\right]^{C_{15}} \right\} \tag{7.15}$$

where

CL = cooling demand (Btu);

CLD = design cooling load (Btu);

A_w = total wall area (ft^2);

A_g = total glass area (ft^2);

A_r = total roof area (ft^2);

U_w = heat transfer coefficient of the wall (Btu/hr-ft^2-°F);

U_g = heat transfer coefficient of the glass (Btu/hr-ft^2-°F);

U_r = heat transfer coefficient of the roof (Btu/hr-ft^2-°F);

S_c = shading coefficient of glass;

$\overline{T}$ = average daily temperature (°F);

T_{max} = maximum daily temperature (°F);

DT = daily temperature range (°F);

$\overline{R}$ = average daily solar insolation (Btu/hr-ft^2);

R_{max} = maximum daily solar insolation (Btu/hr-ft^2);

$\overline{DW}$ = average daily humidity difference (lbm of water/lbm of air);

W_{max} = maximum daily humidity ratio (lbm of water/lbm of air);

T_{base} = balance temperature (°F); and

C_1-C_{15} = constants.

The above equation is a nonlinear and normalized form of the equation that was described earlier (Equation (7.13)). When the building variables are normalized by the product of U_wA_w, in Equation (7.13), and the weather variables are normalized by their maximum quantities, Equation (7.15) is obtained. It is interesting to note that this equation is nondimensional and the variables α, h, I_{fg}, C_p, which were utilized in Equation (7.13) to establish the dimensional consistency, are not present in Equation (7.15). The procedure for determining the values of these constants required the regression analysis of the simulation results of the nine base buildings and the corresponding weather data. The results obtained from this analysis are discussed in detail in the next section. Listing of the computer program to perform the necessary calculations for obtaining these constants is presented in Appendix B.

Heating

The identical procedure that was utilized for cooling was employed for developing a predicting model for estimating heating energy requirements. This procedure consisted of expressing Equation (7.14) in a normalized form, using variable exponents for the normalized building and weather terms. That is:

$$\frac{HL}{HLD} = H_1\left[1 + (H_2 + H_3S_c)\left(\frac{U_gA_g}{U_wA_w}\right)^{H_4} + H_5\left(\frac{U_rA_r}{U_wA_w}\right)^{H_6}\right]\left[H_7\left(\frac{\bar{T}}{T_{max}}\right)^{H_8} + H_9\left(\frac{DT}{T_{max}}\right)^{H_{10}} + H_{11}\left(\frac{\bar{R}}{R_{max}}\right)^{H_{12}} + H_{13}\left(\frac{\overline{DW}}{W_{max}}\right) + H_{14}\left(\frac{T_{base}}{T_{max}}\right)^{H_{15}}\right] \tag{7.16}$$

where HLD is the design heating load of the building under consideration, and the remainder of the terms are as defined earlier. The values of H_1 through H_{15} were calculated using a regression analysis of simulated heating demand (for the nine base buildings) and the corresponding weather data.

The results obtained from this analysis are discussed in detail in the following section and are demonstrated in Table XI. A listing of the computer program which performs the necessary calculations for determining the values of these constants is presented in Appendix B.

It is evident that Equations (7.15) and (7.16) can be utilized for estimating heating and cooling energy requirements of any building. The use of these expressions require access to weather data as well as building data. These expressions were utilized for estimating the energy demand of buildings for different locations using historical weather data (TMY tapes) (29). These estimated values were compared with the computer simulated results to verify the validity of the developed procedure. The results and discussion of these analyses are discussed in the following section.

Results and Discussion

This section analyzes the detailed discussion of the results obtained from analogies that were discussed in previous portions of this

TABLE XI

COEFFICIENTS OF EQUATIONS (7.15) AND (7.16)

Cooling		Heating	
C_1	0.32499970	H_1	0.03742400
C_2	0.00504360	H_2	0.61480000
C_3	-0.00611504	H_3	-0.01246000
C_4	6.57103190	H_4	0.08969900
C_5	-0.03990000	H_5	0.14079970
C_6	2.94984700	H_6	2.56940000
C_7	1.45787300	H_7	0.25037100
C_8	7.16262740	H_8	-2.34760000
C_9	0.0062733	H_9	4.97160050
C_{10}	1.08197340	H_{10}	0.93642000
C_{11}	49.60060000	H_{11}	0.00000140
C_{12}	4.09993900	H_{12}	-7.12680000
C_{13}	0.05404073	H_{13}	0.00000000
C_{14}	0.12950235	H_{14}	5.73864980
C_{15}	-4.26472060	H_{15}	0.94583000
T_{base}	55.0 (°F)	T_{base}	55.0 (°F)

chapter. Following previous format, these results are discussed in two separate sections (cooling and heating).

Results of Cooling Model

It was demonstrated that mathematical developments led to derivation of Equation (7.15) for estimating the cooling demand of a building. This equation predicts the cooling demand of a building for a specified period, utilizing the significant weather and building data. The use of this equation requires calculation of the constants C_1 through C_{15} as well as the value of the design cooling load for the building under consideration. The procedure for calculating the values of these constants involves a nonlinear least squares regression analysis of the simulated cooling demand and the building and weather data. In order to generate the simulation data, the nine base buildings were modeled into the simulation program (25). The cooling demand of these buildings were simulated for several specified periods, using actual weather data (24). The envelope characteristics of these buildings provided the necessary building data to be used with the simulated results and the weather data to perform the regression analysis. The computer program which performs the necessary calculations for determining the values of C_1 through C_{15} is presented in Appendix B. The calculated values of these constants are shown in Table XI. Once these constants are determined, Equation (7.15) can be utilized to estimate the cooling demand of any building.

As mentioned earlier, it is evident that the use of Equation (7.15) requires access to some type of weather data. The most recent weather tapes provide information on an hourly basis for temperature and solar insolation data. The information obtained from these weather tapes cannot be used in a direct manner for evaluating Equation (7.15). Some additional calculations are necessary to obtain the maximum and daily averages of these weather quantities to be used in Equation (7.15). A simple computer program which performs the necessary calculations for obtaining these quantities is shown in Appendix B. This program utilizes a technique described in Reference (30), and can be used in conjunction with any weather data to estimate the cooling demand of any building using Equation (7.15). Furthermore, the weather portion of Equation (7.15) (second bracket) may be used to generate tables of values for different locations so that the use of weather tapes is eliminated. This will be discussed in detail later.

In order to evaluate the validity and performance of the developed model described by Equation (7.15), the following experiments were conducted. First, the cooling demand of some specified buildings were simulated using weather data for several different locations. Using Equation (7.15), the cooling demand of these buildings were predicted for the same locations. These simulated and predicted values were compared to investigate the validity of the predicting model. Table XII demonstrates the results of this analysis. This table presents the values of computer simulated demand and those predicted by Equation (7.15) for different locations.

It is important to note that actual weather data were used for calculating the simulated and predicted demand, employing the typical metereological year data (29) for different locations.

Investigating deviations between the predicted and simulated results revealed that the developed model adequately predicts the computer simulation results. The deviations are well within ±20 percent for all of

TABLE XII

COMPARISON OF SIMULATED AND PREDICTED COOLING DEMAND (BTU X 10^{-9})

Location	Period	Simulation Method (25)	Prediction Eq. (7.15)	Deviation
Oklahoma City[1]	June	0.3072259	0.3057021	0.50
	July	0.3874957	0.3809633	1.69
	Aug.	0.3709760	0.3577925	3.55
	Total	1.0656920	1.0444540	1.99
Fort Worth	June	0.3307656	0.3502966	-5.90
	July	0.4520427	0.4538058	-0.39
	Aug.	0.4227630	0.4181862	1.08
	Total	1.2055670	1.2222830	-1.39
Columbia	June	0.2627943	0.2718943	-3.46
	July	0.3377769	0.3315520	1.84
	Aug.	0.3132849	0.3133586	-0.02
	Total	0.9138501	0.9167992	-0.32
Nashville	June	0.2658297	0.2688604	-1.14
	July	0.3503560	0.3179919	9.24
	Aug.	0.3347763	0.2977697	11.05
	Total	0.9509555	0.8846157	6.98
Charleston	June	0.2542545	0.2501045	1.63
	July	0.3609275	0.3308372	8.34
	Aug.	0.3451684	0.3075448	10.90
	Total	0.9603443	0.8884810	7.48
Washington D.C.	June	0.1993510	0.2164704	-8.59
	July	0.3200233	0.3153879	1.45
	Aug.	0.2998615	0.2906199	3.08
	Total	0.8192300	0.8224732	-0.40
Phoenix	June	0.3903083	0.4540843	-16.34
	July	0.5161347	0.6046781	-17.16
	Aug.	0.4894484	0.5439480	-11.13
	Total	1.3958880	1.6027070	-14.82
Medford	June	0.1282369	0.1322195	-3.11
	July	0.2632565	0.2478811	5.84
	Aug.	0.2555479	0.2107444	10.53
	Total	0.6270413	0.5908408	-5.77
Albuquerque	June	0.2233833	0.2137688	4.30
	July	0.3193923	0.2764803	13.44
	Aug.	0.2914458	0.2390132	17.99
	Total	0.8342152	0.7292570	12.58
Miami	June	0.3159281	0.2734149	13.46
	July	0.3818015	0.3263222	14.53
	Aug.	0.3959314	0.3258337	17.70
	Total	1.0936560	0.9255662	15.37

[1] 1964 Oklahoma City data.

the locations investigated. This is an acceptable error band for any heat transfer related calculation. The deviations are actually within ±10 percent in most cases with very few exceptions. These exceptions include locations with extreme weather conditions (i.e., very hot and dry, very hot and humid, large variations in daily temperatures). In general, the developed model adequately estimates the energy demand using a procedure which is much simpler than the use of computer simulation techniques. One very interesting feature of this developed model is the fact that although this procedure was developed based on a specified weather datum, it can be extrapolated to predict energy demand dictated by a completely different set of weather conditions. This is the major significance of the present model, and is due to direct consideration of the most significant building and weather parameters.

Results of the Heating Model

Based on the same analogy that was discussed for cooling, it was shown that an analytical expression for estimating heating demand of buildings was developed (Equation (7.16)). The use of this expression requires the evaluation of the constants H_1 through H_{15}. The procedure for calculating these constants is identical to that discussed for cooling. This procedure involves the nonlinear least squares regression analysis of the set of data which includes simulated heating demand and the corresponding building and weather data. A computer program which performs the necessary calculations for determining the values of these coefficients is shown in Appendix B. The calculated values of these constants are demonstrated in Table XI.

When these values are replaced in Equation (7.16), an estimate of the heating demand of a building can be made for any specified period of time. It is emphasized again that the use of this expression will require access to some type of weather data. However, these calculations can be conducted on a small calculator and are much simpler to perform than the use of computer simulation techniques.

For the purpose of evaluating the performance and validity of the model expressed by Equation (7.16), the following experiments were conducted. First, the heating demand of some specified buildings were simulated for several different locations. This was achieved by an hour-by-hour computer simulation technique (25) using actual weather data. Utilizing Equation (7.16), heating demand of these same buildings were calculated for the same locations.

The computer simulated demand was compared with the prediction values of Equation (7.16). The deviations of the predicted quantities from the simulated results acted as a measure for determining the validity of the developed procedures. Table XIII lists the computer simulated demand and the corresponding values as predicted by Equation (7.16) for different locations. It is reiterated that actual weather data were used for calculating both the simulated and predicted demand. These data included the typical metereological year data (29) for each location. It is evident from Table XIII that the values predicted by the present model are well within ±10 percent of the simulation results. From these analyses it can be concluded that the developed procedure is an adequate predictor of heating requirements of buildings.

It is interesting to note that once the validity of the developed procedure is proved, this method may be used for generating tables of values for different locations. These values will be functions of

TABLE XIII

COMPARISON OF SIMULATED AND PREDICTED HEATING DEMAND (BTU X 10^{-9})

Location	Period	Simulation Method (25)	Prediction Eq. (7.16)	Percent Deviation
Dodge City	Dec.	0.2290728	0.2090949	8.72
	Jan.	0.2391256	0.2242728	6.21
	Feb.	0.1834659	0.1848928	-0.78
	Total	0.6516643	0.6182574	5.12
Columbia	Dec.	0.2637083	0.2801152	-6.22
	Jan.	0.2127934	0.2244004	-5.45
	Feb.	0.2452276	0.2246708	8.38
	Total	0.7217293	0.7291827	-1.03
Boston	Dec.	0.3168596	0.2873398	9.32
	Jan.	0.2163089	0.2236740	-3.40
	Feb.	0.2714127	0.2524734	6.98
	Total	0.8045812	0.7634824	5.11
Medford	Dec.	0.1879212	0.1733250	7.76
	Jan.	0.1463671	0.1537443	-5.04
	Feb.	0.1892800	0.1734417	8.37
	Total	0.5235683	0.5005140	4.40

weather parameters for different locations and can best be described by the following equations:

$$CU = C_7\left(\frac{\overline{T}}{T_{max}}\right)^{C_8} + C_9\left(\frac{CT}{T_{max}}\right)^{C_{10}} + C_{11}\left(\frac{\overline{R}}{R_{max}}\right)^{C_{12}} + C_{13}\left(\frac{\overline{DW}}{W_{max}}\right)$$

$$+ C_{14}\left(\frac{T_{base}}{T_{max}}\right)^{C_{15}} \qquad (7.17)$$

$$HU = H_7\left(\frac{\overline{T}}{T_{max}}\right)^{H_8} + H_9\left(\frac{DT}{T_{max}}\right)^{H_{10}} + H_{11}\left(\frac{\overline{R}}{R_{max}}\right)^{H_{12}} + H_{13}\left(\frac{\overline{DW}}{W_{max}}\right)$$

$$+ H_{14}\left(\frac{T_{base}}{T_{max}}\right)^{H_{15}} \qquad (7.18)$$

where CU is the cooling unit, and HU is the heating unit. It was mentioned previously that a computer program was adopted (30) and implemented to perform the necessary calculations for evaluating the heating and cooling units; this program is shown in Appendix B. Equations (7.17) and (7.18) may be utilized to calculate the values of CU and HU for any desired location, employing weather data for the location under consideration. The values of HU and CU are tabulated for a sample of locations and are shown in Appendix A. These values were calculated utilizing the TMY weather data (29) for those locations. These values will serve as multipliers for estimating the energy demand of any building, that is:

$$\text{Cooling:} \quad \frac{CL}{CLD} = CBLDG \times CU \qquad (7.19)$$

$$\text{Heating:} \quad \frac{HL}{HLD} = HBLDG \times HU \qquad (7.20)$$

where CBLDG and HBLDG are the building parameters for cooling and heating modes, respectively.

$$\mathrm{CBLDG} = C_1\left[1 + (C_2 + C_3 S_c)\left(\frac{U_g A_g}{U_w A_w}\right)^{C_4} + C_5\left(\frac{U_r A_r}{U_w A_w}\right)^{C_6}\right] \tag{7.21}$$

$$\mathrm{HBLDG} = H_1\left[1 + (H_2 + H_3 S_c)\left(\frac{U_g A_g}{U_w A_w}\right)^{H_4} + H_5\left(\frac{U_r A_r}{U_w A_w}\right)^{H_6}\right] \tag{7.22}$$

The values of C_1 through C_6 and H_1 through H_6 are calculated and tabulated in Table XI. Therefore, estimates of the energy demand can be made by the use of Equations (7.19) and (7.20).

The use of these equations requires the calculation of the product of two terms (building and weather parameters), where the building parameters are calculated from Equations (7.21) or (7.22), and weather parameters are obtained from Equations (7.17) or (7.18) or, more simply, from the weather tables of Appendix A.

In summary, a simplified procedure for estimating the energy demand of commercial structures was developed (Equations (7.15) and (7.16)). These developments were demonstrated to adequately predict the computer simulation results which use dymamic simulation techniques using actual weather data on an hourly basis. These developments were then extended to generate tables of values for a sample of locations, where these values may be used as multipliers for estimating the energy requirements of buildings.

CHAPTER VIII

RECOMMENDED METHOD FOR CALCULATING AN EFFICIENCY PARAMETER FOR ESTIMATING ENERGY CONSUMPTION OF BUILDINGS

This section describes a recommended procedure for calculating an efficiency parameter which adequately represents the system's performance over a set period of time. This parameter is used for estimating energy consumption from estimated energy demand. The proposed procedure is described in two parts (cooling and heating).

Cooling Seasonal Energy Efficiency Ratio

This section outlines a procedure for calculating a cooling seasonal energy efficiency ratio. The procedure is based on a survey of the literature and a comparison of different methods to determine an adequate and simple efficiency parameter. Although the developed procedure is based on the analysis of the manufacturer's data for central air conditioners used in light construction, the same analogy can be utilized to estimate the seasonal energy efficiency ratio of the cooling equipment of commercial structures. Difficulties in calculating a seasonal efficiency parameter are based on the following facts: (1) there is no single, normal operation condition, (2) end use of the equipment and its interaction with the building usually affects the energy used by the cooling system, and (3) outdoor weather conditions vary greatly for different locations. In order to develop a rating program which truly represents the energy used on a seasonal basis, one should at least consider the following effects on energy usage: (1) outdoor temperature and humidity, (2) cycling, (3) percentages of running time, (4) indoor temperature and humidity, and (5) building interaction. If all possible effects of these variables were considered, the developed procedure would be so complex that it would virtually be impossible. On the other hand, a very simple energy rating system can be developed by ignoring all such effects; the rating number would have little or no meaning with respect to the actual seasonal energy used.

A research program conducted at the Ray W. Herrick Laboratories of Purdue University (31) worked on improvements and/or alternative means of determining seasonal energy efficiency ratios (SEER). This work was based on an evaluation of the test procedures as set by the U.S. Department of Energy (DOE). The DOE test procedure calls for conducting two steady state, wet coil tests (tests A and B); these determine the influence of outdoor temperature on energy consumption. In addition, two other dry coil tests (steady state (test C) and cyclic (test D)) are used to determine the effects of cycling on energy consumption. Table XIV lists the conditions of each test. In Reference (31), the data obtained for 148 units supplied by various companies were used to calculate efficiency ratios for each testing method. These experimental data were plotted in various ways to determine whether any relationship could be observed between various functions. The most interesting of these was the plot of EER_D/EER_C versus EER_A/EER_B. Where EER is the energy efficiency ratio (ratio of total capacity of the unit to the total power input at specified indoor and outdoor ambient conditions, BTU/watt-hr),

TABLE XIV

SUMMARY OF TEST AND RATING REQUIREMENTS: INDOOR AND OUTDOOR ENTERING AIR TEMPERATURE AND MODE OF OPERATION (32)

	Indoor Dry-Bulb Temperature	Indoor Wet-Bulb Temperature	Outdoor Dry-Bulb Temperature	Outdoor Wet-Bulb Temperature[1]	Mode of Operation
Test A	80°F (26.7°C)	67°F (19.4°C)	95°F (35.0°C)	75°F (23.9°C)	Steady state
Test B	80°F (26.7°C)	67°F (19.4°C)	82°F (27.8°C)	65°F (18.3°C)	Steady state
Test C	80°F (26.7°C)	See Note 2	82°F (27.8°C)	---	Steady state
Test D	80°F (26.7°C)	See note 2	82°F (27.8°C)	---	Cyclic 6 min on-time 24 min off-time

[1] Applies only to those units which reject condensate to the outdoor coil.

[2] Shall at no time exceed that value of the wet-bulb temperature which results in the production of condensate by the indoor coil at the dry-bulb temperatures existing for the air entering the indoor portion of the unit.

the subscripts denote the test methods. This plot is shown in Figure 19 and has a cluster of points at the approximate coordinates of 0.9, 0.9. Using this clustering relationship, they developed an empirical relationship which allows one to calculate an estimated SEER from only steady state measurements. This relationship is given by the following:

$$\mathrm{SEER} = \mathrm{EER}_B \left\{ 1 - \left| \frac{1 - \mathrm{EER}_A/\mathrm{EER}_B}{1 - 0.19\ (Q_A/Q_B)} \right| 0.5 \right\} \tag{8.1}$$

where

SEER = seasonal energy efficiency ratio, (BTU/watt-hr);

EER = energy efficiency ratio, (BTU/watt-hr); and

Q = total seasonal cooling done, (BTU).

The subscripts A and B denote the test procedures described in Table XIV. A detailed description of the assumptions made in deriving this relationship, and the justification for these assumptions, is shown in Reference (31). This expression allows one to estimate SEER based solely on tests A and B, rather than using the more complicated form described by the DOE procedure (33). Comparison of the SEER values calculated from Equation (8.1), and by a more elaborate technique utilizing DOE's suggested procedure, demonstrated excellent agreement. Figure 20 displays the percentage of SEER estimated by Equation (8.1), which falls within a given percentage of SEER calculated by the DOE method. This figure shows that SEER values calculated for 85 percent of the 148 units fall within 5 percent of the DOE's SEER, and almost all of the units fall within 9 percent of the DOE's SEER. Therefore, one should decide whether a 10 percent deviation is adequate for estimating energy consumption. There is a question of compromising accuracy with economy, time, and availability of data.

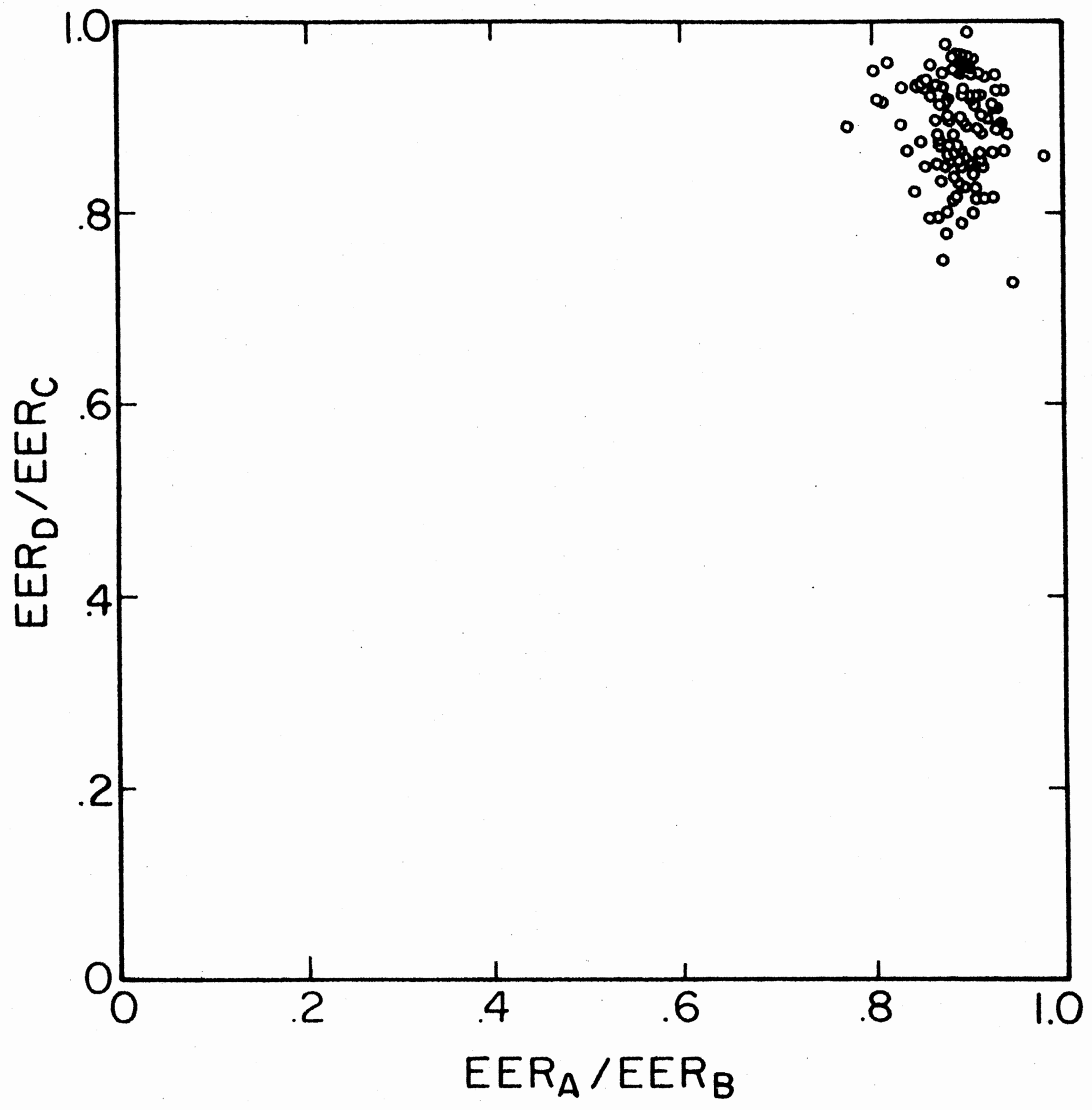

Figure 19. EER_D/EER_C Versus EER_A/EER_B

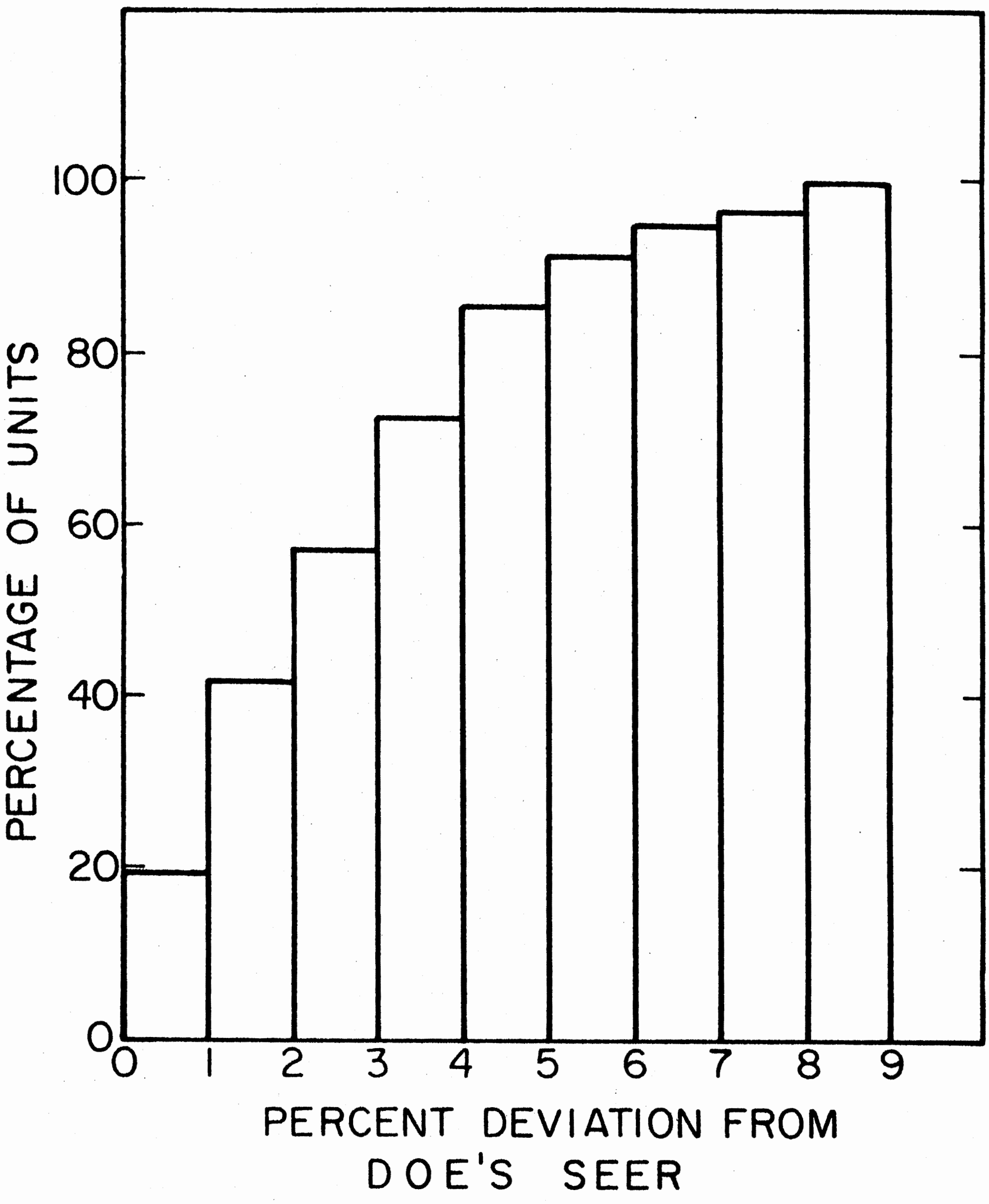

Figure 20. Percentage of Estimated SEER Falling Within a Given Percentage of SEER

It is the belief of this author that this method will provide sufficient and adequate information for estimating energy consumption of buildings via simple calculation of data which are available from most manufacturers. Equation (8.1) may be used in conjunction with previous developments to estimate energy consumption. That is:

$$EC = CL/SEER \tag{8.2}$$

where

EC = seasonal cooling energy consumption (watt-hr);

CL = seasonal cooling demand (BTU);

$SEER$ = seasonal energy efficiency ratio (BTU/watt-hr);

and CL is calculated from Equation (7.19) of the previous chapter by:

$$CL = CLD \times CBLDG \times CU.$$

Seasonal Heating Efficiency

This section describes a recommended procedure for estimating a seasonal efficiency parameter for heating. This method was developed based on a simplified approach, which assumes a linear relationship between the boiler energy demand and the outdoor dry bulb temperature. The following steps were taken to develop this procedure.

1. It is obvious that the boiler output is at its maximum rating for the design temperature, and is zero for the balance temperature of the building. This can be shown mathematically by the following equation:

$$E_b = \begin{cases} 0; & T \geq T_b \\ E_b; & T_d < T < T_b \\ E_{bmax}; & T \leq T_d \end{cases} \tag{8.3}$$

where

E_b = boiler output (BTU);

E_{bmax} = maximum boiler output (BTU);

T = outdoor dry bulb temperature (°F);

T_b = balance temperature of building (°F); and

T_d = design temperature (°F).

The plot of Equation (8.3) in its normalized form is demonstrated in Figure 21. The equation of the line in Figure 21 is given by:

$$y = ax + b \tag{8.4}$$

where

$$y = \frac{E_b}{E_{bmax}} \tag{8.5}$$

$$x = \frac{T - T_d}{T_b - T_d} \tag{8.6}$$

$$a = -1$$

$$b = +1$$

Substituting all of the above information in Equation (8.4), we get:

$$\frac{E_b}{E_{bmax}} = -\left(\frac{T - T_d}{T_b - T_d}\right) + 1 \tag{8.7}$$

Equation (8.7) describes the variation in load ratio (E_b/E_{bmax}) as a function of normalized temperature. This means that for any location, the load ratio can be evaluated from Equation (8.7).

2. Figure 22 demonstrates a typical plot of boiler efficiency versus load ratio (34). This figure can be utilized in estimating the boiler efficiency from the values of load ratio calculated from Equation (8.7).

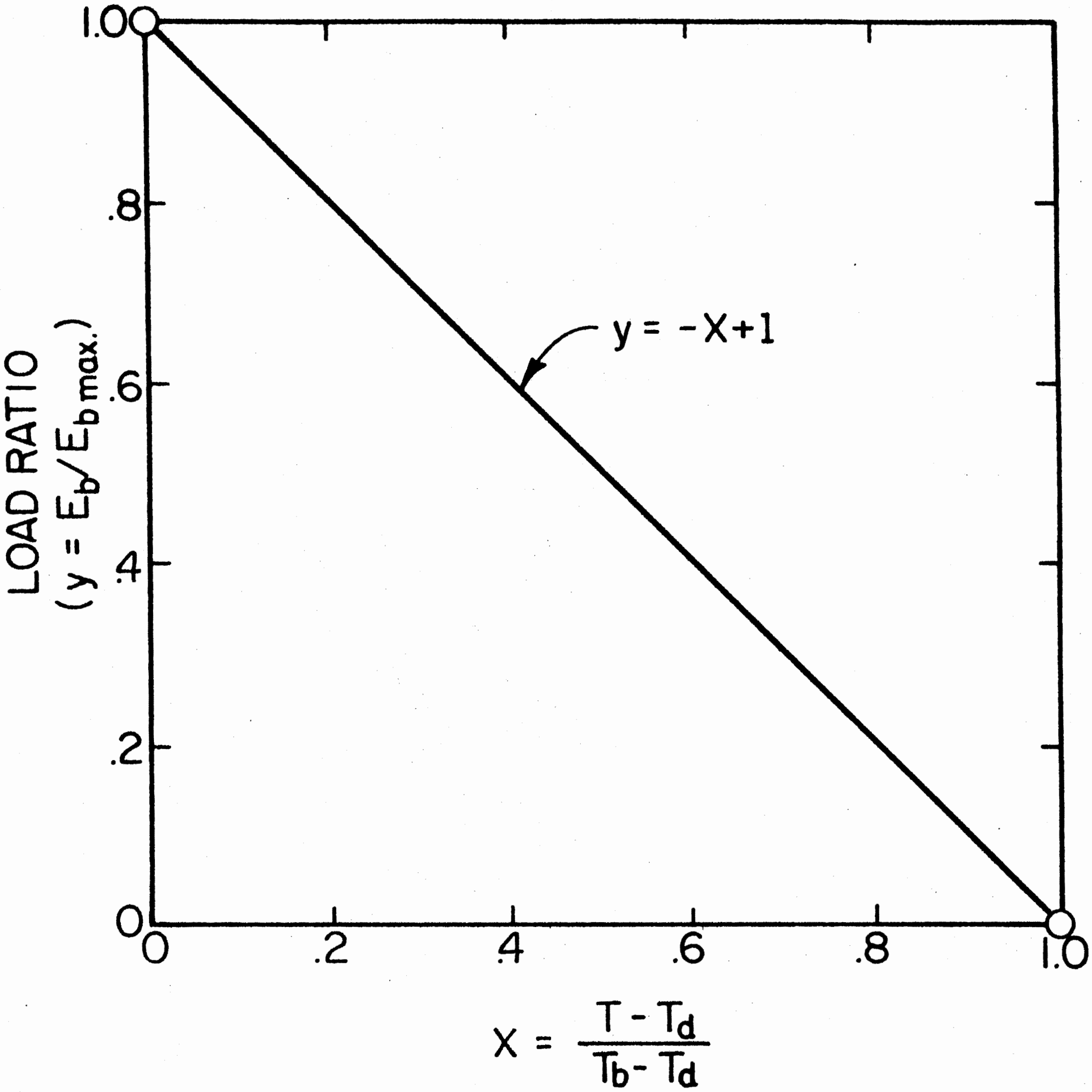

Figure 21. Load Ratio Versus Normalized Temperature

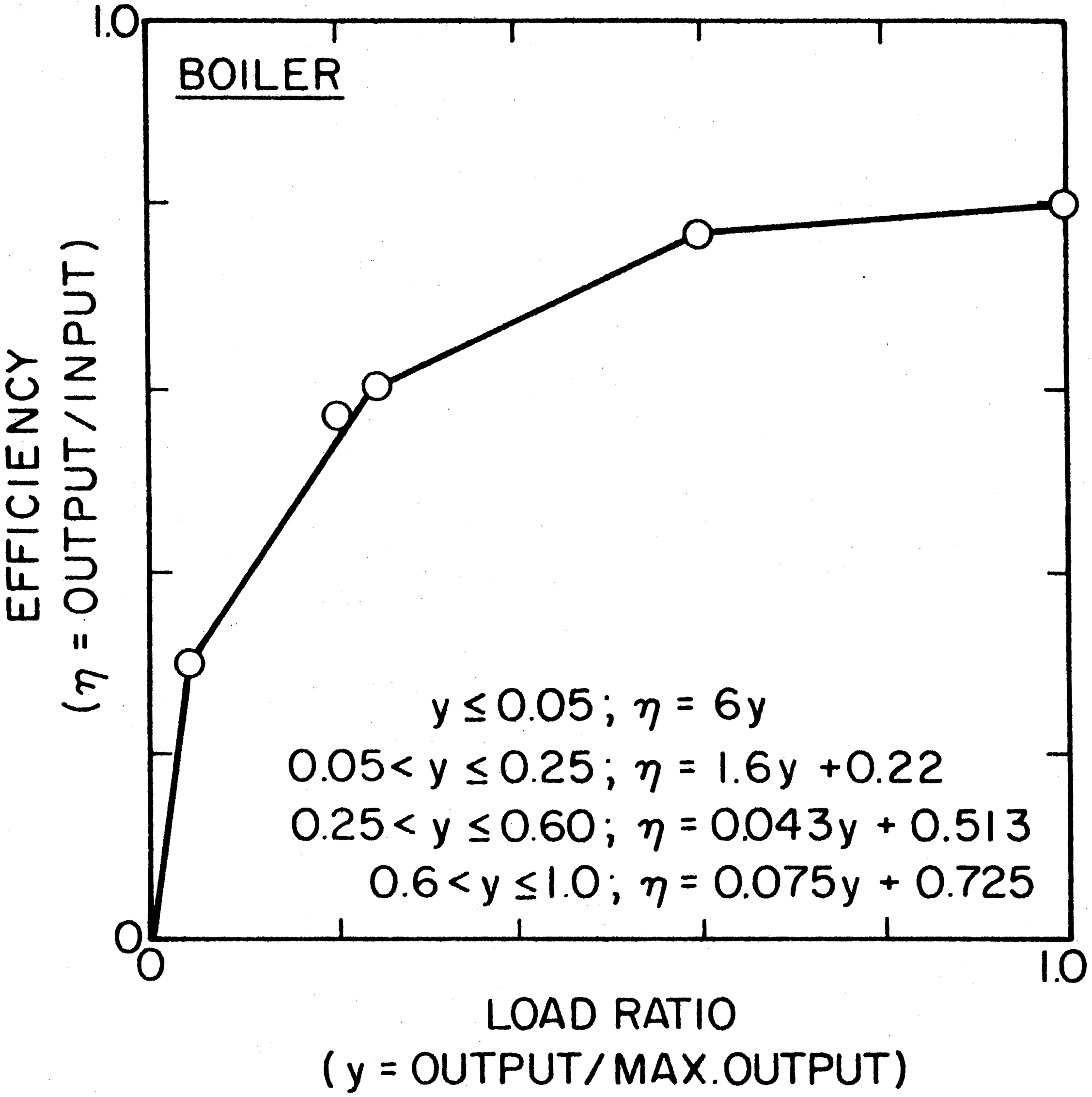

Figure 22. Boiler Efficiency Versus Load Ratio

3. From the table of hourly weather occurrrences (35), which uses temperature bins of 5°F for various locations, the number of hours at which certain temperatures occur annually can be obtained (Table XV) from Equation (8.7) and the temperature bins of Table XV, load ratios can be calculated for a range of temperature values. Figure 22 can be used to evaluate the boiler efficiencies corresponding to these load ratios.

4. The information obtained from descriptions 1 through 3 above can be summarized in a table as follows. This information includes:

T = temperature bins (Table XV);
HR = number of occurrence hours (Table XV);
Y = load ratio (Equation (8.7));
η = boiler efficiency (Figure 22); and
i = subscript.

A sample calculation for Oklahoma City is shown in Table XVI.

5. Upon completion of the above table, a seasonal heating efficiency can be determined from:

$$SHE = \frac{\sum_i \eta_i \times HR_i}{\sum_i HR_i} \qquad (8.8)$$

For the sample case:

$$SHE = \frac{1887.46}{3524} = 0.54$$

Equation (8.8) may be used in evaluation of seasonal heating efficiency SHE. This value may be used for evaluating heating energy consumption by the following relationship:

$$EH = KHL/SHE \qquad (8.9)$$

where

TABLE XV

HOURLY WEATHER OCCURRENCES

	OUTDOOR TEMPERATURE, F																		
LOCATION	72	67	62	57	52	47	42	37	32	27	22	17	12	7	2	-3	-8	-13	-18
Albany, NY	588	733	740	708	652	625	647	769	793	574	404	278	184	110	63	32	10	5	4
Albuquerque, NM	767	831	719	651	687	734	741	689	552	346	154	66	21	4	1	1			
Atlanta, GA	1185	926	823	784	735	676	598	468	271	112	44	19	8	2					
Bakersfield, CA	831	898	966	977	908	746	541	247	77	7									
Birmingham, AL	1138	908	805	742	668	614	528	433	292	143	69	17	6	3					
Bismark, ND	454	566	614	606	563	520	518	604	653	550	474	371	338	292	278	208	131	77	80
Boise, ID	492	575	643	702	786	798	878	829	522	307	148	53	26	14	6	2			
Boston, MA	676	819	804	781	766	757	828	848	674	429	256	151	74	35	4	9	1		
Buffalo, NY	646	772	760	700	666	624	647	756	849	602	426	267	170	81	5	24	2		
Burlington, VT	573	670	703	694	655	603	637	716	752	561	491	336	272	216	135	81	39	17	8
Casper, WY	423	532	592	642	606	670	782	831	806	683	495	324	200	116	73	45	30	15	5
Charleston, SC	1267	1090	889	787	651	576	434	321	192	79	27	5							
Charleston, WV	912	949	767	689	661	667	607	633	630	356	252	135	73	22	7	1			
Charlotte, NC	1115	908	839	752	730	684	634	515	360	166	64	23	5	2					
Chattanooga, TN	1021	895	775	722	713	679	642	553	414	228	113	45	4	4	2				
Chicago, IL	762	769	653	592	569	543	591	800	822	551	335	196	117	85	59	25	12	3	
Cincinnati, OH	879	843	726	639	611	599	627	698	711	460	249	131	68	44	18	8	2		
Cleveland, OH	763	831	732	641	638	607	620	754	806	578	355	201	111	47	22	11	2		
Columbus, OH	774	820	720	648	622	603	658	730	772	502	280	169	94	40	20	10	4	1	
Corpus Christi, TX	1175	1041	748	551	444	302	180	83	27	9	3								
Dallas, TX	831	795	693	656	629	576	504	371	231	91	34	17	4	1					
Denver, CO	549	684	783	731	678	704	692	717	721	553	359	216	119	78	36	22	6	1	1
Des Moines, IA	707	751	681	600	585	512	510	627	747	557	405	281	211	152	104	59	23	8	1
Detroit, MI	721	783	695	633	592	566	595	808	884	618	377	248	131	61	17	4	1		
El Paso, TX	933	839	749	760	687	611	494	369	233	104	34	10	2						
Ft. Wayne, IN	728	777	699	608	569	552	601	725	905	596	381	205	124	69	40	19	6	1	
Fresno, CA	709	803	921	1006	1036	952	673	426	168	34									
Grand Rapids, MI	634	739	712	647	571	565	554	742	938	690	469	293	172	78	31	10	1	1	
Great Falls, MT	407	520	636	754	822	830	832	813	698	533	355	218	167	136	118	101	68	51	62
Harrisburg, PA	807	824	737	692	635	659	722	888	749	427	222	125	52	18	4	1			
Hartford, CT	617	755	751	752	649	575	683	807	825	552	370	233	153	77	33	11	3	2	
Houston, TX	1172	980	772	681	570	452	291	141	64	18	4	2							
Indianapolis, IN	821	815	722	585	586	579	605	712	791	551	293	152	97	60	35	13	3	2	
Jackson, MS	1169	922	790	677	618	605	484	367	224	103	41	6	2	2	1				
Jacksonville, FL	1334	975	879	692	530	355	288	154	83	24	2								

TABLE XV (Continued)

LOCATION	OUTDOOR TEMPERATURE, F																		
	72	67	62	57	52	47	42	37	32	27	22	17	12	7	2	-3	-8	-13	-18
Kansas City, MO	761	723	601	572	553	562	628	625	591	407	265	175	99	51	21	4			
Knoxville, TN	1056	889	746	675	672	689	648	590	456	217	101	41	21	7	2				
Las Vegas, NV	651	644	699	786	769	716	591	396	194	44	7	1							
Little Rock, AR	940	803	725	672	638	669	605	509	363	172	50	25	5	1					
Los Angeles, CA	881	1654	2193	1904	1054	428	107	10											
Louisville, KY	869	758	693	654	619	634	649	703	631	332	169	97	45	25	8	3	1		
Lubbock, TX	833	829	688	700	642	618	620	546	490	346	180	86	33	7	5	1			
Memphis, TN	977	798	715	690	618	633	614	532	374	196	74	25	10	4					
Miami, FL	1705	810	452	277	147	71	26	4											
Milwaukee, WI	597	753	749	634	585	591	611	774	913	659	421	285	176	116	83	47	18	4	3
Minneapolis, MN	621	690	695	602	588	482	500	560	632	609	514	383	311	246	186	119	62	31	16
Mobile, AL	1411	1038	882	698	609	506	377	214	109	49	7	3							
Nashville, TN	933	838	738	697	637	619	627	565	463	263	132	67	28	9	3	1	1		
New Orleans, LA	1189	987	850	692	621	449	282	128	47	9	2								
New York, NY	926	877	754	745	722	796	838	858	603	330	188	2	26	10	1				
Oklahoma City, OK	881	769	717	643	645	611	641	570	468	287	173	77	36	12	3	1			
Omaha, NB	726	721	606	558	539	543	543	655	663	511	390	287	189	135	93	40	15	1	
Philadelphia, PA	863	809	735	710	663	701	758	818	654	335	189	100	32	9					
Phoenix, AZ	762	776	767	769	659	540	391	182	57	8									
Pittsburgh, PA	722	910	799	678	637	587	631	688	774	569	360	233	159	60	30	7	1		
Portland, ME	407	627	780	808	760	748	772	839	820	599	408	293	190	109	60	29	15	5	1
Portland, OR	373	581	1001	1316	1274	1271	1238	772	343	123	40	10	4	1					
Raleigh, NC	1087	937	848	762	707	672	638	527	410	236	103	38	11	1					
Reno, NV	418	477	572	690	845	909	890	829	733	530	387	227	101	37	15	4	1		
Richmond, VA	953	850	784	745	690	673	699	632	478	285	138	67	19	2	1				
Sacramento, CA	630	773	1071	1329	1298	1049	701	355	93	8									
Salt Lake City, UT	569	615	614	635	682	685	755	831	798	564	328	158	80	41	16	2			
San Antonio, TX	1086	943	789	669	569	445	387	190	94	31	11	4	1	1					
San Francisco, CA	285	665	1264	2341	2341	1153	449	99	10										
Seattle, WA	258	448	750	1272	1462	1445	1408	914	427	104	39	20	3						
Shreveport, LA	1063	886	772	679	619	609	516	361	200	72	23	6	2						
Sioux Falls, SD	566	684	669	605	522	498	501	625	712	585	520	448	293	208	152	102	59	43	18
St. Louis, MO	823	728	646	575	585	578	620	671	650	411	219	134	77	40	15	7	1		
Syracuse, NY	627	735	723	717	656	641	651	720	830	547	392	282	190	102	55	23	5	2	2
Tampa, FL	1387	1187	877	570	345	216	137	48	10	1									

TABLE XVI

CALCULATION OF SEASONAL HEATING EFFICIENCY

T	HR_i	Y_i	η_i	$\eta_i \times HR_i$
-3	1	1.000	0.800	0.80
2	3	1.000	0.800	2.40
7	12	1.000	0.800	9.60
12	36	1.000	0.800	28.80
17	77	0.905	0.793	61.06
22	173	0.786	0.784	135.63
27	287	0.667	0.775	222.42
32	468	0.548	0.537	251.32
37	570	0.429	0.531	302.67
42	641	0.310	0.526	337.17
47	611	0.190	0.524	320.16
52	645	0.071	0.334	215.43
	$\Sigma = 3524$			$\Sigma = 1887.46$

EH = seasonal heating energy consumption (watt-hr);

HL = seasonal heating demand (BTU);

SHE = seasonal heating efficiency;

K = conversion coefficient (0.293 watt-hr/BTU);

and HL is calculated from Equation (7.20) of the previous chapter by:

$$HL = HLD \times HBLDG \times HU.$$

In summary, simplified procedures for estimating a cooling and heating efficiency parameter were suggested. The analogies in development of these procedures were described and the final formulations are demonstrated by Equations (8.1) and (8.8) for cooling and heating. These quantities may be used to estimate the cooling and heating energy consumption utilizing Equations (8.2) and (8.9).

It is interesting to note that an identical method which was developed for estimating the seasonal heating efficiency can be structured for estimating the seasonal efficiency of the cooling system. This technique will require the development of the plots that are similar to those shown by Figures 21 and 22. These plots will demonstrate the chiller load ratio (ratio of chiller output to maximum output) versus normalized temperature (i.e., $(T_{eq} - T_d)/(T_b - T_d)$), and the chiller efficiency versus the load ratio, respectively. Then, utilizing weather data for numerous locations, a table identical to Table XV can be structured. This table will list the number of hours of occurrence of 5°F temperature bins for the cooling period. By following the same analogy that was described previously, a table similar to Table XVI can be structured and the seasonal cooling efficiency (SCE) can be calculated from:

$$SCE = \frac{\sum_i \eta_i \times HR_i}{\sum_i HR_i} .$$

where

SCE = seasonal cooling efficiency;

η = chiller efficiency;

HR = number of hours of occurrence of 5°F temperature bins during cooling season; and

i = summation index.

As mentioned previously, this method will require structuring a table similar to Table XV, where temperature bins and the number of hours of their occurrence during the cooling season are tabulated.

CHAPTER IX

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary and Conclusions

An investigation was undertaken to develop a simplified procedure for estimating energy requirements of commercial structures. The accomplishments of this investigation may be summarized as follows:

1. The significant environmental parameters were identified. This was achieved by conducting various computational experiments which involved a sensitivity analysis of the thermal response of buildings to perturbations in climate. The significant environmental variables were found to be atmospheric dry bulb temperature, solar insolation, humidity ratio difference of indoor and outdoor air, and daily temperature range (see Chapter IV).

2. A hypothetical representative building, which typifies the thermal response of a sample of institutional buildings, was modeled. This building was modeled by analysis of the envelope information from several institutional buildings (see Chapter V).

3. Improved cooling and heating degree-days were developed from a combination of significant environmental parameters. These quantities were demonstrated by analytical expressions that are functions of these significant climatic variables (Equations (6.5) and (6.11)). The improved degree-day expressions were utilized to predict the heating and cooling demand of the representative building. These expressions were found

to adequately predict the computer simulation results. The improved degree-day procedure was also compared with the conventional procedure. The results of these analyses indicated the advantages of the present model as compared with the conventional technique (Figures 13, 14, 15, and Table VIII). Furthermore, the improved degree-day procedure was extended to predict the heating and cooling demand of a residential structure. The results of this analysis, when compared with the results obtained from the conventional degree-day technique, revealed the advantages of the present model (Figures 16, 17, 18, and Table VIII). It was concluded that the improved degree-day procedure developed in this study was a more realistic and desirable way of relating building demand to weather. The primary reason for improved results by use of the improved degree-day technique is due to consideration of the effects of all the significant environmental parameters in a direct manner.

4. A simplified procedure for estimating the energy demand of commercial structures was developed (Chapter VII). The heating and cooling demand of any building was expressed as a function of two distinct parameters. These parameters were found to be the fundamental building and weather variables (Equations (7.15) and (7.16)). The cooling and heating units were developed from a combination of significant weather variables by utilizing a set of constants, which were obtained from a regression analysis of the simulated demand and weather data (Equations (7.17) and (7.18)). These quantities may be used for generating tables of values for different locations which can be employed to estimate the heating and cooling demand (Equations (7.19) and (7.20)). The results obtained from these developments were used to predict the computer simulated demand for various locations utilizing TMY weather data. Excellent predictions were

obtained which suggested the feasibility and validity of the present technique (Tables XII and XIII).

5. Simplified procedures for estimating seasonal heating and cooling efficiency parameters were developed (Chapter VIII). These develments included the seasonal energy efficiency ratio, SEER (Equation (8.1)), and the seasonal heating efficiency, SHE (Equation (8.8)). These quantities may be used to calculate the energy consumption of buildings via use of Equations (8.2) and (8.9) for cooling and heating.

Recommendations

Based on the observations made during the course of this study, the following recommendations are made:

1. The identical procedure which was developed in the present study for commercial structures should be extended to include other classes of structures (i.e., light, medium). This procedure should be general and its application should utilize correction factors to account for variation in buildings of different categories.

2. The results of the previous recommendation will be useful in developing tables of values for heating and cooling units for various locations. These tables will eventually replace the existing degree-day tables and will eliminate the use of weather data in estimating the energy requirements.

3. Finally, the procedure for estimating the efficiency parameter, which was described in this content, is simply a suggested method. It is recommended that actual consumption data from reliable sources (monitored buildings) should be analyzed to develop a more fundamental procedure for estimating seasonal efficiency parameters.

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APPENDIX A

HEATING AND COOLING UNITS FOR SELECTED CITIES IN THE UNITED STATES

TABLE XVII

HEATING AND COOLING UNITS FOR SELECTED CITIES IN THE UNITED STATES

Location	Season	Design Temperature (°F)	Daily Range Temperature (°F)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Seasonal Total
Boston,	Cooling	88	16	---	---	---	---	38.23	51.69	55.38	52.05	37.90	---	---	---	235.25
MA	Heating	9		369.25	277.23	294.30	229.46	---	---	---	---	---	215.85	247.20	333.86	1967.15
Charleston,	Cooling	92	13	---	---	---	40.72	49.67	56.24	64.11	59.22	50.98	---	---	---	320.94
SC	Heating	28		368.37	237.95	214.91	---	---	---	---	---	---	209.10	210.94	247.78	1489.05
Columbia,	Cooling	94	22	---	---	---	---	44.92	55.46	62.99	59.35	41.29	---	---	---	264.01
MO	Heating	4		420.58	327.52	289.71	218.88	---	---	---	---	---	216.16	270.20	348.85	
Dodge City,	Cooling	97	25	---	---	---	---	45.56	59.81	64.26	63.17	39.91	---	---	---	272.71
KS	Heating	5		386.15	284.03	293.32	219.48	---	---	---	---	---	219.76	258.77	339.21	2000.72
Medford,	Cooling	94	35	---	---	---	---	32.31	48.54	61.38	51.95	39.64	---	---	---	233.82
OR	Heating	23		299.15	254.59	256.23	228.41	---	---	---	---	---	230.06	251.85	308.50	1828.79
Nashville,	Cooling	94	21	---	---	---	---	45.64	56.37	60.25	56.02	48.29	---	---	---	266.57
TN	Heating	14		283.87	252.34	240.86	238.70	---	---	---	---	---	203.93	226.58	283.48	1729.76
Phoenix,	Cooling	107	27	---	---	---	43.55	82.25	86.67	96.41	88.68	85.51	83.28	---	---	566.35
AZ	Heating	34		226.79	201.41	208.26	---	---	---	---	---	---	---	194.94	236.01	1067.41
Sterling,	Cooling	91	18	---	---	---	---	43.47	49.48	60.62	55.02	44.18	---	---	---	252.77
VA	Heating	17		366.47	302.13	268.15	242.58	---	---	---	---	---	213.11	248.77	297.47	1938.68

*Typical metereological year weather data (see Reference (29)).

APPENDIX B

LISTING OF COMPUTER PROGRAMS

```
C                                                                       SIMU0010
C                                                                       SIMU0020
C                                                                       SIMU0030
C     HEATING AND AIR CONDITIONING SYSTEM SIMULATION PROGRAM            SIMU0040
C                                                                       SIMU0050
C                                                                       SIMU0060
C                                                                       SIMU0070
C     THIS PROGRAM CALCULATES THERMAL LOAD OF A BUILDING                SIMU0080
C     USING TRANSFER FUNCTION TECHNIQUE AND                             SIMU0090
C     HOURLY WEATHER INFORMATION FROM TMY WEATHER TAPES                 SIMU0100
C     THIS PROGRAM UTILIZES AN HOUR BY HOUR DYNAMIC SIMULATION TECHNIQUESIMU0110
C                                                                       SIMU0120
C                                                                       SIMU0130
C                                                                       SIMU0140
C                                                                       SIMU0150
      INTEGER*2 IH,ITDB,ITWB,IV                                         SIMU0160
      REAL*8 ORIENT,ZORNT                                               SIMU0170
C                                                                       SIMU0180
      COMMON/SOL1/  ATDB(24),SOLH(24),XID(24),XIDHV(24),XIT(24)         SIMU0190
      COMMON/SOL2/XLATR,EPR,PSIR,DLONG,IDAY1                            SIMU0200
      COMMON/SOL3/  SH(24),CH(24),CZ(24),CT(24),CE                      SIMU0210
      COMMON/BLOCK1/ IIN,IOT,MC,NPRT,INWRIT,TROOM,OFST,OFCT,CFMD,XKT,   SIMU0220
     $ XLF,INIT,INIHX,MONTH,IDAYM                                       SIMU0230
      COMMON/BLOCK2/ QTOTAL(24),ENER(24)                                SIMU0240
C                                                                       SIMU0250
      DIMENSION ATWB(24),DATR(24),DW(24),ALPAJ(8),TAUJ(8)               SIMU0260
      DIMENSION SHGF(24),QEW(24),TSW(24),TSWR(30,48),AT(7),DT(7)        SIMU0270
      DIMENSION QEWR(30,48),QSSW(48),QSSWR(48),QED(24),QSWR(24)         SIMU0280
      DIMENSION QFLS(48),QTLS(24),QPPS(24),QPPL(24),QOTHS(24),QOTHL(24),SIMU0290
     * QIVS(24),QIVL(24),Q30(24),Q31(24),Q34(48),Q35(24)                SIMU0300
      DIMENSION SGV(12),CHRV(12),HGLV(12),HGEPRV(12),RTFW(12)           SIMU0310
      DIMENSION QSFW(48),Q37(48),Q38(48),Q39(48),Q1SHL(24)              SIMU0320
      DIMENSION CRATFG(12),CRATFP(12),NDYM(13)                          SIMU0330
      DIMENSION ZWRL(30),ZWRH(30),ZAD(30),ZAW(30),ZEPR(30),ZPSIR(30),   SIMU0340
     *ZHO(30),ZHI(30),ZROG(30),ZALP(30),ZEPSWR(30),ZSCG(30),ZUWRA(30),  SIMU0350
     *ZUW(30),ZUD(30),ZORNT(30),ZBT(30,7),ZUWRT(30),ZDT(30,7),          SIMU0360
     *ZAWR(30),ZANI(30),ZCNS(30),ZCNST(30)                              SIMU0370
      NAMELIST /NAM1/NWAR,MC,MONTH1,MONTH2,MDAY1,MDAY2,NPRT,INWRIT,XLAT,SIMU0380
     $ACLONG,STLONG,XLF                                                 SIMU0390
     $    /NAM2/WPL,WKW,AD,AW,EPSILN,PSI,HO,HI,ROG,ALPHWR,EPSWR,SCG,UWRA SIMU0400
     $    ,UW,UD,CHIL                                                   SIMU0410
     $    /NAM3/BT,DT,UWRT                                              SIMU0420
     $    /NAM4/NPN,NPD,CFMN,CFMD,QOTSN,QOTSD,QOTLN,QOTLD,QFLN,QFLD,QTLN SIMU0430
     $    ,QTLD,OFST,OFCT,TROOM,PHI1,PHI2,NHTX,IENERG                   SIMU0440
C                                                                       SIMU0450
      DATA SGV/0.2727,-0.3400,0.1169,-0.0064,0.2217,-0.3354,0.1448,     SIMU0460
     * -0.0129,0.2155,-0.3712,0.1790,-0.0166/                           SIMU0470
      DATA CHRV/0.6982,-1.2017,0.6617,-0.1150,0.7108,-1.4456,0.9639,    SIMU0480
     * -0.2108,0.7055,-1.5668,1.1378,-0.2698/                           SIMU0490
      DATA HGLV/0.3178,-0.4507,0.2099,-0.0328,0.2505,-0.4562,0.2819,    SIMU0500
     * -0.0574,0.2430,-0.5085,0.3547,-0.0825/                           SIMU0510
      DATA HGEPRV/0.3251,-0.4267,0.1526,-0.0076,0.2574,-0.4038,0.1830,  SIMU0520
     * -0.0183,0.2503,-0.4446,0.2255,-0.0245/                           SIMU0530
      DATA RTFW/0.000,-1.8260,1.0697,-0.2005,0.000,-2.1092,1.4606,      SIMU0540
     * -0.3331,0.000,-2.2908,1.7252,-0.4277/
      DATA CRATFG/1.73,-3.50,2.22,-0.45,1.88,-4.22,3.08,-0.74,1.89,     SIMU0550
     * -4.55,3.61,-0.95/                                                SIMU0560
      DATA CRATFP/1.000,-1.8260,1.0697,-0.2005,1.000,-2.1092,1.4606,    SIMU0570
     * -0.3331,1.000,-2.2908,1.7252,-0.4277/                           SIMU0580
C                                                                       SIMU0590
C     COEFFICIENTS FOR REGULAR DS SHEET GLASS                           SIMU0600
C                                                                       SIMU0610
      DATA ALPAJ/0.01154,.77674,-3.94657,8.57881,-8.38135,3.01188,0.,0./SIMU0620
      DATA TAUJ/-0.00885,2.71235,-0.62062,-7.07329,9.75995,-3.89922,0.0,SIMU0630
     * 0.0/                                                             SIMU0640
C                                                                       SIMU0650
      DATA  NAT,NSCS,MONTH1,MONTH2/6,0,1,1/                             SIMU0660
      DATA NDYM/ 1,32,61,92,122,153,183,214,245,275,306,336,366/        SIMU0670
      DATA  RTD/57.29578/                                               SIMU0680
C                                                                       SIMU0690
   10 FORMAT(1X )                                                       SIMU0700
   20 FORMAT(/)                                                         SIMU0710
   30 FORMAT(1H1)                                                       SIMU0720
   40 FORMAT(56X,'LOAD CALCULATIONS')                                   SIMU0730
   50 FORMAT( 52X,'*************************',/)                         SIMU0740
   70 FORMAT( 3( 2X,8(5X ,I2 ,2X,F5.1 ) ,/))                            SIMU0750
   80 FORMAT( 5X,'SOLAR INCIDENT ENERGY ON SURFACE',2X,A8,2X,'IN BTU/HR-SIMU0760
     *FT**2')                                                           SIMU0770
   90 FORMAT( 5X,'SOL-AIR TEMPERATURE FOR SURFACE',2X,A8,2X,'IN F')     SIMU0780
  100 FORMAT( 5X,'SOLAR HEAT GAIN FACTOR FOR WINDOW ON SURFACE',2X,A8,2XSIMU0790
     *,'IN BTU/HR-FT**2')                                               SIMU0800
  110 FORMAT( 5X,'SOL-AIR TEMPERATURE FOR WINDOW ON SURFACE',2X,A8,2X,  SIMU0810
     *'IN F')                                                           SIMU0820
  120 FORMAT( 5X,'HEAT GAIN THROUGH SURFACE',2X,A8,' IN BTU/HR     AREA=SIMU0830
     * ',F8.0,1X,'SQ.FT.')                                              SIMU0840
  130 FORMAT( 3( 4X,8(2X ,I2,2X,F8.0),/))                               SIMU0850
  150 FORMAT( 5X,'HEAT GAIN THROUGH WINDOW ON SURFACE',2X,A8,' IN BTU/HRSIMU0860
     *      AREA= ',F5.1,' SQ.FT.')                                     SIMU0870
  160 FORMAT( 5X,'HEAT GAIN THROUGH  DOOR  ON SURFACE',2X,A8,5X,'AREA=',SIMU0880
     *F6.1,'FT**2',2X,'IN BTU/HR')                                      SIMU0890
  180 FORMAT( 52X,'INST SENSIBLE HEAT GAIN (BTU/HR)')                   SIMU0900
  190 FORMAT( 10X,'TIME',3X,'ON-OFF LIGHTS',4X,'ON LIGHTS',6X,'PEOPLE', SIMU0910
     * 9X,'EQUIPMENT',6X,'INFL&VENT', 7X,'SURFACES', 13X,'TOTAL')       SIMU0920
  200 FORMAT( 10X,I3,1X,6E15.4, E18.4)                                  SIMU0930
  210 FORMAT( 52X,'LATENT HEAT LOADS (BTU/HR)')                         SIMU0940
  220 FORMAT( 10X,'TIME',5X,'PEOPLE',9X,'EQUIPMENT',6X,'INFL&VENT',13X, SIMU0950
     *  'TOTAL')                                                        SIMU0960
  230 FORMAT( 10X,I3,1X,3E15.4,E18.4)                                   SIMU0970
  240 FORMAT( 35X,'SENSIBLE COOLING LOAD COMPONENTS DUE TO VARIOUS HEAT SIMU0980
     *GAINS (BTU/HR)')                                                  SIMU0990
  250 FORMAT( 10X ,'TIME' ,5X,'INSTANT',5X,'LIGHTS ON OFF',5X,'SURFACES'SIMU1000
     * ,5X,'PEOPLE&EQUIP',5X,'WINDOWS UNSH',7X,'TOTAL')                 SIMU1010
  260 FORMAT( 10X,I4 ,5E15.4,E18.4)                                     SIMU1020
  270 FORMAT( 52X,'TOTAL COOLING LOAD (BTU/HR)')                        SIMU1030
  280 FORMAT( 10X,'TIME',5X,'DB TEMP',3X,'WB TEMP',3X,'HUM DIF',10X,    SIMU1040
     $'SENSIBLE',12X,'LATENT',15X,'TOTAL')                              SIMU1050
  290 FORMAT( 10X,I4,2F10.1,F13.6,3E20.5)                               SIMU1060
  300 FORMAT(10X,'THE TOTAL LOAD FOR THE WHOLE DAY =',I3,2X,'OF  MONTH =SIMU1070
     &',I3,2X, /,10X,'COOLING =',E12.5, 2X, 'HEATING =',E12.5, 5X,      SIMU1080
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     & 'ROOM TEMP =',F5.1,5X,'R.H1 =',F5.3,2X,'R.H2 =',F5.3)               SIMU1090
C                                                                          SIMU1100
C                                                                          SIMU1110
C     LOGCPP=LOGIC CONTROL FOR PRINTING AND PUNCHING                       SIMU1120
C     LOGCPP=0--PRINT THE RESULTS ONLY                                     SIMU1130
C     LOGCPP=1--PRINT AND PUNCH THE RESULTS                                SIMU1140
      READ(5,11111)LOGCPP                                                  SIMU1150
11111 FORMAT(I2)                                                           SIMU1160
      IIN=5                                                                SIMU1170
      IOT=6                                                                SIMU1180
      INIT=0                                                               SIMU1190
      NPRT=1                                                               SIMU1200
      NC=2                                                                 SIMU1210
      NWAR=6                                                               SIMU1220
      MONTH1=1                                                             SIMU1230
      MONTH2=1                                                             SIMU1240
      MDAY1=1                                                              SIMU1250
      MDAY2=0                                                              SIMU1260
      IFLAGD=0                                                             SIMU1270
      INWRIT=0                                                             SIMU1280
      XLF=0.0                                                              SIMU1290
      XKT = 0.0                                                            SIMU1300
      XLAT=36.0                                                            SIMU1310
      STLONG=90.0                                                          SIMU1320
      ACLONG=97.0                                                          SIMU1330
      PB=14.7                                                              SIMU1340
      DLONG=(STLONG-ACLONG)/15.0                                           SIMU1350
      DO 305 I=1,24                                                        SIMU1360
      ENERA(I)=0.0                                                         SIMU1370
305   CONTINUE                                                             SIMU1380
      READ(IIN,NAM1)                                                       SIMU1390
      IF(INWRIT.LE.0)  GO TO 310                                           SIMU1400
      WRITE(IOT,30)                                                        SIMU1410
      WRITE(IOT,NAM1)                                                      SIMU1420
310   CONTINUE                                                             SIMU1430
      NOT=NDYM(MONTH1)+MDAY1-2                                             SIMU1440
      IF(NOT.LE.0)  GO TO 320                                              SIMU1450
      NOT24=NOT*24                                                         SIMU1460
      DO 330 I=1,NOT24                                                     SIMU1470
      READ(9)TDB,TWB,Q                                                     SIMU1480
330   CONTINUE                                                             SIMU1490
320   XLATR=XLAT/RTD                                                       SIMU1500
      DO 340  NS=1,NWAR                                                    SIMU1510
      WRL=0.0                                                              SIMU1520
      WRW=0.0                                                              SIMU1530
      AD=0.0                                                               SIMU1540
      AW=0.0                                                               SIMU1550
      PSI=0.0                                                              SIMU1560
      EPSILN=90.0                                                          SIMU1570
      HO=3.0                                                               SIMU1580
      HI=1.46                                                              SIMU1590
      ROG=0.2                                                              SIMU1600
      ALPHWR=0.8                                                           SIMU1610
      EPSWR=0.9                                                            SIMU1620
      SCG=0.0                                                              SIMU1630
      UWRA=0.0                                                             SIMU1640
      UW=0.0                                                               SIMU1650
      UD=0.0                                                               SIMU1660
      DO 342 I=1,7                                                         SIMU1670
      BT(I)=0.0                                                            SIMU1680
      DT(I)=0.0                                                            SIMU1690
342   CONTINUE                                                             SIMU1700
      READ(IIN,NAM2)                                                       SIMU1710
      UWRT=UWRA                                                            SIMU1720
      READ(IIN,NAM3)                                                       SIMU1730
      IF(INWRIT.LE.0)  GO TO 344                                           SIMU1740
      WRITE(IOT,20)                                                        SIMU1750
      WRITE(IOT,NAM2)                                                      SIMU1760
      WRITE(IOT,20)                                                        SIMU1770
      WRITE(IOT,NAM3)                                                      SIMU1780
344   ZWRL(NS)=WRL                                                         SIMU1790
      ZWRW(NS)=WRW                                                         SIMU1800
      ZAD(NS) = AD                                                         SIMU1810
      ZAW(NS) = AW                                                         SIMU1820
      ZEPR(NS) = EPSILN/RTD                                                SIMU1830
      ZPSIR(NS) = PSI/RTD                                                  SIMU1840
      ZHO(NS) = HO                                                         SIMU1850
      ZHI(NS) = HI                                                         SIMU1860
      ZROG(NS) = ROG                                                       SIMU1870
      ZALP(NS) = ALPHWR                                                    SIMU1880
      ZEPSWR(NS) = EPSWR                                                   SIMU1890
      ZSCG(NS) = SCG                                                       SIMU1900
      ZUWRA(NS) = UWRA                                                     SIMU1910
      ZUW(NS) = UW                                                         SIMU1920
      ZUD(NS) = UD                                                         SIMU1930
      ZORNT(NS) = ORIENT                                                   SIMU1940
      ZAWR(NS) = (WRL*WRW)-AD-AW                                           SIMU1950
      XKT=XKT+(ZAWR(NS)*UWRA)+(AD*UD)+(AW*UW)                              SIMU1960
      UR = UWRA/UWRT                                                       SIMU1970
      ZXNI(NS) = HI/(HI+HO)                                                SIMU1980
      ZCNS(NS) =0.0                                                        SIMU1990
      DO 346 I=1,7                                                         SIMU2000
      ZBT(NS,I)=BT(I)*UR                                                   SIMU2010
      ZDT(NS,I)=DT(I)                                                      SIMU2020
      ZCNS(NS)=ZCNS(NS)+ZBT(NS,I)                                          SIMU2030
346   CONTINUE                                                             SIMU2040
      ZCT(NS,1)=0.0                                                        SIMU2050
340   CONTINUE                                                             SIMU2060
      XKT=XKT/XLF                                                          SIMU2070
      IF(XKT.GT.17.0)  XKT=17.0                                            SIMU2080
      FC1=1.0-(0.019*XKT)                                                  SIMU2090
      FC2=1.0-(0.014*XKT)                                                  SIMU2100
      FC3=1.0-(0.022*XKT)                                                  SIMU2110
      FC4=1.0-(0.025*XKT)                                                  SIMU2120
      I=(4*NC)-3                                                           SIMU2130
      I3=I+3                                                               SIMU2140
      IJ=1                                                                 SIMU2150
      DO 350 J=1,I3                                                        SIMU2160
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      SCV(IJ)=SCV(J)*FC1                                                SIMU2170
      CWAV(IJ)=CWAV(J)*FC2                                              SIMU2180
      HGLV(IJ)=HGLV(J)*FC3                                              SIMU2190
      HGEPRV(IJ)=HGEPRV(J)*FC4                                          SIMU2200
      RTFW(IJ)=RTFW(J)                                                  SIMU2210
      IJ=IJ+1                                                           SIMU2220
  350 CONTINUE                                                          SIMU2230
      IF(MDAY1.LT.1)  MDAY1=1                                           SIMU2240
      IF(MDAY2.LE.0)  IFLAGO=1                                          SIMU2250
      IF(MDAY1.EQ.1.AND.MDAY2.EQ.1)  MONTH2=MONTH1                      SIMU2260
      IF(MDAY2.LT.1)  MDAY2=1                                           SIMU2270
      IF(MDAY1.NE.MDAY2)  MONTH2=MONTH1                                 SIMU2280
      IF(IFLAGO.EQ.1)  MDAY2=32                                         SIMU2290
      IF(MONTH2.LT.MONTH1)  MONTH2=MONTH1                               SIMU2300
      DO 400 MONTH=MONTH1,MONTH2                                        SIMU2310
      INDEX=0                                                           SIMU2320
      NPN=0                                                             SIMU2330
      NPD=0                                                             SIMU2340
      CFMN=0.0                                                          SIMU2350
      CFMC=0.0                                                          SIMU2360
      QOTSN=0.0                                                         SIMU2370
      QOTSD=0.0                                                         SIMU2380
      QOTLN=0.0                                                         SIMU2390
      QOTLO=0.0                                                         SIMU2400
      QFLN=0.0                                                          SIMU2410
      QFLD=0.0                                                          SIMU2420
      QTLN=0.0                                                          SIMU2430
      QTLD=0.0                                                          SIMU2440
      OFSI=8.0                                                          SIMU2450
      OFCI=17.0                                                         SIMU2460
      TROOM=70.0                                                        SIMU2470
      NMTX=0                                                            SIMU2480
      IENERG=0                                                          SIMU2490
      PHI1=0.4                                                          SIMU2500
      PHI2=0.5                                                          SIMU2510
      READ(IIN,NAM4)                                                    SIMU2520
      PO=PSL(TROOM)                                                     SIMU2530
      PS1=PHI1*PO                                                       SIMU2540
      PS2=PHI2*PO                                                       SIMU2550
      WSP1=0.622*PS1/(PB-PS1)                                           SIMU2560
      WSP2=0.622*PS2/(PB-PS2)                                           SIMU2570
      DO 405 NS=1,NWAR                                                  SIMU2580
      ZCNST(NS)=ZCNS(NS)*TROOM                                          SIMU2590
  405 CONTINUE                                                          SIMU2600
      IF(INWRIT.LE.0) GO TO 410                                         SIMU2610
      WRITE(IOT,20)                                                     SIMU2620
      WRITE(IOT,NAM4)                                                   SIMU2630
  410 WRITE(IOT,30)                                                     SIMU2640
      WRITE(IOT,40)                                                     SIMU2650
      WRITE(IOT,50)                                                     SIMU2660
      NOMM=NDYM(MONTH+1)-NDYM(MONTH)                                    SIMU2670
      IF(MDAY2.GT.NOMM)  MDAY2=NOMM                                     SIMU2680
      DO 420 IDAYM=MDAY1,MDAY2                                          SIMU2690
      IDAY1=0                                                           SIMU2700
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      IDAYY=NDYM(MONTH)+IDAYM-1                                         SIMU2710
      WSPAMA=0.0                                                        SIMU2720
      DO 430 NH=25,48                                                   SIMU2730
      I=NH-24                                                           SIMU2740
      READ(9)TDB,TWB,Q                                                  SIMU2750
      ATDB(I)=TDB                                                       SIMU2760
      ATWB(I)=TWB                                                       SIMU2770
      SOLH(I)=Q                                                         SIMU2780
      DATR(I)=ATDB(I)-TROOM                                             SIMU2790
      WSPA=0.0                                                          SIMU2800
      PSA=0.0                                                           SIMU2810
      IF(ATDB(I).LT.10.0.OR.ATWB(I).LT.10.0)   GO TO 425                SIMU2820
      PW=PSL(ATWB(I))                                                   SIMU2830
      WW=0.622*PW/(PB-PW)                                               SIMU2840
      WSPA=(((1093.0-0.556*ATWB(I))*WW)-0.240*(ATDB(I)-ATWB(I)))/(1093.0+SIMU2850
     $(0.444*ATDB(I))-ATWB(I))                                          SIMU2860
      IF(WSPA.LT.0.0)   WSPA=0.0                                        SIMU2870
      WSPAMA=AMAX1(WSPAMA,WSPA)                                         SIMU2880
      PSA=WSPA*PB/(0.622+WSPA)                                          SIMU2890
      DW(I)=0.0                                                         SIMU2900
      IF(PSA.GT.PHI2) DW(I)=WSPA-WSP2                                   SIMU2910
  425 IF(PSA.LT.PHI1) DW(I)=WSPA-WSP1                                   SIMU2920
      QSSWR(NH)=0.0                                                     SIMU2930
      QSSW(NH)=0.0                                                      SIMU2940
  430 CONTINUE                                                          SIMU2950
      SATDB=0.0                                                         SIMU2960
      SSOLH=0.0                                                         SIMU2970
      SDW=0.0                                                           SIMU2980
      DO 111 LL=25,48                                                   SIMU2990
      L=LL-24                                                           SIMU3000
      SATDB=SATDB+ATDB(L)                                               SIMU3010
      SSOLH=SSOLH+SOLH(L)                                               SIMU3020
      SDW=SDW+DW(L)                                                     SIMU3030
  111 CONTINUE                                                          SIMU3040
      ATDBA=SATDB/24.0                                                  SIMU3050
      SOLHA=SSOLH/24.0                                                  SIMU3060
      DWA=SDW/24.0                                                      SIMU3070
      TDBMAX=0.0                                                        SIMU3080
      TDBMIN=100.0                                                      SIMU3090
      SOLHMA=0.0                                                        SIMU3100
      SOLHMI=100.0                                                      SIMU3110
      DO 112 NN=25,48                                                   SIMU3120
      N=NN-24                                                           SIMU3130
      TDBMAX=AMAX1(TDBMAX,ATDB(N))                                      SIMU3140
      TDBMIN=AMIN1(TDBMIN,ATDB(N))                                      SIMU3150
      SOLHMA=AMAX1(SOLHMA,SOLH(N))                                      SIMU3160
      SOLHMI=AMIN1(SOLHMI,SOLH(N))                                      SIMU3170
  112 CONTINUE                                                          SIMU3180
      DELTT=TDBMAX-TDBMIN                                               SIMU3190
      DELTR=SOLHMA-SOLHMI                                               SIMU3200
      DO 440 NS=1,NWAR                                                  SIMU3210
      FPR=ZEPR(NS)                                                      SIMU3220
      PSIR=ZPSIR(NS)                                                    SIMU3230
      CALL SOLAR(IDAYY)                                                 SIMU3240
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```
      DO 450 IH=25,48
      I=IH-24
      QEW(I)=0.0
      IF(ZAW(NS).LE.0.0)  GO TO 452
      ALPAD=ALPAJ(1)
      TAUD=TAUJ(1)
      DUM=1.0
      DO 454 J=2,NAT
      DUM=DUM*CT(I)
      ALPAD=ALPAD+(ALPAJ(J)*DUM)
      TAUD=TAUD+(TAUJ(J)*DUM)
  454 CONTINUE
      SALPAJ=0.0
      STAUJ=0.0
      DO 456 J=1,NAT
      XJ=1.0/(J+1)
      SALPAJ=SALPAJ+(ALPAJ(J)*XJ)
      STAUJ= STAUJ+(TAUJ(J)*XJ)
  456 CONTINUE
      SHGTC=(XID(I)*TAUD)+(XIDHV(I)*2.0*STAUJ)
      SHGAC=(XID(I)*ALPAD)+(XIDHV(I)*2.0*SALPAJ)
      ALPAW=0.0
      IF(SHGAC.LE.0.0.OR.XIT(I).LE.0.0)  GO TO 458
      ALPAW=SHGAC/XIT(I)
  458 EMEW=ALPAW
      SHGF(I) = SHGTC+ZXNI(NS)*SHGAC
      QEW(I) = ZAW(NS)*(ZUW(NS)*DATR(I)+ZSCG(NS)*SHGF(I))
C
C     SOL-AIR TEMPERATURE CALCULATIONS
C
      TSW(I) = ATDB(I)+(ALPAW*XIT(I)/ZHO(NS))-(EMEW*20.0*CE/ZHO(NS))
  452 TSWR(NS,IH)=ATDB(I)+(ZALP(NS)*XIT(I)/ZHO(NS))-( ZEPSWR(NS)*20.0*CES
     $ /ZHO(NS))
  450 CONTINUE
      IF(INIT.GT.0)  GO TO 480
      DO 490 I=1,24
      IH=I+24
      QEWR(NS,I) = ZUWR(NS)*(TSWR(NS,IH)-TROOM)
      TSWR(NS,I) = TSWR(NS,IH)
  490 CONTINUE
  480 DO 500 K=25,48
      QEWAT=ZBT(NS,1)*TSWR(NS,K)
      DO 502 J=2,7
      JJ = K+1-J
      QEWAT = (ZBT(NS,J)*TSWR(NS,JJ))-(ZDT(NS,J)*QEWR(NS,JJ))+QEWAT
  502 CONTINUE
      QEWR(NS,K) = QEWAT-ZCNST(NS)
  500 CONTINUE
      DO 510 I=1,24
      IH=I+24
      QEWR(NS,I) = ZAWR(NS)*QEWR(NS,IH)
      QED(I)=ZAD(NS)*ZUD(NS)*(TSWR(NS,IH)-TROOM)
      QSWA(I)=QEWR(NS,I)+QED(I)+QEW(I)
      QSSWA(IH) = QSSWA(IH)+QSWA(I)
      TSWR(NS,I)=TSWR(NS,IH)
  510 CONTINUE
      IF(ZAW(NS).LE.0.0.OR.ZSCG(NS).LT.0.0)  GO TO 520
      NSCC=1
      DO 530 I=1,24
      IH=I+24
      QSSW(IH) = QSSW(IH)+QEW(I)
  530 CONTINUE
  520 IF(NPRT.LT.4)  GO TO 545
      WRITE(IOT,20)
      IF(ZALP(NS).LE.0.0)   GO TO 535
      WRITE(IOT,80)  ZORNT(NS)
      WRITE(IOT,70)  ((I,XIT(I),I=N,24,3),N=1,3)
      WRITE(IOT,10)
  535 WRITE(IOT,90)  ZORNT(NS)
      WRITE(IOT,70)  ((I,TSWR(NS,I),I=N,24,3),N=1,3)
      IF(ZAW(NS).LE.0.0)  GO TO 538
      WRITE(IOT,20)
      WRITE(IOT,100) ZORNT(NS)
      WRITE(IOT,70)  ((I,SHGF(I),I=N,24,3),N=1,3)
      WRITE(IOT,20)
      WRITE(IOT,110) ZORNT(NS)
      WRITE(IOT,70)  ((I,TSW(I),I=N,24,3),N=1,3)
  538 WRITE(IOT,20)
      WRITE(IOT,120)  ZORNT(NS),ZAWR(NS)
      WRITE(IOT,130)  ((I,QEWR(NS,I),I=N,24,3),N=1,3)
      IF(ZAW(NS).LE.0.0)  GO TO 540
      WRITE(IOT,20)
      WRITE(IOT,150)  ZORNT(NS),ZAW(NS)
      WRITE(IOT,130)   ((I,QEW(I),I=N,24,3),N=1,3)
  540 IF(ZAD(NS).LE.0.0)  GO TO 545
      WRITE(IOT,20)
      WRITE(IOT,160)   ZORNT(NS),ZAD(NS)
      WRITE(IOT,130)  ((I,QED(I),I=N,24,3),N=1,3)
  545 DO 550  I=1,24
      IH=I+24
      QEWR(NS,I)=QEWR(NS,IH)
  550 CONTINUE
  440 CONTINUE
C
C  CALCULATION OF HEAT GAIN DUE TO PEOPLE, LIGHTS, OTHER EQUIPMENT,
C     VENTILATION AND INFILTRATION
C
      DO 600 I=1,24
      IH=I+24
      XI=I
      CIVL=4440.0*DW(I)
      CFM=CFMN
      XNP=XNPN
      QOTS=QOTSN
      QOTL=QOTLN
      QFLE=QFLN
      QTLE=QTLN
      IF(XI.LT.OFST. OR.XI.GT.OFCT)  GO TO 610
```

```
C
C   OFFICE HOURS
C
      CFM=CFMO
      XNP=NPO
      QOTS=QOTSO
      QOTL=QOTLO
      QFLE=QFLO
      QTLE=QTLO
C
C   OFF OFFICE HOURS
C
610   QFLS(IH)=4095.6*QFLE
      QTLS(I)=3413.0*QTLE
      QPPS(I)=250.0*XNP
      QPPL(I)=200.0*XNP
      QOTHS(I)=QOTS
      QOTHL(I)=QOTL
      QIVS(I)=CFM*1.08*DATR(I)
      QIVL(I)=CFM*CIVL
      Q30(I)=QIVL(I)+QPPL(I)+QOTHL(I)
      Q31(I)=QTLS(I)+QIVS(I)+(0.5*QPPS(I))+QOTHS(I)
      Q34(IH)=0.5*QPPS(I)
      Q35(I) = Q31(I)+QFLS(IH)+QSSWR(IH)+Q34(IH)
600   CONTINUE
C
C   SENSIBLE COOLING LOAD DUE TO UNSHADED WINDOWS
C
      IF(INIT.GT.0)   GO TO 620
      DO 630 I=1,24
      IH=I+24
      QFLS(I)=QFLS(IH)
      QSSWR(I)=QSSWR(IH)
      QSSW(I)=QSSW(IH)
      Q34(I)=Q34(IH)
      QSFW(I)=QSSW(IH)
      Q37(I)=QFLS(IH)
      Q38(I)=QSSWR(IH)
      Q39(I)=Q34(IH)
      QSFW(IH)=0.0
630   CONTINUE
620   IF( NSCG.NE.1)   GO TO 640
      DO 650 I=25,48
      QSSWR(I)=QSSWR(I)-QSSW(I)
650   CONTINUE
      DO 660 K=25,48
      QSFWT = SGV(1)*QSSW(K)
      DO 655 J=2,4
      JJ = K+1-J
      QSFWT = QSFWT+SGV(J)*QSSW(JJ)-RTFW(J)*QSFW(JJ)
655   CONTINUE
      QSFW(K) = QSFWT
660   CONTINUE
C
```

```
C   SENSIBLE COOLING LOAD DUE TO LIGHTS,SURFACES,AND RAD.FRAC. OF PEOPLE
C
640   DO 670 K=25,48
      QFWRT=CWRV(1)*QSSWR(K)
      QFFLT=HGLV(1)*QFLS(K)
      QF34T=HGEPRV(1)*Q34(K)
      DO 680 J=2,4
      JJ=K+1-J
      QFFLT = QFFLT+HGLV(J)*QFLS(JJ)-RTFW(J)*Q37(JJ)
      QFWRT=QFWRT+CWRV(J)* QSSWR(JJ)-RTFW(J)*Q38(JJ)
      QF34T=QF34T+HGEPRV(J)*Q34(JJ)-RTFW(J)*Q39(JJ)
680   CONTINUE
      Q37(K) = QFFLT
      Q38(K) = QFWRT
      Q39(K) = QF34T
670   CONTINUE
      DO 700 I=1,24
      IH=I+24
      QSSW(I)=QSSW(IH)
      QSSWR(I)=QSSWR(IH)
      Q37(I)=Q37(IH)
      Q38(I)=Q38(IH)
      Q39(I)=Q39(IH)
      QSFW(I)=QSFW(IH)
      QFLS(I)=QFLS(IH)
      Q34(I)=Q34(IH)
700   CONTINUE
      QTOTFC=0.0
      QTOTFH=0.0
      DO 710 I=1,24
      QTSHL(I)=QSFW(I)+Q37(I)+Q38(I)+Q39(I)+Q31(I)
      QTOTAL(I)=QTSHL(I)+Q30(I)
      IF(QTOTAL(I).GT.0.0)   QTOTFC=QTOTFC+QTOTAL(I)
      IF(QTOTAL(I).LT.0.0)   QTOTFH=QTOTFH+QTOTAL(I)
710   CONTINUE
      QTOTFH=-QTOTFH
      IF(NPRT.LE.1)   GO TO 800
      IF(NPRT.LE.2)   GO TO 810
C
C   WRITE INSTANTANEOUS SENSIBLE HEAT GAINS
C
      WRITE(IOT,30)
      WRITE(6,180)
      WRITE(6,50)
      WRITE(6,190)
      WRITE(6,20)
      DO 820 I=1,24
      WRITE(6,200) I,QFLS(I),QTLS(I),QPPS(I),QOTHS(I),QIVS(I),QSSWR(I),
     *Q35(I)
      WRITE(6,10)
820   CONTINUE
C
C   WRITE LATENT HEAT GAINS
C
```

```
      WRITE(6,30)
      WRITE(6,210)
      WRITE(6,50)
      WRITE(6,220)
      WRITE(6,20)
      DO 830 I=1,24
      WRITE(6,230) I,QPPL(I),QOTHL(I),QIVL(I),Q30(I)
      WRITE(6,10)
  830 CONTINUE
C
C  WRITE SENSIBLE COOLING LOAD DUE TO VARIOUS HEAT GAINS
C
      WRITE(6,30)
      WRITE(6,240)
      WRITE(6,50)
      WRITE(IOT,250)
      WRITE(6,20)
      DO 840 I=1,24
      WRITE(6,260) I,Q31(I),Q37(I),Q38(I),Q39(I),QSFW(I),QTSHL(I)
      WRITE(6,10)
  840 CONTINUE
  810 CONTINUE
      WRITE(6,30)
      WRITE(6,270)
      WRITE(6,50)
      WRITE(6,280)
      WRITE(6,20)
      DO 850 I=1,24
      WRITE(6,290) I,ATDB(I),ATWB(I),DW(I),QTSHL(I),Q30(I),QTOTAL(I)
      WRITE(6,10)
  850 CONTINUE
      WRITE(6,222)ATDBA,SOLHA,DWA
  222 FORMAT(1H ,'AVG DAILY TEMP=',F6.2,5X,'AVG DAILY RAD=',F6.2,5X,'AVG
     $ DAILY HUM RATIO DIFF =',F10.6)
      WRITE(6,333)DELTT,DELTR,TDBMAX,SOLHMA,WSPAMA
  333 FORMAT(1H ,'DELTT=',F6.2,5X,'DELTR=',F6.2,5X,'TMAX=',F6.2,5X,'RMAX
     $=',F6.2,5X,'WMAX=',F10.6)
      WRITE(IOT,300)   IDAYM,MONTH,QTOTFC,QTOTFH,TRCOP,PHI1,PHI2
      IF(LOSCPP.EQ.0)GO TO 555
      WRITE(7,444)MONTH,IDAYM,ATDBA,DELTT,SOLHA,DWA,TDBMAX,SOLHMA,WSPAMA
     $,QTOTFH,QTOTFC
  444 FORMAT(I3,I2,3F6.2,F10.6,2F6.2,F10.6,2E12.5)
  555 CONTINUE
  800 CONTINUE
      IF(NHTX.GE.1)  CALL HEATX
      IF(IENCAG.GE.1)  CALL ENERGY(ATDB,QTOTAL,ENER,INIHX,NPRT)
      INIT=1
      INIHX=1
  420 CONTINUE
      MDAY1=1
      MDAY2=32
  400 CONTINUE
      STOP
      END
```

```
      SUBROUTINE ENERGY(ATDB,QTOTAL,ENER,INIHX,NPRT)
      RETURN
      END
      SUBROUTINE SOLAR(IDAY)
      COMMON/SOL1/  ATDR(24),SOLH(24),XID(24),XIDHV(24),XIT(24)
      COMMON/SOL2/XLATR,EPR,PSIR,DLONG,IDAY1
      COMMON/SOL3/  SH(24),CH(24),CZ(24),CT(24),CE
      DIMENSION  SID(24),SIDHV(24)
      SC=428.0
      IF(IDAY.EQ.IDAY1)  GO TO 10
      DAY=IDAY
      EQTIME=-0.092075+1.367238*COS(0.017214*DAY)-7.044381*SIN(0.017214*
     1DAY)-1.287451*COS(0.034429*DAY)-10.175641*SIN(0.034428*DAY)-0.1117
     263*COS(0.051643*DAY)-1.084028*SIN(0.051643*DAY)-0.144821*COS(0.068
     3857*DAY)-0.616121*SIN(0.068857*DAY)+0.061813*COS(0.086071*DAY)-0.4
     428534*SIN(0.086071*DAY)-0.096942*COS(0.103285*DAY)-0.256195*SIN(0.
     5103285*DAY)
      STC=(EQTIME/60.0)+DLONG
      D= 0.40928*SIN(6.28319*(284.0+IDAY)/365.0)
      SD=SIN(D)
      CD=COS(D)
      SL=SIN(XLATR)
      CL=COS(XLATR)
      CZT=SD*SL
      CDL=CD*CL
      DO 20 I=1,24
      STLTIM=STC+I
      H=3.1416-(0.2618*STLTIM)
      SH(I)=SIN(H)
      CH(I)=COS(H)
      CZ(I)=CZT+(CDL*CH(I))
      IF(CZ(I).LT.0.05)  CZ(I)=0.05
      XKK=SOLH(I)/(SC*CZ(I))
      IF(XKK.GT.0.75)  XKK=0.75
      RATIO=0.5*(1.0+COS(XKK*3.14159))
      SIDHV(I)=RATIO*SOLH(I)
      SID(I)=SOLH(I)-SIDHV(I)
   20 CONTINUE
   10 SE=SIN(EPR)
      CE=COS(EPR)
      SP=SIN(PSIR)
      CP=COS(PSIR)
      CTT=SD*(SL*CE-CL*SE*CP)
      DO 30  I=1,24
      CT(I)=0.0
      XIT(I)=0.0
      XID(I)=0.0
      XIDHV(I)=0.0
      IF(SOLH(I).LE.0.0)  GO TO 30
      CT(I)=CTT+(CH(I)*CD)*((CL*CE)+(SL*SE*CP))+(CD*SE*SP*SH(I))
      IF(CT(I).LT.0.0)  CT(I)=0.0
      RB=CT(I)/CZ(I)
      IF(RB.GT.5.0)  RB=1.0
      XIDHV(I)=SIDHV(I)*0.5*(1.0+CE)
```

```
      XID(I)=SID(I)*RB                                                  SIMU6490
      XIT(I)=XID(I)+XIDHV(I)                                            SIMU6500
30    CONTINUE                                                          SIMU6510
      ICAYI=IDAY                                                        SIMU6520
      RETURN                                                            SIMU6530
      END                                                               SIMU6540
      SUBROUTINE HEATX                                                  SIMU6550
      COMMON/BLOCK1/ IIN,IOT,MC,NPRT,INWRIT,TROOM,OFST,OFCT,CFMD,XKT,   SIMU6560
     $ XLF,INIT,INIHX,MONTH,IDAYM                                       SIMU6570
      COMMON/BLOCK2/ QTOTAL(24),ENER(24)                                SIMU6580
      DIMENSION  G(4),P(4),ZG(12),ZP(12)                                SIMU6590
       DIMENSION XI(24),QTOT(48),ER(48),T(48)                           SIMU6600
      NAMELIST/NAMS/ERMAX,ERMIN,FLAREA,THRANG,THSETD,THSETN,THTIMN,     SIMU6610
     $ THTIMD                                                           SIMU6620
      DATA ZG/1.73,-3.5,2.22,-0.45,1.88,-4.22,3.08,-0.74,1.89,-4.55,3.61SIMU6630
     *,-0.95/                                                           SIMU6640
      DATA ZP/1.00,-1.8260,1.0697,-0.2005,1.000,-2.1092,1.4506,-0.3331, SIMU6650
     *1.000,-2.2908,1.7252,-0.4277/                                     SIMU6660
   10 FORMAT(1X )                                                       SIMU6670
   20 FORMAT(/)                                                         SIMU6680
25    FORMAT(1H1)                                                       SIMU6690
   30 FORMAT( 51X,'*********************************',//)               SIMU6700
35    FORMAT(52X,'HEAT EXTRACTION RATES (BTU/HR)')                      SIMU6710
36    FORMAT(52X,'HEAT  ADDITION  RATES (BTU/HR)')                      SIMU6720
   40 FORMAT( 3( 2X,A15X ,I2 ,2X,F5.1 ) ,/))                            SIMU6730
50    FORMAT( 5X,'ROOM AIR TEMPERATURES 1-24HRS',5X,'THERMOSTAT SETTING'SIMU6740
     *,F5.1,1X,'F',1X,'AT',F4.0,'HRS',3X,F5.1,1X,'F',1X,'AT',F4.0,'HRS')SIMU6750
60    FORMAT( 5X,'HEAT EXTRACTION RATES 1-24 HRS',5X,'ERMIN=',G13.6,2X ,SIMU6760
     *'ERMAX=',F9.0,2X,'BTU/HOUR ')                                     SIMU6770
61    FORMAT( 5X,'HEAT  ADDITION  RATES 1-24 HRS',5X,'ERMIN=',G13.6,2X ,SIMU6780
     *'ERMAX=',F9.0,2X,'BTU/HOUR ')                                     SIMU6790
70    FORMAT( 3( 4X,8(2X ,I2,1X,F9.0),/))                               SIMU6800
80    FORMAT(5X,'TOTAL COOLING LOAD PROVIDED DURING THE 24 HRS =',E14.6,SIMU6810
     $1X,'BTU/DAY')                                                     SIMU6820
81    FORMAT(5X,'TOTAL HEATING LOAD PROVIDED DURING THE 24 HRS =',E14.6,SIMU6830
     $1X,'BTU/DAY')                                                     SIMU6840
90    FORMAT(5X,'TOTAL COOLING LOAD FROM BEGINING (OF MONTH) TO TODAY', SIMU6850
     $ '=',E14.6, 1X,'BTU')                                             SIMU6860
91    FORMAT(5X,'TOTAL HEATING LOAD FROM BEGINING (OF MONTH) TO TODAY', SIMU6870
     $ '=',E14.6, 1X,'BTU')                                             SIMU6880
100   FORMAT(  5X,'MONTH = ',I2,5X,'DAY = ',I3,/)                       SIMU6890
      IF(INIHX.GT.0)  GO TO 200                                         SIMU6900
      IFLAGH=0                                                          SIMU6910
      ERTOPC=0.0                                                        SIMU6920
      ERTOPH=0.0                                                        SIMU6930
      ERMIN=0.0                                                         SIMU6940
      ERMAX=0.0                                                         SIMU6950
      FLAREA=0.0                                                        SIMU6960
      THRANG=2.0                                                        SIMU6970
      I=4*MC-3                                                          SIMU6980
      IP3=I+3                                                           SIMU6990
      IJ=1                                                              SIMU7000
      DO  210 J=I,IP3                                                   SIMU7010
      G(IJ)=ZG(J)                                                       SIMU7020
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      P(IJ)=ZP(J)                                                       SIMU7030
      IJ=IJ+1                                                           SIMU7040
210   CONTINUE                                                          SIMU7050
      SUMP=P(1)+P(2)+P(3)+P(4)                                          SIMU7060
      IF(INIT.GT.0)   GO TO 205                                         SIMU7070
      DO  215  I=1,24                                                   SIMU7080
      QTOT(I)=QTOTAL(I)                                                 SIMU7090
      ER(I)=QTOTAL(I)                                                   SIMU7100
215   CONTINUE                                                          SIMU7110
205   CONTINUE                                                          SIMU7120
      THSETD=TROOM                                                      SIMU7130
      THSETN=TROOM                                                      SIMU7140
      THTIMN=OFCT                                                       SIMU7150
      THTIMD=OFST-1.0                                                   SIMU7160
      READ(IIN,NAMS)                                                    SIMU7170
      IF(INWRIT.GE.1)  WRITE(6,NAMS)                                    SIMU7180
      IF(ERMAX.LT.0.0)   IFLAGH=1                                       SIMU7190
      ID=THTIMD                                                         SIMU7200
      IN=THTIMN                                                         SIMU7210
      G(1)=( G(1)*FLAREA)+(((XKT*XLF)+(CFMD*1.08))*SUMP)                SIMU7220
      G(2)=  G(2)*FLAREA                                                SIMU7230
      G(3)=  G(3)*FLAREA                                                SIMU7240
      G(4)=  G(4)*FLAREA                                                SIMU7250
      SUMG=G(1)+G(2)+G(3)+G(4)                                          SIMU7260
      DO  220  I=1,24                                                   SIMU7270
      T(I)=THSETN                                                       SIMU7280
      IF(I.GE.ID.AND.I.LT.IN)  T(I)=THSETD                              SIMU7290
      T(I+24)=T(I)                                                      SIMU7300
220   CONTINUE                                                          SIMU7310
      ED=ERMAX-ERMIN                                                    SIMU7320
      S=ED/THRANG                                                       SIMU7330
      S=ABS(S)                                                          SIMU7340
      WN=(ED/2.0)-S*THSETN                                              SIMU7350
      WD=(ED/2.0)-S*THSETD                                              SIMU7360
      DUM = 1./(S+G(1))                                                 SIMU7370
      GT1=G(1)*DUM                                                      SIMU7380
      ST1=S*DUM                                                         SIMU7390
230   CONTINUE                                                          SIMU7400
      DO  300  I=1,24                                                   SIMU7410
      QTOT(I+24)=QTOTAL(I)                                              SIMU7420
300   CONTINUE                                                          SIMU7430
      KOUNT=1                                                           SIMU7440
      II=25                                                             SIMU7450
      IL=ID-1+24                                                        SIMU7460
340   WT=WN                                                             SIMU7470
330   DO  310 K=II,IL                                                   SIMU7480
      XIT=0.0                                                           SIMU7490
      DO  320  J=2,4                                                    SIMU7500
      JJ = K+1-J                                                        SIMU7510
      XIT=XIT-G(J)*T(JJ)+P(J)*QTOT(JJ)-P(J)*ER(JJ)                      SIMU7520
320   CONTINUE                                                          SIMU7530
      KJ=K-24                                                           SIMU7540
      XI(KJ) = XIT+TROOM*SUMG+P(1)*QTOT(K)                              SIMU7550
      ER(K)=(GT1*WT)+(ST1*XI(KJ))                                       SIMU7560
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      IF(IFLAGH.EQ.1)  GO TO 325                                        SIMU7570
      IF(ER(K).LT.ERMIN)  ER(K)=ERMIN                                   SIMU7580
      IF(ER(K).GT.ERMAX)  ER(K)=ERMAX                                   SIMU7590
      GO TO 315                                                         SIMU7600
  325 IF(ER(K).GT.ERMIN)  ER(K)=ERMIN                                   SIMU7610
      IF(ER(K).LT.ERMAX)  ER(K)=ERMAX                                   SIMU7620
  315 T(K)=(XI(KJ)-ER(K))/G(1)                                          SIMU7630
  310 CONTINUE                                                          SIMU7640
      KOUNT=KOUNT+1                                                     SIMU7650
      II=IL+1                                                           SIMU7660
      IL=IN+24                                                          SIMU7670
      WT=.0                                                             SIMU7680
      IF(KOUNT.EQ.2) GO TO 330                                          SIMU7690
      IL=48                                                             SIMU7700
      IF(KOUNT.EQ.3) GO TO 340                                          SIMU7710
      ERTOTC=0.0                                                        SIMU7720
      ERTOTH=0.0                                                        SIMU7730
      DO 350 I=1,24                                                     SIMU7740
      IP24=I+24                                                         SIMU7750
      QTOT(I)=QTOT(IP24)                                                SIMU7760
      ER(I)=ER(IP24)                                                    SIMU7770
      T(I)=T(IP24)                                                      SIMU7780
  350 CONTINUE                                                          SIMU7790
      IF(NPRT.EQ.0)  GO TO 360                                          SIMU7800
      IF(IFLAGH.EQ.1)  GO TO 370                                        SIMU7810
      WRITE(IOT,25)                                                     SIMU7820
      WRITE(IOT,20)                                                     SIMU7830
      WRITE(IOT,35)                                                     SIMU7840
      WRITE(IOT,30)                                                     SIMU7850
      WRITE(IOT,100)   MONTH,IDAYM                                      SIMU7860
      WRITE(IOT,50) THSETD,THTIMD,THSETN,THTIMN                         SIMU7870
      WRITE(IOT,10)                                                     SIMU7880
      WRITE(6,40)  ((   I ,T(I),I=N,24,3),N=1,3)                        SIMU7890
      WRITE(6,20)                                                       SIMU7900
      WRITE(IOT,60) ERMIN,ERMAX                                         SIMU7910
      WRITE(6,10)                                                       SIMU7920
      WRITE(IOT,70)  ((I ,ER(I),I=N,24,3),N=1,3)                        SIMU7930
      WRITE(6,20)                                                       SIMU7940
  380 CONTINUE                                                          SIMU7950
      DO 365 I=1,24                                                     SIMU7960
      ENER(I)=ER(I)                                                     SIMU7970
      ERTOTC=ERTOTC+ER(I)                                               SIMU7980
  365 CONTINUE                                                          SIMU7990
      ERTOPC=ERTOPC+ERTOTC                                              SIMU8000
      WRITE(IOT,80)  ERTOTC                                             SIMU8010
      WRITE(6,20)                                                       SIMU8020
      WRITE(IOT,90)    ERTOPC                                           SIMU8030
      WRITE(IOT,20)                                                     SIMU8040
      RETURN                                                            SIMU8050
  370 ERMAXH=-ERMAX                                                     SIMU8060
      ERMINH=ABS(ERMIN)                                                 SIMU8070
      WRITE(IOT,25)                                                     SIMU8080
      WRITE(IOT,20)                                                     SIMU8090
      WRITE(IOT,36)                                                     SIMU8100
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      WRITE(IOT,30)                                                     SIMU8110
      WRITE(IOT,100)   MONTH,IDAYM                                      SIMU8120
      WRITE(IOT,50) THSETD,THTIMD,THSETN,THTIMN                         SIMU8130
      WRITE(IOT,10)                                                     SIMU8140
      WRITE(6,40)  ((   I ,T(I),I=N,24,3),N=1,3)                        SIMU8150
      WRITE(6, 20)                                                      SIMU8160
      WRITE(IOT,61) ERMINH,ERMAXH                                       SIMU8170
      WRITE(6, 10)                                                      SIMU8180
      DO 376 I=1,24                                                     SIMU8190
      XI(I)=-ER(I)                                                      SIMU8200
  376 CONTINUE                                                          SIMU8210
      WRITE(IOT,70)  ((I ,XI(I),I=N,24,3),N=1,3)                        SIMU8220
      WRITE(6, 20)                                                      SIMU8230
  390 CONTINUE                                                          SIMU8240
      DO 375 I=1,24                                                     SIMU8250
      XI(I)=-ER(I)                                                      SIMU8260
      ENER(I)=XI(I)                                                     SIMU8270
      ERTOTH=ERTOTH+XI(I)                                               SIMU8280
  375 CONTINUE                                                          SIMU8290
      ERTOPH=ERTOPH+ERTOTH                                              SIMU8300
      WRITE(IOT,81)  ERTOTH                                             SIMU8310
      WRITE(6, 20)                                                      SIMU8320
      WRITE(IOT,91)    ERTOPH                                           SIMU8330
      WRITE(IOT,20)                                                     SIMU8340
      RETURN                                                            SIMU8350
  360 WRITE(IOT,100)   MONTH,IDAYM                                      SIMU8360
      IF(IFLAGH.EQ.1)  GO TO 390                                        SIMU8370
      GO TO 380                                                         SIMU8380
      END                                                               SIMU8390
      FUNCTION PSL(T)                                                   SIMU8400
      TK = (T-32.0)/1.8+273.16                                          SIMU8410
      X = 647.27-TK                                                     SIMU8420
      Y=X*(3.2438+(5.8683E-03+1.17024E-08*X*X)*X)/(TK*(1.0+2.18785E-03*XSIMU8430
     1))                                                                SIMU8440
      PSL = 14.696*218.167/(10.0**Y)                                    SIMU8450
      RETURN                                                            SIMU8460
      END                                                               SIMU8470
```

```
C                                                                       PSYC0010
C                                                                       PSYC0020
C                                                                       PSYC0030
C     THIS PROG AM UTILIZES THE TMY WEATHER TAPES TO PERFORM           PSYC0040
C     THE NECES ARY CALCULATIONS IN DETERMINING THE VARIOUS TERMS      PSYC0050
C     USED IN E UATIONS (7.18) AND (7.19) FOR CALCULATING              PSYC0060
C     THE HEATI G AND COOLING UNITS (HU AND CU)                        PSYC0070
C     THIS PROG AM PERFORMS AN ACCUMULATIVE SUM OF THE HEATING         PSYC0080
C     AND COOLI G UNITS OVER EACH MONTH AND PRINTS OUT THE             PSYC0090
C     RESULTS F R EACH MONTH OF THE YEAR                               PSYC0100
C                                                                       PSYC0110
C                                                                       PSYC0120
C                                                                       PSYC0130
      DIMENSION NOM .3)                                                 PSYC0140
      DATA NOM/ ,31,59,90,120,151,181,212,243,273,304,334,365/          PSYC0150
      READ(5,1) BASE,PB,WI                                              PSYC0160
1     FORMAT(3F 0.5)                                                    PSYC0170
      READ(5,2) 7,C8,C9,C10,C11,C12,C13,C14,C15                         PSYC0180
      READ(5,2) 7,H8,H9,H10,H11,H12,H13,H14,H15                         PSYC0190
2     FORMAT(5F 6.8)                                                    PSYC0200
      DO 1000 K 1,12                                                    PSYC0210
      SCU=0.0                                                           PSYC0220
      SHU=0.0                                                           PSYC0230
      L=NOM(K)+                                                         PSYC0240
      M=NOM(K+1                                                         PSYC0250
      DO 500 J= ,M                                                      PSYC0260
      STDB=0.0                                                          PSYC0270
      SQ=0.0                                                            PSYC0280
      SDW=0.0                                                           PSYC0290
      TDBMAX=-1 0.0                                                     PSYC0300
      TDBMIN=10 .0                                                      PSYC0310
      QMAX=0.0                                                          PSYC0320
      WMAX=-1.0                                                         PSYC0330
      DO 250 I= ,24                                                     PSYC0340
      READ(7,10 )Q1,Q2,TDB,TWB                                          PSYC0350
101   FORMAT(T5 ,F4.0,T55,F4.0,T104,2F4.1)                              PSYC0360
      TDB=1.8*T B+32.0                                                  PSYC0370
      TWB=1.8*T B+32.0                                                  PSYC0380
      IF(Q1.NE. 999.0)GO TO 20                                          PSYC0390
      IF(Q2.NE. 999.0)GO TO 10                                          PSYC0400
      Q=0.0                                                             PSYC0410
      GO TO 30                                                          PSYC0420
10    Q=Q2                                                              PSYC0430
      Q=0.088*Q                                                         PSYC0440
      GO TO 30                                                          PSYC0450
20    Q=Q1                                                              PSYC0460
      Q=0.088*Q                                                         PSYC0470
30    CONTINUE                                                          PSYC0480
      CALL PSY1 (TDB,TWB,PB,DP,PV,W,H,V,RH)                             PSYC0490
      STDB=STDB TDB                                                     PSYC0500
      SQ=SQ+Q                                                           PSYC0510
      DW=W-WI                                                           PSYC0520
      SDW=SDW+DW                                                        PSYC0530
      TDBMAX=AM X1(TDBMAX,TDB)                                          PSYC0540
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      TDBMIN=AM N1(TDBMIN,TDB)                                          PSYC0550
      QMAX=AMAX (QMAX,Q)                                                PSYC0560
      WMAX=AMAX (WMAX,W)                                                PSYC0570
250   CONTINUE                                                          PSYC0580
      ATDB=STDB 24.0                                                    PSYC0590
      AQ=SQ/24.                                                         PSYC0600
      ADW=SDW/2 .0                                                      PSYC0610
      DT=TDBMAX TDBMIN                                                  PSYC0620
      X1=(ATDB/ DBMAX)                                                  PSYC0630
      X2=DT/TDB AX                                                      PSYC0640
      X3=AQ/QMA                                                         PSYC0650
      X4=ADW/WM X                                                       PSYC0660
      X5=TBASE/ DBMAX                                                   PSYC0670
      HU=H7*X1* H8+H9*X2**H10+H11*X3**H12+H13*X4+H14*X5**H15            PSYC0680
      CU=C7*X1* C8+C9*X2**C10+C11*X3**C12+C13*X4+C14*X5**C15            PSYC0690
      IF(CU.LT. .0)CU=0.0                                               PSYC0700
      IF(HU.LT. .0)HU=0.0                                               PSYC0710
      SCU=SCU+C                                                         PSYC0720
      SHU=SHU+H                                                         PSYC0730
500   CONTINUE                                                          PSYC0740
      WRITE(6,1 )K,SCU,SHU                                              PSYC0750
11    FORMAT(1H ,I3,2F15.4)                                             PSYC0760
1000  CONTINUE                                                          PSYC0770
      STOP                                                              PSYC0780
      END                                                               PSYC0790
C                                                                       PSYC0800
C                                                                       PSYC0810
C                                                                       PSYC0820
C     THIS SUBR UTINE CALCULATES VAPOR PRESSURE(PV),HUMIDITY RATIO(W),  PSYC0830
C     ENTHALPY( ),SPECIFIC VOLUME(V),RELATIVE HUMIDITY(RH),             PSYC0840
C     AND DEW P INT TEMPERATURE(DP) WHEN THE DRY BULB TEMPERATURE(DB),  PSYC0850
C     WET BULB EMPERATURE (WB) AND BAROMETRIC PRESSURE(PB)              PSYC0860
C     ARE GIVEN                                                         PSYC0870
C                                                                       PSYC0880
C                                                                       PSYC0890
C                                                                       PSYC0900
      SUBROUTIN  PSY1 (DB,WB,PB,DP,PV,W,H,V,RH)                         PSYC0910
      PVP=PVSF( B)                                                      PSYC0920
      IF(DB-WB) 0,30,10                                                 PSYC0930
10    WSTAR=0.6 2*PVP/(PB-PVP)                                          PSYC0940
      IF(WB-32. 20,20,40                                                PSYC0950
20    PV=PVP-5. 04E-4*PB*(DB-WB)/1.8                                    PSYC0960
      GO TO 50                                                          PSYC0970
30    PV=PVP                                                            PSYC0980
      GO TO 50                                                          PSYC0990
40    CDB=(DB-3 .)/1.8                                                  PSYC1000
      CWB=(WB-3 .)/1.8                                                  PSYC1010
      HL=597.31 .4409*CDB-CWB                                           PSYC1020
      CH=0.2402 0.4409*WSTAR                                            PSYC1030
      EX=(WSTAR C4*(CDB-CWB) /HL) /0.622                                PSYC1040
      PV=PB*(EX/ 1.+EX)                                                 PSYC1050
50    W=0.622*P /(PB-PV)                                                PSYC1060
      V=0.754*( B+459.7)*(1.+7000.*W/4360.)/PB                          PSYC1070
      H=0.24*DB (1061.+0.444*DB)*W                                      PSYC1080
```

```
        IF(PV.LE. .0)GO TO 70                                           PSYC1090
        IF(DB.NE. B)GO TO 60                                            PSYC1100
        DP=DB                                                           PSYC1110
        RH=1.                                                           PSYC1120
        GO TO 70                                                        PSYC1130
 60     CONTINUE                                                        PSYC1140
        DP=DPF(PV                                                       PSYC1150
        RH=PV/PVS (DB)                                                  PSYC1160
 70     RETURN                                                          PSYC1170
        END                                                             PSYC1180
        FUNCTION  VSF (X)                                               PSYC1190
        DIMENSION A(6),B(4),P(4)                                        PSYC1200
        DATA A,B/ 7.90298,5.02808,-1.3816E-07,11.344,8.1328E-03,-3.49149, PSYC1210
       1-9.09718, 3.56654,0.876793,0.0060273/                           PSYC1220
        T=(X+459. 68)/1.8                                               PSYC1230
        IF(T.LT.2 3.16)GO TO 10                                         PSYC1240
        Z=373.16/                                                       PSYC1250
        P(1)=A(1) (Z-1.)                                                PSYC1260
        P(2)=A(2) ALOG10(Z)                                             PSYC1270
        Z1=A(4)*( .-1./Z)                                               PSYC1280
        P(3)=A(3) (10**Z1-1.)                                           PSYC1290
        Z1=A(6)*( -1.)                                                  PSYC1300
        P(4)=A(5) (10**Z1-1.)                                           PSYC1310
        GO TO 20                                                        PSYC1320
 10     Z=273.16/                                                       PSYC1330
        P(1)=B(1) (Z-1.)                                                PSYC1340
        P(2)=B(2) ALOG10(Z)                                             PSYC1350
        P(3)=B(3) (1.-1./Z)                                             PSYC1360
        P(4)=ALOG 0(B(4))                                               PSYC1370
 20     SUM=0.0                                                         PSYC1380
        DO 30 I=1 4                                                     PSYC1390
 30     SUM=SUM+P I)                                                    PSYC1400
        PVSF=29.9 1*10**SUM                                             PSYC1410
        RETURN                                                          PSYC1420
        END                                                             PSYC1430
        FUNCTION  PF(PV)                                                PSYC1440
        Y=LOG(PV)'                                                      PSYC1450
        IF(PV.GT. .1836) GO TO 1                                        PSYC1460
        DPF=71.98 24.873*Y+0.8927*Y*Y                                   PSYC1470
        GO TO 2                                                         PSYC1480
 1      DPF=79.04 +30.579*Y+1.8893*Y*Y                                  PSYC1490
 2      RETURN                                                          PSYC1500
        END                                                             PSYC1510
```

```
      SUBROUTINE STEPT (FUNK)                                           STMARQ 1
C                                                                       STMARQ 2
C  INTERFACE TO MAKE MARQ LOOK LIKE STEPT.                              STMARQ 3
C                                                                       STMARQ 4
C  TO USE THIS ROUTINE, SET THE VALUE OF LPCOL AND THE DIMENSIONS OF    STMARQ 5
C  THE ARRAYS P, FITSV, FIT, Y, AND YSIG.  THE DIMENSIONS ARE....       STMARQ 6
C       P(LPCOL,NVMAX), FITSV(LPCOL), FIT(LPCOL), Y(LPCOL), YSIG(LPCOL) STMARQ 7
C  WHERE LPCOL IS THE MAXIMUM VALUE OF NPTS AND NVMAX IS THE MAXIMUM    STMARQ 8
C  VALUE OF NV.  (IF LEQU.EQ.1, YSIG MAY BE DIMENSIONED YSIG(1).)       STMARQ 9
C  COMMON/CDAT/ DOES NOT APPEAR IN ANY ROUTINE OF THE MARQ PACKAGE      STMARQ10
C  OTHER THAN THIS ONE, SO THAT THIS IS THE ONLY ONE WHICH MUST BE      STMARQ11
C  RECOMPILED WHEN LPCOL AND THE DIMENSIONS OF THE ARRAYS ARE CHANGED.  STMARQ12
C                                                                       STMARQ13
C  THE FOLLOWING EXTERNAL STATEMENT IS REQUIRED BY SOME COMPILERS       STMARQ14
C  (WATFIV, FOR EXAMPLE) AND FORBIDDEN BY OTHERS (MODCOMP II).          STMARQ15
      EXTERNAL FUNK                                                     STMARQ16
C                                                                       STMARQ17
      DOUBLE PRECISION FIT,FITSV                                        STMARQ18
C                                                                       STMARQ19
C     DIMENSION P(275,8),FITSV(275)                                     STMARQ20
      DIMENSION P(25,20),FITSV(25)                                      STMARQ21
C                                                                       STMARQ22
C     COMMON /CDAT/ FIT(275),Y(275),YSIG(275),NPTS                      STMARQ23
      COMMON /CDAT/ FIT(25),Y(25),YSIG(25),NPTS                         STMARQ24
C                                                                       STMARQ25
      LPCOL=1                                                           STMARQ26
      LPCOL=275                                                         STMARQ27
      LPCOL=25                                                          STMARQ28
C                                                                       STMARQ29
C                                                                       STMARQ30
      CALL MARQ (FUNK,Y,YSIG,NPTS,FIT,FITSV,P,LPCOL)                    STMARQ31
C                                                                       STMARQ32
      RETURN                                                            STMARQ33
      END                                                               STMARQ35
C                                                                       STMARQ36
      SUBROUTINE STSET                                                  STSETM 1
C                                                                       STSETM 2
C  STSET SETS SOME INPUT QUANTITIES TO DEFAULT VALUES, FOR MARQ.        STSETM 3
C                                                                       STSETM 4
C  NOTE..........                                                       STSETM 5
C  THIS VERSION OF STSET MAY ALSO BE USED WITH STEPIT, SIMPLEX,         STSETM 6
C  STP, KAUPE, AND MINF.                                                STSETM 7
C                                                                       STSETM 8
C  USAGE.....                                                           STSETM 9
C  CALL STSET.  THEN SET SOME INPUT QUANTITIES (NV AND NPTS, AT LEAST)  1000TM 9
C  AND RESET ANY OF THOSE SET IN STSET (BETTER VALUES OF X, ETC.)       2000TM 9
C  BEFORE CALLING MARQ OR THE STEPT-MARQ INTERFACE ROUTINE.             3000TM 9
C                                                                       STSETM13
      DOUBLE PRECISION X                                                STSETM14
C                                                                       STSETM15
      COMMON /CSTEP/ X(20),XMAX(20),XMIN(20),DELTX(20),DELMN(20),       STSETM16
     *     ERR(20,21),FOBJ,NV,NTRAC,MATRX,MASK(20),                     STSETM17
     *     NFMAX,NFLAT,JVARY,NXTRA,KFLAG,NOREP,KERFL,KW                 STSETM18
      COMMON /MLLS2/FLAMB,RELDF,METHD,KALCP,KORDF,MAXIT,LEQU,MXSUB,MXUPDSTSETM19
C                                                                       STSETM20
C                             KW ...  LOGICAL UNIT NUMBER OF THE PRINTER STSETM21
      KW=6                                                              STSETM22
      NVMAX=20                                                          STSETM23
C                             THE USER MUST SET NV AFTER CALLING STSET.  STSETM24
      NV=-1                                                             STSETM25
      NPTS=-1                                                           STSETM26
      HUGE=1.E30                                                        STSETM27
      RZERO=0.                                                          STSETM28
      NTRAC=0                                                           STSETM29
      NFMAX=32767                                                       STSETM30
      MAXIT=20                                                          STSETM31
      MXSUB=50                                                          STSETM32
      METHD=1                                                           STSETM33
      KALCP=0                                                           STSETM34
      KORDF=1                                                           STSETM35
      LEQU=0                                                            STSETM36
      NFLAT=1                                                           STSETM37
      MATRX=100                                                         STSETM38
      NXTRA=0                                                           STSETM39
      FLAMB=1.                                                          STSETM40
      RELDF=1.E-8                                                       STSETM41
C                                                                       STSETM42
      DO 10 JX=1,NVMAX                                                  STSETM43
        X(JX)=RZERO                                                     STSETM44
        XMAX(JX)=HUGE                                                   STSETM45
        XMIN(JX)=-HUGE                                                  STSETM46
        DELTX(JX)=RZERO                                                 STSETM47
        DELMN(JX)=RZERO                                                 STSETM48
        MASK(JX)=0                                                      STSETM49
 10   CONTINUE                                                          STSETM50
C                                                                       STSETM51
      RETURN                                                            STSETM52
      END                                                               STSETM54
C                                                                       STSETM55
      SUBROUTINE FOFX (JPT,NV,X,F)                                      FOFXDUM1
C                                                                       FOFXDUM2
C  THIS IS A DUMMY VERSION OF SUBROUTINE FOFX.                          FOFXDUM3
C  A NON-DUMMY VERSION OF FOFX MAY BE USED (OPTIONALLY) TO SUPPLY       FOFXDUM4
C  TO MARQ VALUES OF THE FUNCTION BEING FITTED, INSTEAD OF USING A      FOFXDUM5
C  -FUNK- SUBROUTINE TO DO THIS.  THE USE OF FOFX REQUIRES              FOFXDUM6
C  SUBSTANTIALLY MORE OVERHEAD TIME DURING EXECUTION, BUT SAVES         FOFXDUM7
C  CONSIDERABLE STORAGE BY NOT REQUIRING THAT THE JACOBIAN MATRIX, P,   FOFXDUM8
C  BE STORED.  THE MINI-MARQ PACKAGE REQUIRES THE USE OF FOFX.          FOFXDUM9
C  TO SEE HOW TO USE A NON-DUMMY FOFX, SEE THE LISTING OF MARQ.         FOFXDU10
C                                                                       FOFXDU11
      DOUBLE PRECISION X,F                                              1000DU11
      DIMENSION X(20)                                                   2000DU11
      RETURN                                                            FOFXDU12
      END                                                               FOFXDU13
C                                                                       FOFXDU14
      SUBROUTINE CALCD (JPT,P,LPCOL)                                    CALCDUM1
C                                                                       CALCDUM2
C  THIS IS A DUMMY VERSION OF SUBROUTINE CALCD.                         CALCDUM3
C  A NON-DUMMY VERSION OF CALCD MAY BE USED (OPTIONALLY) TO SUPPLY      CALCDUM4
C  TO MARQ OR MINI-MARQ ANALYTIC VALUES OF THE ELEMENTS OF THE          CALCDUM5
C  JACOBIAN MATRIX, INSTEAD OF CALCULATING THEM USING FINITE            CALCDUM6
C  DIFFERENCES.  MOST USERS USE FINITE DIFFERENCES MOST OF THE TIME.    CALCDUM7
C  TO SEE HOW TO USE A NON-DUMMY CALCD, SEE THE LISTING OF MARQ.        CALCDUM8
C                                                                       CALCDUM9
      DIMENSION P(LPCOL,1)                                              1000DUM9
      RETURN                                                            CALCDU10
      END                                                               CALCDU11
C                                                                       CALCDU12
      SUBROUTINE MARQ (FUNK,Y,YSIG,NPTS,FIT,FITSV,P,LPCOL)              MARQ   1
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C
C  MARQ 2.5       A.N.S.I. STANDARD FORTRAN          AUGUST 1976
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C
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C              DEPARTMENT OF COMPUTING AND INFORMATION SCIENCES
C              OKLAHOMA STATE UNIVERSITY, STILLWATER, OKLAHOMA 74074
C
C  MARQ PERFORMS A NONLINEAR LEAST SQUARES FIT OF A USER-SUPPLIED
C  FUNCTION TO A GIVEN SET OF DATA, USING MARQUARDT-S METHOD, OR THE
C  GAUSS-NEWTON METHOD, OR A MODIFIED GAUSS-NEWTON METHOD.
C  D. W. MARQUARDT, J.SOC.IND.APPL.MATH. 11 (1963) 431-441
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C  INPUT QUANTITIES.....  FUNK,X(*),XMIN(*),MASK(*),DELMN(*),MATRX,
C                              Y(*),YSIG(*),NV,NPTS,LPCOL,FLAMB,NFMAX,
C                              NTRAC,KALCP,KORDF,METHD,NFLAT,RELDF,
C                              MAXIT,LEQU,KW
C  OUTPUT QUANTITIES....  X(*),FOBJ,ERR(*,*),KFLAG,FIT(*)
C  UNUSED QUANTITIES (INCLUDED FOR COMPATIBILITY WITH STEPIT COMMON)....
C                         DELTA(*),JVARY,MATRA,NOREP,KERFL
C
C     FUNK        --  THE NAME OF THE FUNCTION CALLED TO OBTAIN
C                         THE FITTED VALUES IF KALCP=0
C     NV          --  THE NUMBER OF PARAMETERS
C     X(JX)       --  THE JX-TH PARAMETER
C     FOBJ        --  RETURNS THE FINAL VALUE OF PHI, THE WEIGHTED
C                         SUM OF SQUARES (PHI IS BEING MINIMIZED AS A
C                         FUNCTION OF THE X(JX))
C     XMAX(JX)    --  THE UPPER LIMIT FOR X(JX)
C     XMIN(JX)    --  THE LOWER LIMIT FOR X(JX)
C     MASK(JX)    --  NONZERO IF X(JX) IS TO BE HELD FIXED
C     DELMN(JX)   --  THE CONVERGENCE TOLERANCE FOR X(JX)
C     NTRAC       --  USER PRINT CONTROL
C                         =-3, NO OUTPUT EXCEPT FATAL ERROR MESSAGES
C                         =-2, NO OUTPUT EXCEPT DIAGNOSTIC MESSAGES
C                         =-1, STANDARD OUTPUT EXCEPT FINAL FIT VALUES
C                         = 0, STANDARD OUTPUT
C                         = 1, ALSO PRINTS RESULTS OF EACH ITERATION
C                         = 2, ALSO PRINTS THE COEFFICIENT MATRIX, QSAV
C                         = 3, ALSO PRINTS THE JACOBIAN MATRIX, P
C     NFMAX       --  THE MAXIMUM NUMBER OF FUNCTION COMPUTATIONS
C     NFLAT       --  NONZERO IF THE SEARCH IS TO TERMINATE WHEN TWO
C                         ITERATIONS GIVE IDENTICAL VALUES OF PHI
C     KW          --  THE LOGICAL UNIT NUMBER OF THE PRINTER
C     ERR(JX,KX)  --  RETURNS THE ERROR MATRIX
C     KFLAG       --  RETURNED .GT. ZERO FOR A NORMAL EXIT,
C                         RETURNED .LT. ZERO FOR AN ABNORMAL EXIT
C
C     NPTS        --  THE NUMBER OF DATA OBSERVATIONS
C     Y(JPT)      --  THE JPT-TH DATA ORDINATE
C     YSIG(JPT)   --  THE EXPECTED ERROR IN Y(JPT)
C     FIT(JPT)    --  THE JPT-TH FITTED VALUE
C     FITSV       --  A SCRATCH VECTOR OF NPTS VALUES
C     P(JPT,JX)   --  THE FIRST PARTIAL DERIVATIVE
C                         OF FIT(JPT) WITH RESPECT TO X(JX)
C     LPCOL       --  THE FIRST DIMENSION OF THE ARRAY CONTAINING P
C                       (LPCOL MUST BE .GE. NPTS IF KALCP IS .GE. ZERO)
C     LEQU        --  SAVES STORAGE IF ALL YSIG(JPT) ARE THE SAME
C                         =1 IF ALL YSIG(JPT) ARE EQUAL (IN THIS CASE
C                              ONLY YSIG(1) IS REFERENCED)
C                         =0 OTHERWISE
C     FLAMB       --  MARQUARDT-S LAMBDA, THE RELATIVE AMOUNT BY WHICH
C                         THE DIAGONAL COEFFICIENTS OF THE NORMAL
C                         EQUATIONS ARE AUGMENTED
C     MXSUB       --  THE MAXIMUM NUMBER OF SUBITERATIONS PERMITTED
C     KALCP       --  DETERMINES WHICH ROUTINE IS CALLED TO COMPUTE THE
C                         JACOBIAN MATRIX OF FIRST PARTIAL DERIVATIVES
C                         =-1, ONE ROW OF P RETURNED BY DERIV OR CALCO,
C                                DERIV CALLS FOFX
C                         = 0, ALL OF P RETURNED BY DERIV OR CALCO,
C                                DERIV CALLS FUNK
C                         = 1, ALL OF P RETURNED BY DERIV OR CALCO,
C                                DERIV CALLS FOFX
C     KORDF       --  DETERMINES HOW P IS TO BE CALCULATED
C                         = 1, FIRST ORDER APPROXIMATION USED BY DERIV
C                         = 2, SECOND ORDER APPROXIMATION USED BY DERIV
C                         = 3, ANALYTICAL DERIVATIVE SUPPLIED BY CALCO
C     METHD       --  DETERMINES THE METHOD USED
C                         =-1, MODIFIED GAUSS-NEWTON METHOD
C                         = 0, GAUSS-NEWTON METHOD
C                         = 1, MODIFIED FORM OF MARQUARDT-S METHOD
C                         = 2, MARQUARDT-S METHOD
C     RELDF       --  DETERMINES THE MAGNITUDE OF THE DIFFERENCING STEP
C     MAXIT       --  THE MAXIMUM NUMBER OF ITERATIONS TO BE PERFORMED
C
C  MODIFICATIONS TO MARQUARDT-S METHOD...
C    1.  THE QUANTITY (1+LAMBDA) IS NOT ALLOWED TO INCREASE BY MORE
C        THAN A FACTOR OF TWO, IN ANY SINGLE INCREASE.
C    2.  WHEN CUTSTEPS ARE USED IN A LINE SEARCH (WHEN THE ANGLE
C        GAMMA .LT. GAMMA SUB ZERO), THE VALUE OF LAMBDA IS INCREASED
C        PROPORTIONATELY.
C  IN BOTH THE MODIFIED MARQUARDT-S METHOD AND THE MODIFIED
C  GAUSS-NEWTON METHOD, A HALF STEP IS ATTEMPTED FOLLOWING EACH
C  SUCCESSFUL STEP.  THIS AVOIDS ONE FORM OF VERY SLOW CONVERGENCE.
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C  THE FOLLOWING EXTERNAL STATEMENT IS REQUIRED BY SOME COMPILERS
C  (WATFIV, FOR EXAMPLE) AND FORBIDDEN BY OTHERS (MODCOMP II).
      EXTERNAL FUNK
C
C  ON A MACHINE HAVING LESS THAN ABOUT TEN SIGNIFICANT DIGITS IN
C  SINGLE PRECISION (FOR EXAMPLE THE IBM 360 OR 370), IF P IS
C  COMPUTED USING FINITE DIFFERENCES (KORDF.LT.3), THIS PART OF THE
C  COMPUTATION SHOULD BE DONE IN DOUBLE PRECISION.  TO ACCOMPLISH
C  THIS, ACTIVATE THE DOUBLE PRECISION STATEMENT IN EACH SUBROUTINE.
C  ORDINARILY THE OTHER COMPUTATIONS MAY BE DONE IN SINGLE PRECISION.
C
      DOUBLE PRECISION X,XSAVE,XTEMP,GRAD,FIT,FITSV,
     *                 XSAV,SIG,RTERM,YY,PHI,PHNEW,PHALF,XLIM,STFAC
C
C  THE DIMENSIONS OF THE VECTORS AND MATRICES (AS OPPOSED TO ARRAYS)
C  ARE....
C        P(NPTS,NACTV) (OR P(1,NACTV) IF KALCP.EQ.-1),
C        FITSV(NPTS) (OR FITSV(1) IF KALCP.EQ.-1),
C        X(NV),XMAX(NV),XMIN(NV),DELMN(NV),ERR(NV,NV+1),
C        XSAVE(NV),H(NV),MASKT(NV),
C        GRAD(NACTV),SCALE(NACTV),
```

```
C         Y(NPTS),FIT(NPTS),YSIG(NPTS) (OR YSIG(1) IF LEQU.NE.0).
C   WHERE NACTV IS THE NUMBER OF ACTIVE (UNMASKED) X(J).
C
      DIMENSION P(LPCOL,1)
      DIMENSION Y(1),YSIG(1),FIT(1),FITSV(1)
      DIMENSION XSAVE(20),H(20),GRAD(20),SCALE(20),MASKT(20),STEPP(20)
C
C   USER COMMON.....
      COMMON /CSTEP/ X(20),XMAX(20),XMIN(20),DELTX(20),DELMN(20),
     *     ERR(20,21),FOBJ,NV,NTRAC,MATRX,MASK(20),
     *     NFMAX,NFLAT,JVARY,NXTRA,KFLAG,NOREP,KERFL,KW
C
C   MARQ COMMON.....
      COMMON /NLLS2/FLAMB,RELDF,METHD,KALCP,KORDF,MAXIT,LEQU,MXSUB,MXUPD
C
C   SET THE LIBRARY FUNCTION FOR SINGLE PRECISION (SQRT) OR FOR
C   DOUBLE PRECISION (DSQRT).  NO OTHER FUNCTIONS ARE USED, EITHER
C   EXTERNAL OR INTRINSIC.
C   THE ONLY SUBROUTINES CALLED ARE FUNC, DERIV, CALCO, AND PUERR.
C
      DSQRT(ARG)=SQRT(ARG)
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C   SET FIXED QUANTITIES ....
C
C                                HUGE ...  A VERY LARGE REAL NUMBER
C                                     (DEFAULT VALUE FOR XMAX AND -XMIN)
      HUGE=1.E37
C
C   NVMAX IS THE MAXIMUM PERMISSIBLE VALUE OF NV.  IT IS ALSO THE
C   DIMENSION OF THE ARRAYS X, XMAX, XMIN, MASK, DELMN,
C   XSAVE, H, MASKT, GRAD, AND SCALE, AND THE FIRST DIMENSION OF ERR.
C   THE SECOND DIMENSION OF ERR IS NVMAX+1.
C
      NVMAX=20
C                                FNU ...  MARQUARDT-S NU, THE FACTOR BY
C                                              WHICH FLAMB IS CHANGED
      FNU=10.
C                                CRIT ...  COSINE OF MARQUARDT-S CRITICAL
C                                              ANGLE, GAMMA SUB ZERO
      CRIT=.70711
C                                FLDEF ...  DEFAULT VALUE FOR FLAMB
      FLDEF=1.
C                                RELMN ...  USED TO SET DEFAULT VALUE OF
C                                              DELMN
      RELMN=1.E-5
C                                RLTOL ...  TOLERANCE FOR A WARNING MESSAGE
      RLTOL=1.E-5
C
      RZERO=0.
      RUNIT=1.
      RTWO=2.
C
C   NO REAL CONSTANTS ARE USED BEYOND THIS POINT.
C
      NTRPT=NTRAC-(-2)
      NTRPU=NTRAC-(-1)
      NTRMU=NTRAC-1
      KFLAG=0
      NCREP=0
      ITER=0
      PHI=HUGE
C
      IF(NTRPU)1020,1000,1000
 1000 WRITE(KW,1010)
 1010 FORMAT(49H1MARQ....  BEGIN NONLINEAR LEAST SQUARES SOLUTION)
 1020 NACTV=0
      IF(NV)1070,1070,1030
 1030 IF(NV-NVMAX)1040,1040,1070
 1040 IF(NPTS)1070,1070,1050
 1050 IF(KALCP)1080,1060,1060
 1060 IF(NPTS-LPCOL)1080,1080,1070
 1070 KFLAG=-1
      GO TO 1210
C
C   CHECK SOME INPUT QUANTITIES, AND SET THEM TO DEFAULT VALUES IF
C   DESIRED.
C                                NACTV ...  NUMBER OF ACTIVE X(J)
 1080 DO 1190 JX=1,NV
        DELN=DELMN(JX)
        IF(MASK(JX))1190,1090,1190
 1090   NACTV=NACTV+1
        IF(DELN)1120,1100,1130
 1100   DELN=RELMN*X(JX)
        IF(DELN)1120,1110,1130
 1110   DELN=RELMN
        GO TO 1130
 1120   DELN=-DELN
 1130   IF(XMAX(JX)-XMIN(JX))1140,1140,1150
 1140   XMAX(JX)=HUGE
        XMIN(JX)=-HUGE
C
C  SET X(JX) TO AMAX1(XMIN(JX),AMIN1(XMAX(JX),X(JX))).
C
 1150   IF(X(JX)-XMAX(JX))1170,1170,1160
 1160   X(JX)=XMAX(JX)
 1170   IF(X(JX)-XMIN(JX))1180,1190,1190
 1180   X(JX)=XMIN(JX)
 1190   DELMN(JX)=DELN
C
      IF(NACTV)1200,1200,1230
 1200 KFLAG=-2
 1210 CONTINUE
      WRITE(KW,1220)NV,NVMAX,NACTV,NPTS,LPCOL,KALCP
 1220 FORMAT(//29H ILLEGAL INPUT VALUE IN MARQ.,4X,5H NV =,I3,4X,
     *     8H NVMAX =,I3,4X,8H NACTV =,I3/10X,7H NPTS =,I5,4X,
     *     8H LPCOL =,I5,4X,8H KALCP =,I3)
      GO TO 3690
 1230 CONTINUE
      IF(NTRPU)1310,1240,1240
 1240 WRITE(KW,1250)(MASK(J),J=1,NV)
 1250 FORMAT(/10H MASK    = ,I7,7I13/(4X,8I13))
      WRITE(KW,1260)(X(J),J=1,NV)
 1260 FORMAT(/10H X       = ,8E13.5/(10X,8E13.5))
      WRITE(KW,1270)(XMAX(J),J=1,NV)
 1270 FORMAT(/10H XMAX    = ,8E13.5/(10X,8E13.5))
      WRITE(KW,1280)(XMIN(J),J=1,NV)
 1280 FORMAT(/10H XMIN    = ,8E13.5/(10X,8E13.5))
      WRITE(KW,1290)(DELMN(J),J=1,NV)
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```
 1290 FORMAT(/10H DELTA  = ,8E13.5/(10X,8E13.5))
      WRITE(KW,1300)NV,NPTS,LPCOL,NTRAC,METHD,KALCP,KORDF,NFLAT,
     *     NFMAX,MAXIT,MXSUB,CRIT
 1300 FORMAT(//6H NV = ,I4,5X,8H NPTS = ,I6,5X,9H LPCOL = ,I6,
     *      5X,9H NTRAC = ,I2,5X,9H METHD = ,I2,5X,9H KALCP = ,I2,
     *      5X,9H KORDF = ,I2//9H NFLAT = ,I2,5X,9H NFMAX = ,I7,
     *      5X,9H MAXIT = ,I5,5X,9H MXSUB = ,I5,5X,
     *      28H COSINE OF CRITICAL ANGLE = ,E12.5)
 1310 JMARY=0
C
C  SET FNGN, FLUPB, AND, IF NECESSARY, FLAMB.
C
      FNGN=RUNIT
      FLUPB=RTWO
      IF(METHD)1320,1320,1330
 1320 FLAMB=RZERO
      GO TO 1390
 1330 IF(FLAMB)1340,1340,1350
 1340 FLAMB=FLOEF
 1350 IF(METHD-2)1390,1380,1390
 1380 FLUPB=RUNIT
C
C  COMPUTE THE INITIAL GOODNESS OF FIT OF THE MODEL TO THE DATA.
C  CALL FUNC TO CALCULATE THE VECTOR OF FITTED VALUES.
C
 1390 CALL FUNC (FUNK,Y,YSIG,NPTS,FIT,PHI)
C
C                             NF ...  EQUIVALENT NUMBER OF CALLS TO FUNC
      NF=1
      IF(NTRPU)1420,1400,1400
 1400 WRITE(KW,1410)PHI,FLAMB
 1410 FORMAT(//28H PHI (THE SUM OF SQUARES) = ,E15.8,56X,9H LAMBDA =,
     *     E12.5//1H )
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C  BEGIN THE NEXT ITERATION.
C  THIS IS THE ENTRY POINT AFTER A SUCCESSFUL STEP IF THE CONVERGENCE
C  CRITERION IS NOT MET.
C
 1420 JSUB=0
      ITER=ITER+1
      IF(NTRMU)1425,1421,1421
 1421 WRITE(KW,1422)ITER,FNGN,FLAMB
 1422 FORMAT(//17H BEGIN ITERATION ,I4,44X,7H FNGN =,E12.5,15X,
     X     9H LAMBDA =,E12.5)
 1425 IF(NTRAC-3)1450,1430,1430
 1430 WRITE(KW,1440)
 1440 FORMAT(/28H P (THE JACOBIAN MATRIX)..../1H )
C
C                             INITIALIZE FOR THIS ITERATION.
 1450 STFAC=RUNIT
      DO 1460 JX=1,NACTV
        GRAD(JX)=RZERO
        DO 1460 KX=1,NACTV
 1460     ERR(JX,KX)=RZERO
C
C  CALL DERIV (OR CALCD) TO COMPUTE THE JACOBIAN MATRIX, P.
C  DERIV IS CALLED NPTS TIMES IF KALCP=-1.
C
      SIG=YSIG(1)
      DO 1590 JPT=1,NPTS
        KPT=JPT
        IF(KALCP)1470,1490,1490
 1470   KPT=1
        IF(KORDF-2)1500,1500,1480
 1480   CALL CALCD (JPT,P,LPCOL)
        GO TO 1510
 1490   IF(JPT-1)1510,1500,1510
 1500   CALL DERIV (JPT,FUNK,NPTS,FIT,FITSV,P,LPCOL)
 1510   CONTINUE
        IF(NTRAC-3)1540,1520,1520
 1520   WRITE(KW,1530)JPT,(P(KPT,JX),JX=1,NACTV)
 1530   FORMAT(1X,I3,2X,6E15.7/(6X,6E15.7))
C
C  COMPUTE OSAV AND GRAD.
C  OSAV, WHICH IS STORED IN ONE HALF OF THE ARRAY ERR(*,*), IS PT*P.
C  GRAD IS EQUAL TO HALF THE NEGATIVE OF THE GRADIENT VECTOR.
C
 1540   IF(LEQU)1560,1550,1560
 1550   SIG=YSIG(JPT)
 1560   YY=Y(JPT)
        RTERM=(FIT(JPT)-YY)/SIG**2
        DO 1580 JX=1,NACTV
          GRAD(JX)=GRAD(JX)-P(KPT,JX)*RTERM
          PTERM=P(KPT,JX)/SIG**2
          DO 1570 KX=1,JX
 1570       ERR(JX,KX)=ERR(JX,KX)+P(KPT,KX)*PTERM
 1580     CONTINUE
 1590   CONTINUE
C                             RESTORE FIT IF IT WAS DESTROYED IN DERIV.
      IF(KORDF-2)1630,1600,1630
 1600 IF(KALCP)1620,1610,1620
 1610 CALL FUNC (FUNK,Y,YSIG,NPTS,FIT,PHI)
      NF=NF+1
 1620 NF=NF+NACTV
 1630 NF=NF+NACTV
C
C  COMPUTE THE SCALE FACTORS AND SCALE GRAD.
C
      DO 1660 JX=1,NACTV
        SCALJ=DSQRT(ERR(JX,JX))
        IF(SCALJ)1650,1640,1650
 1640   SCALJ=RUNIT
 1650   SCALE(JX)=SCALJ
 1660   GRAD(JX)=GRAD(JX)/SCALJ
      IF(NTRMU)1690,1670,1670
 1670 WRITE(KW,1680)(GRAD(JX),JX=1,NACTV)
 1680 FORMAT(/2X,19H SCALED GRADIENT = ,6E15.7/(21X,6E15.7))
C
C  SCALE OSAV.  THE DIAGONAL ELEMENTS OF OSAV ARE SCALED TO UNITY.
C
 1690 DO 1770 JX=1,NACTV
        DO 1770 KX=1,JX
          SA=ERR(JX,KX)/(SCALE(JX)*SCALE(KX))
          IF(KX-JX)1720,1700,1720
 1700     IF(SA)1710,1740,1710
 1710     SA=RUNIT
          GO TO 1770
 1720     IF(SA-(RUNIT-RLTOL))1730,1740,1740
```

```
 1730     IF(SA*(RUNIT-RLTOL))1740,1740,1770
 1740     CONTINUE
          IF(NTRPT)1770,1750,1750
 1750     WRITE(KW,1760)JX,KX,SA
 1760     FORMAT(38H ********  POSSIBLY DANGEROUS VALUE OF ,
     *       16H COEFFICIENT....,5X,6H QSAV(,I3,1H,,I3,4H) = ,E14.7)
 1770     ERR(JX,KX)=SA
      IF(NTRAC-2)1810,1780,1780
 1780 WRITE(KW,1790)
 1790 FORMAT(/49H QSAV (PT*P, SCALED, WHERE P IS THE JACOBIAN)..../1H )
      DO 1800 JX=1,NACTV
 1800   WRITE(KW,1530)JX,(ERR(JX,KX),KX=1,JX)
 1810 DO 1820 JX=1,NV
 1820   XSAVE(JX)=X(JX)
C                                INITIALIZE MASKT AND NACT.
 1830 NACT=NACTV
      DO 1840 JX=1,NV
 1840   MASKT(JX)=MASK(JX)
C
C  COPY QSAV INTO Q AND GRAD INTO H, AND SET THE DIAGONAL ELEMENTS OF Q.
C  THIS IS THE ENTRY POINT FOR SUBITERATIONS IN WHICH FLAMB IS
C  INCREASED OR CONSTRAINTS ARE IMPOSED.
C
 1850 KRANK=0
      JQ=0
      JT=0
      DO 1940 JX=1,NV
        IF(MASK(JX))1940,1860,1940
 1860   JQ=JQ+1
        IF(MASKT(JX))1940,1870,1940
 1870   JT=JT+1
        H(JT)=GRAD(JQ)
        KQ=0
        KT=0
        DO 1930 KX=1,JX
          IF(MASK(KX))1930,1880,1930
 1880     KQ=KQ+1
          IF(MASKT(KX))1930,1890,1930
 1890     KT=KT+1
          SA=ERR(JQ,KQ)
          IF(KX-JX)1920,1900,1920
 1900     IF(SA)1910,1920,1910
 1910     SA=RUNIT+FLAMB
          KRANK=KRANK+1
 1920     ERR(KT,JT+1)=SA
 1930     CONTINUE
 1940   CONTINUE
C
C  SOLVE THE NORMAL EQUATIONS FOR H, THE CORRECTION VECTOR.
C  THE METHOD USED IS GAUSSIAN ELIMINATION WITHOUT PIVOTING.
C  (PIVOTING IS NOT NECESSARY FOR A POSITIVE DEFINITE MATRIX.)
C  ONLY ABOUT N**3/6 MULTIPLICATIONS ARE DONE.
C  THE CHOICE OF GAUSSIAN ELIMINATION RATHER THAN CHOLESKY
C  DECOMPOSITION IS INTENTIONAL.
C
      NSMAL=0
      NMU=NACT-1
      IF(NMU)2100,2010,1950
C                                REDUCE THE SYSTEM TO TRIANGULAR FORM,
C                                   UTILIZING THE SYMMETRY OF THE MATRIX.
 1950 DO 2000 J=1,NMU
        PIVOT=ERR(J,J+1)
        IF(PIVOT)1960,2000,1960
 1960   JPU=J+1
        DO 1990 K=JPU,NACT
          EM=ERR(J,K+1)/PIVOT
          IF(EM)1970,1990,1970
 1970     DO 1980 L=K,NACT
 1980       ERR(K,L+1)=ERR(K,L+1)-ERR(J,L+1)*EM
 1990     H(K)=H(K)-H(J)*EM
 2000   CONTINUE
C                                DO THE BACK SOLUTION.
 2010 DO 2090 JINV=1,NACT
        J=(NACT+1)-JINV
        PIVOT=ERR(J,J+1)
        IF(PIVOT)2020,2020,2030
 2020   NSMAL=NSMAL+1
 2030   IF(PIVOT)2050,2040,2050
 2040   H(J)=RZERO
        GO TO 2090
 2050   SUM=RZERO
        IF(J-NACT)2060,2080,2080
 2060   JPU=J+1
        DO 2070 K=JPU,NACT
 2070     SUM=SUM+ERR(J,K+1)*H(K)
 2080   H(J)=(H(J)-SUM)/PIVOT
 2090   CONTINUE
C
 2100 NRANK=NACT-NSMAL
C
C  IF THE COEFFICIENT MATRIX WAS RANK DEFICIENT, PRINT A MESSAGE.
C
      IF(NRANK-NACT)2110,2180,2110
 2110 COSIN=HUGE
      IF(NTRPT)2140,2120,2120
 2120 WRITE(KW,2130)NRANK,NACT
 2130 FORMAT(/41H RANK-DEFICIENT NORMAL EQUATIONS IN MARQ.,3X,
     X     7H RANK =,I3,7X,18H ORDER OF MATRIX =,I3)
 2140 IF(NRANK)2150,2150,2160
 2150 KFLAG=-4
      GO TO 3470
 2160 IF(METHD)2180,2180,2170
 2170 IF(NRANK-KRANK)2770,2180,2180
C
C  UNPACK AND DE-SCALE THE CORRECTION VECTOR H.
C  COMPUTE THE INNER PRODUCTS SA, SB, AND SC.
C
 2180 SA=RZERO
      SB=RZERO
      SC=RZERO
      KX=NV
      KQ=NACTV
      KT=NACT
      DO 2230 JX=1,NV
        HH=RZERO
        IF(MASKT(KX))2190,2200,2190
 2190   IF(MASK(KX))2220,2210,2220
 2200   HH=H(KT)
        SA=SA+HH*GRAD(KQ)
        SB=SB+HH*HH
```

```
          SC=SC+GRAD(KB)**2
          HH=HH*FNGN/SCALE(KB)
          KT=KT-1
 2210     KB=KB-1
 2220     H(KI)=HH
 2230     KI=KI-1
C
C  ADD THE CORRECTION VECTOR TO THE PARAMETER VECTOR AND
C  INSURE THAT NO CONSTRAINTS ARE VIOLATED.
C  THIS IS THE ENTRY POINT FOLLOWING A CUTSTEP.
C
 2240 CONTINUE
      IF(NTRMU)2270,2250,2250
 2250 WRITE(KW,2260)(H(JX),JX=1,NV)
 2260 FORMAT(/7X,14H CORRECTION = ,6E15.7/(21X,6E15.7))
 2270 NACSV=NACT
      FRMIN=RUNIT
      NLOOP=0
      JXLIM=0
 2280 DO 2500 JX=1,NV
          IF(MASKT(JX))2500,2290,2500
 2290     XSAV=XSAVE(JX)
          XMX=XMAX(JX)
          XMN=XMIN(JX)
          HH=H(JX)
          IF(XSAV-XMX)2310,2300,2300
 2300     IF(HH)2310,2310,2330
 2310     IF(XSAV-XMN)2320,2320,2360
 2320     IF(HH)2330,2360,2360
 2330     MASKT(JX)=1
          NACT=NACT-1
          X(JX)=XSAV
          IF(NTRPU)2500,2340,2340
 2340     WRITE(KW,2350)JX,XSAV
 2350     FORMAT(/8H FIX  X(,I3,6H) = ,E12.5,
     *         46H TEMPORARILY, TO AVOID VIOLATING A CONSTRAINT. )
          GO TO 2500
 2360     XLIM=XSAV+HH*FRMIN
          IF(JX-JXLIM)2380,2370,2380
 2370     IF(KBND)2410,2390,2390
 2380     X(JX)=XLIM
          IF(XLIM-XMX)2400,2400,2390
 2390     X(JX)=XMX
          JBND=1
          GO TO 2420
 2400     IF(XLIM-XMN)2410,2500,2500
 2410     X(JX)=XMN
          JBND=-1
 2420     IF(JX-JXLIM)2460,2430,2460
 2430     CONTINUE
          IF(NTRPU)2500,2440,2440
 2440     WRITE(KW,2450)JX,X(JX),FRMIN
 2450     FORMAT(/26H CONSTRAINT VIOLATED BY X(,I3,
     *         20H).    VALUE RESET TO ,E15.8,24H USING CUTSTEP FACTOR = ,
     *         E12.5 )
          GO TO 2500
 2460     IF(NLOOP)2500,2470,2500
 2470     DENOM=XLIM-XSAV
          IF(DENOM)2480,2500,2480
 2480     FRAC=(X(JX)-XSAV)/DENOM
          IF(FRAC-FRMIN)2490,2500,2500
 2490     FRMIN=FRAC
          JXLIM=JX
          KBND=JBND
 2500     CONTINUE
C
C  IF THE PROPOSED STEP WOULD VIOLATE ANY ALREADY ACTIVE CONSTRAINTS,
C  FIX THOSE COMPONENTS OF H EQUAL TO ZERO AND RECOMPUTE THE
C  OTHER COMPONENTS.
C
      IF(NACT)2510,2510,2540
 2510 KFLAG=3
      IF(NTRPT)3470,2520,2520
 2520 WRITE(KW,2530)
 2530 FORMAT(////47H APPARENT CONSTRAINED OPTIMUM LIES IN A CORNER. )
      GO TO 3470
 2540 IF(NACT-NACSV)1050,2550,2550
 2550 IF(NLOOP)2570,2560,2570
 2560 NLOOP=1
      IF(JXLIM)2280,2570,2280
 2570 CONTINUE
      IF(NTRMU)2600,2580,2580
 2580 WRITE(KW,2590)(X(JX),JX=1,NV)
 2590 FORMAT(/16X,5H X = ,6E15.7/(21X,6E15.7))
C
C  CALCULATE THE NEW FITTED VALUES.
C
 2600 CALL FUNC (FUNK,Y,YSIG,NPTS,FIT,PHNEW)
      NF=NF+1
      IF(PHNEW-PHI)2910,2610,2650
C
C  THE NEW VALUE OF PHI IS EXACTLY EQUAL TO THE OLD VALUE.
C  CHECK FOR CONVERGENCE UNDER THE NFLAT OPTION.
C
 2610 IF(NFLAT)2620,2910,2620
 2620 KFLAG=2
      IF(NTRPU)2730,2630,2630
 2630 WRITE(KW,2640)
 2640 FORMAT(//45H CONVERGENCE ACHIEVED UNDER THE NFLAT OPTION.)
      GO TO 2730
C
C  THE NEW VALUE OF PHI IS GREATER THAN THE OLD VALUE.
C
 2650 CONTINUE
      IF(NTRMU)2680,2660,2660
 2660 WRITE(KW,2670)PHI,PHNEW
 2670 FORMAT(/33X,11H OLD PHI = ,E15.8,4X,11H NEW PHI = ,E15.8)
C
C  INSURE THAT JSUB HAS NOT EXCEEDED MXSUB.
C
 2680 JSUB=JSUB+1
      IF(JSUB-MXSUB)2690,2690,2700
 2690 IF(METHD)2840,3240,2750
 2700 KFLAG=-1
      IF(NTRPU)2730,2710,2710
 2710 WRITE(KW,2720)MXSUB
 2720 FORMAT(//44H EXCEEDED MAXIMUM NUMBER OF SUBITERATIONS = ,I5,
     *        9H IN MARQ.)
C                                 RESTORE X TO THE BASE POINT.
 2730 DO 2740 JX=1,NV
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 2740   X(JX)=XSAVE(JX)                                                MARQ 603
      CALL FUNC (FUNK,Y,YSIG,NPTS,FIT,PHI)                             MARQ 604
      GO TO 3470                                                       MARQ 605
C                                                                      MARQ 606
C  THE NEW FIT IS WORSE THAN THE OLD FIT.  COMPUTE COSIN, THE COSINE   MARQ 607
C  OF THE ANGLE BETWEEN THE SCALED GRADIENT AND THE SCALED CORRECTION  MARQ 608
C  VECTOR.                                                             MARQ 609
C                                                                      MARQ 610
 2750 DENOM=SB*SC                                                      MARQ 611
      IF(DENOM)2770,2770,2760                                          MARQ 612
 2760 COSIN=SA/DSQRT(DENOM)                                            MARQ 613
      IF(COSIN-CRIT)2770,2770,2840                                     MARQ 614
C                                                                      MARQ 615
C  COSIN IS NOT GREATER THAN CRIT.  INCREASE THE VALUE OF LAMBDA.      MARQ 616
C                                                                      MARQ 617
 2770 UPFAC=FNU                                                        MARQ 618
      IF(METHD-1)2800,2780,2800                                        MARQ 619
 2780 IF(FLAMB*(FNU-RTWO)-RUNIT)2800,2800,2790                         MARQ 620
 2790 UPFAC=RTWO+RUNIT/FLAMB                                           MARQ 621
 2800 FLAMB=FLAMB*UPFAC                                                MARQ 622
      IF(NTRMU)2830,2810,2810                                          MARQ 623
 2810 WRITE(KW,2820)JSUB,COSIN,FLAMB                                   MARQ 624
 2820 FORMAT(/10H **** SUBITERATION,I3,4X,17H INCREASE LAMBDA.,        MARQ 625
     *      4X,14H COS(GAMMA) = ,E12.5,27X,9H LAMBDA =,E12.5)          MARQ 626
 2830 CONTINUE                                                         MARQ 627
C                           GO BACK AND FORM THE NORMAL EQUATIONS      MARQ 628
C                               USING A LARGER VALUE OF LAMBDA.        MARQ 629
      GO TO 1030                                                       MARQ 630
C                                                                      MARQ 631
C  COSIN IS GREATER THAN CRIT.  CUT THE MAGNITUDE OF THE STEP, H.      MARQ 632
C                                                                      MARQ 633
 2840 STFAC=STFAC/RTWO                                                 MARQ 634
      FLAMB=FLAMB*FLUPB                                                MARQ 635
      IF(METHD)2850,2860,2860                                          MARQ 636
 2850 FMGN=FMGN/RTWO                                                   MARQ 637
 2860 DO 2870 JX=1,NV                                                  MARQ 638
 2870   H(JX)=(X(JX)-XSAVE(JX))/RTWO                                   MARQ 639
      IF(NTRMU)2900,2880,2880                                          MARQ 640
 2880 WRITE(KW,2890)JSUB,COSIN,STFAC                                   MARQ 641
 2890 FORMAT(/10H **** SUBITERATION,I3,4X,16H TAKE CUT STEPS.,4X,      MARQ 642
     *      14H COS(GAMMA) = ,E12.5,4X,17H CUTSTEP FACTOR =,E12.5 )    MARQ 643
 2900 CONTINUE                                                         MARQ 644
C                           GO BACK AND TRY A SMALLER CUTSTEP.         MARQ 645
      GO TO 2240                                                       MARQ 646
C                                                                      MARQ 647
C  THE VALUE OF PHI HAS DECREASED.  TRY A HALF STEP.                   MARQ 648
C                                                                      MARQ 649
 2910 IF(METHD)2930,3240,2920                                          MARQ 650
 2920 IF(METHD-2)2930,3240,2930                                        MARQ 651
 2930 DO 2980 JX=1,NV                                                  MARQ 652
        XTEMP(JX)=X(JX)                                                MARQ 653
        IF(MASK(JX))2980,2940,2980                                     MARQ 654
 2940   X(JX)=XSAVE(JX)+(X(JX)-XSAVE(JX))/RTWO                         MARQ 655
        IF(X(JX)-XMAX(JX))2960,2960,2950                               MARQ 656
 2950   X(JX)=XMAX(JX)                                                 MARQ 657
 2960   IF(X(JX)-XMIN(JX))2970,2980,2980                               MARQ 658
 2970   X(JX)=XMIN(JX)                                                 MARQ 659
 2980   CONTINUE                                                       MARQ 660
      DO 2990 JPT=1,NPTS                                               MARQ 661
 2990   FITSV(JPT)=FIT(JPT)                                            MARQ 662
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      CALL FUNC (FUNK,Y,YSIG,NPTS,FIT,PHALF)                           MARQ 663
      NF=NF+1                                                          MARQ 664
C                                                                      MARQ 665
C  USE QUADRATIC INTERPOLATION, IN ORDER TO TRY TO REFINE THE          MARQ 666
C  POSITION OF THE MINIMUM OF PHI.                                     MARQ 667
C                                                                      MARQ 668
      RLFAC=RUNIT                                                      MARQ 669
      DENOM=RTWO*((PHNEW-PHALF)-(PHALF-PHI))                           MARQ 670
      IF(DENOM)3020,3020,3000                                          MARQ 671
 3000 STFAC=(PHI-PHNEW)/DENOM                                          MARQ 672
      RSFAC=(RUNIT+STFAC)/RTWO                                         MARQ 673
C                                                                      MARQ 674
C                                DO NOT EXTRAPOLATE.                   MARQ 675
      IF(STFAC-RUNIT)3030,3020,3020                                    MARQ 677
 3020 STFAC=RZERO                                                      MARQ 678
 3030 DO 3040 JX=1,NV                                                  MARQ 679
        XSAVE(JX)=X(JX)                                                MARQ 680
 3040   X(JX)=X(JX)+(XTEMP(JX)-X(JX))*STFAC                            MARQ 681
      IF(PHALF-PHNEW)3050,3100,3100                                    MARQ 682
 3050 RLFAC=RUNIT/RTWO                                                 MARQ 684
      JSUB=JSUB+1                                                      MARQ 685
      DO 3060 JX=1,NV                                                  MARQ 686
 3060   XTEMP(JX)=XSAVE(JX)                                            MARQ 687
      DO 3070 JPT=1,NPTS                                               MARQ 688
 3070   FITSV(JPT)=FIT(JPT)                                            MARQ 689
      IF(NTRMU)3095,3080,3080                                          MARQ 690
 3080 WRITE(KW,3090)PHNEW,PHALF                                        MARQ 691
 3090 FORMAT(/21H HALF STEP SUCCEEDED.,15X,8H PHNEW =,E15.8,10X,       1000 691
     X      8H PHALF =,E15.8)                                          2000 691
 3095 PHNEW=PHALF                                                      3000 691
 3100 IF(STFAC)3110,3120,3110                                          MARQ 693
 3110 CALL FUNC (FUNK,Y,YSIG,NPTS,FIT,PHI)                             MARQ 694
      NF=NF+1                                                          MARQ 695
      IF(PHI-PHNEW)3180,3120,3120                                      MARQ 696
 3120 DO 3130 JX=1,NV                                                  MARQ 697
 3130   X(JX)=XTEMP(JX)                                                MARQ 698
      DO 3140 JPT=1,NPTS                                               MARQ 699
 3140   FIT(JPT)=FITSV(JPT)                                            MARQ 700
      IF(STFAC)3150,3210,3150                                          MARQ 701
 3150 CONTINUE                                                         MARQ 702
      IF(NTRMU)3210,3160,3160                                          MARQ 703
 3160 WRITE(KW,3170)RSFAC,PHI                                          MARQ 704
 3170 FORMAT(/32H QUADRATIC INTERPOLATION FAILED.,15X,8H RSFAC =,E12.5, 1000 704
     X      12X,6H PHI =,E15.8)                                        2000 704
      GO TO 3210                                                       MARQ 706
 3180 RLFAC=RSFAC                                                      MARQ 707
      PHNEW=PHI                                                        MARQ 708
      IF(NTRMU)3210,3190,3190                                          MARQ 709
 3190 WRITE(KW,3200)RLFAC,PHI                                          MARQ 710
 3200 FORMAT(/35H QUADRATIC INTERPOLATION SUCCEEDED.,12X,8H RLFAC =,   MARQ 711
     *      E12.5,12X,6H PHI =,E15.8)                                  MARQ 712
 3210 IF(RLFAC)3240,3240,3220                                          MARQ 713
 3220 FLAMB=FLAMB/RLFAC                                                MARQ 714
      IF(METHD)3230,3240,3240                                          MARQ 715
 3230 FMGN=FMGN*RLFAC                                                  MARQ 716
C                                                                      MARQ 717
C  THE STEP IS ACCEPTED.  TEST FOR CONVERGENCE IF NO CONSTRAINT        MARQ 718
C  BECAME ACTIVE DURING THIS ITERATION.                                MARQ 719
C                                                                      MARQ 720
 3240 CONTINUE                                                         MARQ 721
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      IF(NTRMU)3270,3250,3250                                           MARQ 722
 3250 WRITE(KW,3260)ITER,PHNEW                                          1000 722
 3260 FORMAT(/17H END   ITERATION ,I4,58X,6H PHI =,E15.8)               2000 722
 3270 PHI=PHNEW                                                         MARQ 726
      IF(JXLIM)3280,3280,3350                                           MARQ 727
 3280 DO 3320 JX=1,NV                                                   MARQ 728
        IF(MASK(JX))3320,3290,3320                                      MARQ 729
 3290   DIF=X(JX)-XSAVE(JX)                                             MARQ 730
        IF(DIF)3300,3310,3310                                           MARQ 731
 3300   DIF=-DIF                                                        MARQ 732
 3310   IF(DIF-DELMN(JX))3320,3320,3350                                 MARQ 733
 3320   CONTINUE                                                        MARQ 734
      KFLAG=1                                                           MARQ 735
      IF(NTRPU)3470,3330,3330                                           MARQ 736
 3330 WRITE(KW,3340)                                                    MARQ 737
 3340 FORMAT(//38H CONVERGED WHEN THE STEP BECAME SMALL.)               MARQ 738
      GO TO 3470                                                        MARQ 739
C                                                                       MARQ 740
C  THE ITERATION HAS NOT YET CONVERGED.                                 MARQ 741
C                                                                       MARQ 742
 3350 IF(ITER-MAXIT)3380,3380,3360                                      MARQ 743
 3360 KFLAG=-6                                                          MARQ 744
      WRITE(KW,3370)MAXIT                                               MARQ 745
 3370 FORMAT(//47H MAXIMUM NUMBER OF ITERATIONS EXCEEDED IN MARQ.,5X,   MARQ 746
     *      9H MAXIT = ,I6 )                                            MARQ 747
      GO TO 3470                                                        MARQ 748
C                                                                       MARQ 749
C  IF SUBITERATIONS WERE NOT PERFORMED THIS ITERATION, DECREASE LAMBDA. MARQ 750
C                                                                       MARQ 751
 3380 IF(NF-NFMAX)3390,3390,3450                                        MARQ 752
 3390 IF(JSUB)3400,3400,3440                                            MARQ 753
 3400 FMGN=FMGN*RTWO                                                    MARQ 754
      IF(FMGN-RUNIT)3420,3420,3410                                      MARQ 755
 3410 FMGN=RUNIT                                                        MARQ 756
 3420 SCALJ=RUNIT+FLAMB                                                 MARQ 757
      IF(SCALJ-RUNIT)3440,3440,3430                                     MARQ 758
 3430 FLAMB=FLAMB/FNU                                                   MARQ 759
 3440 CONTINUE                                                          MARQ 760
C                               GO BACK AND DO ANOTHER ITERATION.       MARQ 761
      GO TO 1420                                                        MARQ 762
 3450 KFLAG=-7                                                          MARQ 763
      WRITE(KW,3460)NFMAX                                               MARQ 764
 3460 FORMAT(//25H NF HAS EXCEEDED NFMAX = ,I7,9H IN MARQ. )            MARQ 765
C                                                                       MARQ 766
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * MARQ 767
C                                                                       MARQ 768
C  THE ITERATION HAS TERMINATED.                                        MARQ 769
C  PRINT OUT THE DATA, FITTED VALUES, AND RESIDUALS.                    MARQ 770
C  COMPUTE AND PRINT THE STANDARD DEVIATION OF THE DATA FROM THE FIT.   MARQ 771
C                                                                       MARQ 772
 3470 CONTINUE                                                          MARQ 773
      IF(NTRPU)3670,3480,3480                                           MARQ 774
 3480 WRITE(KW,3490)ITER,NF,PHI,FMGN,FLAMB                              MARQ 775
 3490 FORMAT(/1X,I4,11H ITERATIONS,7X,5H NF =,I5,9X,6H PHI =,E15.8,     1000 775
     X      10X,7H FMGN =,E12.5,7X,9H LAMBDA =,E12.5)                   2000 775
      WRITE(KW,2590)(X(JX),JX=1,NV)                                     MARQ 778
      IF(NTRAC)3520,3500,3500                                           MARQ 779
 3500 WRITE(KW,3510)                                                    MARQ 780
 3510 FORMAT(///14X,1HJ,9X,5H Y(J),14X,7H FIT(J),10X,                   MARQ 781
     *      12H Y(J)-FIT(J),7X,8H YSIG(J),11X,13H (Y-FIT)/YSIG/1H )     MARQ 782
 3520 SIG=YSIG(1)                                                       MARQ 783
      RMSDV=RZERO                                                       MARQ 784
      SDVMX=RZERO                                                       MARQ 785
      DO 3610 JPT=1,NPTS                                                MARQ 786
        IF(LEQU)3540,3530,3540                                          MARQ 787
 3530   SIG=YSIG(JPT)                                                   MARQ 788
 3540   YY=Y(JPT)                                                       MARQ 789
        PTERM=YY-FIT(JPT)                                               MARQ 790
        RTERM=PTERM/SIG                                                 MARQ 791
        IF(NTRAC)3570,3550,3550                                         MARQ 792
 3550   WRITE(KW,3560)JPT,YY,FIT(JPT),PTERM,SIG,RTERM                   MARQ 793
 3560   FORMAT(10X,I5,5X,E15.8,5X,E15.8,5X,E12.5,5X,E12.5,10X,E12.5)    MARQ 794
 3570   RMSDV=RMSDV+RTERM**2                                            MARQ 795
        IF(RTERM)3580,3590,3590                                         MARQ 796
 3580   RTERM=-RTERM                                                    MARQ 797
 3590   IF(RTERM-SDVMX)3610,3610,3600                                   MARQ 798
 3600   SDVMX=RTERM                                                     MARQ 799
 3610   CONTINUE                                                        MARQ 800
      DENOM=NPTS-NACTV                                                  MARQ 801
      WRITE(KW,3620)DENOM                                               MARQ 802
 3620 FORMAT(//32H NUMBER OF DEGREES OF FREEDOM = ,E12.5 )              MARQ 803
      IF(DENOM)3650,3650,3630                                           MARQ 804
 3630 RMSDV=DSQRT(RMSDV/DENOM)                                          MARQ 805
      WRITE(KW,3640)RMSDV                                               MARQ 806
 3640 FORMAT(/43H R.M.S. SCALED DEVIATION OF DATA FROM FIT =,E12.5)     MARQ 807
 3650 CONTINUE                                                          MARQ 808
      WRITE(KW,3660)SDVMX                                               MARQ 809
 3660 FORMAT(/27H MAXIMUM SCALED DEVIATION =,E12.5)                     MARQ 810
C                                                                       MARQ 811
C  CALL FUNC TO SET THE FINAL VALUES.                                   MARQ 812
C                                                                       MARQ 813
 3670 CALL FUNC (FUNK,Y,YSIG,NPTS,FIT,PHI)                              MARQ 814
      FOBJ=PHI                                                          MARQ 815
C                                                                       MARQ 816
C  CALL MQERR TO PRINT THE PARAMETER ERRORS AND CORRELATIONS.           MARQ 817
C  A DUMMY ROUTINE MAY BE SUBSTITUTED FOR MQERR IF THESE ARE NOT NEEDED.MARQ 818
C                                                                       MARQ 819
      IF(MATRX)3690,3690,3680                                           MARQ 820
 3680 CALL MQERR (NACTV,N,SCALE,NPTS)                                   MARQ 821
C                                                                       MARQ 822
 3690 RETURN                                                            MARQ 823
C  END MARQ.                                                            MARQ 824
      END                                                               MARQ 825
C                                                                       MARQ 826
      SUBROUTINE FUNC (FUNK,Y,YSIG,NPTS,FIT,PHI)                        FUNC   1
C                                                                       FUNC   2
C  FUNC CALLS FUNK OR FOFX TO COMPUTE THE ARRAY OF FITTED VALUES FITN.  FUNC   3
C                                                                       FUNC   4
      DOUBLE PRECISION X,FIT,F,PHI,SIG,YY                               FUNC   5
C                                                                       FUNC   6
      DIMENSION Y(1),YSIG(1),FIT(1)                                     FUNC   7
C                                                                       FUNC   8
      COMMON /CSTEP/ X(20),XMAX(20),XMIN(20),DELTX(20),DELMN(20),       FUNC   9
     *      ERR(20,21),FOBJ,NV,NTRAC,MATRX,MASK(20),                    FUNC  10
     *      NFMAX,NFLAT,JVARY,NXTRA,KFLAG,NOREP,KERFL,KW                FUNC  11
      COMMON /MLLS2/FLAMB,RELDF,METHD,KALCP,KORDF,MAXIT,LEQU,MXSUB,MXUPDFUNC  12
C                                                                       FUNC  13
      RZERO=0.                                                          FUNC  14
      IF(KALCP)5050,5040,5050                                           FUNC  21
C                                                                       FUNC  22
```

```
 5040 CALL FUNK (FIT)
      GO TO 5070
C
 5050 DO 5060 JPT=1,NPTS
        CALL FOFX(JPT,NV,X,F)
 5060   FIT(JPT)=F
C
 5070 PHI=RZERO
      SIG=YSIG(1)
      DO 5130 JPT=1,NPTS
        IF(LEQU)5090,5080,5090
 5080   SIG=YSIG(JPT)
C                            CHECK FOR AN ILLEGAL VALUE OF SIG.
 5090   IF(SIG)5100,5100,5120
 5100   WRITE(KW,5110)LEQU,JPT,SIG
 5110   FORMAT(/20H ERROR IN MARQ....   LEQU = ,I1,5X,6HJPT = ,I5,5X,
     *      7HYSIG = ,E12.5,14H IS .LE. ZERO.)
        STOP
C
 5120   YY=Y(JPT)
 5130   PHI=PHI+((FIT(JPT)-YY)/SIG)**2
C
      RETURN
C  END FUNC.
      END
C
      SUBROUTINE DERIV (JPT,FUNK,NPTS,FIT,FITSV,P,LPCOL)
C
C  DERIV 4.0        A.N.S.I. STANDARD FORTRAN        JUNE 1975
C
C  DERIV COMPUTES THE JACOBIAN MATRIX P USING FINITE DIFFERENCES.
C
C  P(J,K) IS THE PARTIAL DERIVATIVE OF FIT(J) WITH RESPECT TO X(K).
C  IF KORDF.EQ.1, DERIV USES A NONCENTRAL DIFFERENCE FORMULA.
C  IF KORDF.EQ.2, DERIV USES A CENTRAL DIFFERENCE FORMULA.
C  KORDF.EQ.1 IS ABOUT TWICE AS FAST AS KORDF.EQ.2, BUT LESS ACCURATE.
C
C  ON A MACHINE HAVING LESS THAN ABOUT TEN SIGNIFICANT DIGITS IN
C  SINGLE PRECISION (FOR EXAMPLE THE IBM 360 OR 370), THE
C  DIFFERENCING SHOULD BE DONE IN DOUBLE PRECISION.  TO ACCOMPLISH
C  THIS, ACTIVATE THE DOUBLE PRECISION STATEMENT BELOW.
C
      DOUBLE PRECISION X,FIT,FITSV,DEL,TWODL,XSAVE,FX0,FX1
C
      DIMENSION FIT(1),FITSV(1),P(LPCOL,1)
C
      COMMON /CSTEP/ X(20),XMAX(20),XMIN(20),DELTX(20),DELMN(20),
     *      ERR(20,21),FOBJ,NV,NTRAC,MATRX,MASK(20),
     *      NFMAX,NFLAT,JVARY,NXTRA,KFLAG,NOREP,KERFL,KW
      COMMON /NLLS2/FLAMB,RELDF,METHD,KALCP,KORDF,MAXIT,LEQU,MXSUB,MXUPD
C
      JVARY=0
C
C  SAVE FIT IF KALCP.GE.0 .
      IF(KALCP)6020,6000,6000
 6000 DO 6010 J=1,NPTS
 6010   FITSV(J)=FIT(J)
C
C  LOOP OVER THE ACTIVE PARAMETERS X(JX).
C
```

```
 6020 KX=0
      DO 6210 JX=1,NV
        IF(MASK(JX))6210,6030,6210
 6030   KX=KX+1
        DEL=RELDF*X(JX)
        IF(DEL)6050,6040,6050
 6040   DEL=RELDF
 6050   XSAVE=X(JX)
        X(JX)=XSAVE+DEL
        TWODL=DEL+DEL
        IF(KALCP)6160,6060,6120
C
C  KALCP.EQ.0 .  COMPUTE P, ONE COLUMN AT A TIME.
C
 6060   CALL FUNK (FIT)
        IF(KORDF-2)6070,6090,6240
 6070   DO 6080 J=1,NPTS
 6080     P(J,KX)=(FIT(J)-FITSV(J))/DEL
        GO TO 6200
C
C  KALCP.EQ.0 AND KORDF.EQ.2 .  IN THIS CASE, THE INPUT VALUES OF
C  FIT(J) WILL BE DESTROYED.
C
 6090   X(JX)=XSAVE-DEL
        OC 6100 J=1,NPTS
 6100     FITSV(J)=FIT(J)
        JVARY=JX
        CALL FUNK (FIT)
        JVARY=0
        DO 6110 J=1,NPTS
 6110     P(J,KX)=(FITSV(J)-FIT(J))/TWODL
        GO TO 6200
C
C  KALCP.GT.0 .  COMPUTE P, ONE ELEMENT AT A TIME.
C
 6120   DO 6150 J=1,NPTS
          CALL FOFX (J,NV,X,FX1)
          IF(KORDF-2)6130,6140,6240
 6130     P(J,KX)=(FX1-FITSV(J))/DEL
          GO TO 6150
 6140     X(JX)=XSAVE-DEL
          CALL FOFX (J,NV,X,FX0)
          P(J,KX)=(FX1-FX0)/TWODL
          X(JX)=XSAVE+DEL
 6150     CONTINUE
        GO TO 6200
C
C  KALCP.LT.0 .  COMPUTE ONE ROW OF P, ONE ELEMENT AT A TIME.
C
 6160   FITSV(1)=FIT(JPT)
        CALL FOFX (JPT,NV,X,FX1)
        IF(KORDF-2)6170,6180,6170
 6170   P(1,KX)=(FX1-FITSV(1))/DEL
        GO TO 6190
 6180   X(JX)=XSAVE-DEL
        CALL FOFX (JPT,NV,X,FX0)
        P(1,KX)=(FX1-FX0)/TWODL
 6190   FIT(JPT)=FITSV(1)
 6200   X(JX)=XSAVE
 6210   CONTINUE
```

```
C
      IF(KALCP)6240,6220,6220
 6220 DO 6230 J=1,NPTS
 6230   F(J)=FITSV(J)
C
 6240 RETURN
C  END DERIV.
      END
C
      SUBROUTINE MOERR (NACTV,H,SCALE,NPTS)
C
C  MOERR 1.3         A.N.S.I. STANDARD FORTRAN         FEBRUARY 1978
C
C  MOERR IS CALLED BY MARQ TO COMPUTE AND PRINT APPROXIMATE VALUES OF
C  THE PARAMETER ERRORS AND CORRELATIONS.
C
C  FOR THE MEANING OF THE -MAXIMUM VARIANCE INFLATION FACTOR- BELOW,
C  SEE...       D. W. MARQUARDT AND R. D. SNEE,
C               RIDGE REGRESSION IN PRACTICE,
C               THE AMERICAN STATISTICIAN 29 (1975) 3-20
C
C  INPUT QUANTITIES.....  KW,ERR,NACTV,SCALE,NPTS,NV,NTRAC,MASK,FOBJ
C  OUTPUT QUANTITIES....  ERR
C  SCRATCH STORAGE......  H
C
      DOUBLE PRECISION X
C
      DIMENSION H(1),SCALE(1)
C
      COMMON /CSTEP/ X(20),XMAX(20),XMIN(20),DELTX(20),DELMN(20),
     *     ERR(20,21),FOBJ,NV,NTRAC,MATRX,MASK(20),
     *     NFMAX,NFLAT,JVARY,NXTRA,KFLAG,NOREP,KERFL,KW
C
      DSQRT(ARG)=SQRT(ARG)
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      RZERO=0.
      RUNIT=1.
      HUGE=1.E30
C                                PRINT OSAV.
      IF(NTRAC-(-1))4040,4000,4000
 4000 WRITE(KW,4010)
 4010 FORMAT(///18H SUBROUTINE MOERR.//26H OSAV (PT*P, SCALED, WHERE,
     *     23H P IS THE JACOBIAN)....)
      DO 4030 JX=1,NACTV
        WRITE(KW,4020)JX,(ERR(JX,KX),KX=1,JX)
 4020   FORMAT(/1X,I3,2X,6E15.7/(6X,6E15.7))
 4030   CONTINUE
C
C  COMPUTE THE SCALED ERROR MATRIX, WHICH IS THE INVERSE OF OSAV.
C  INVERT OSAV USING THE GAUSS-JORDAN METHOD WITHOUT PIVOTING.
C  (PIVOTING IS NOT NECESSARY FOR A POSITIVE DEFINITE MATRIX.)
C  ONLY ABOUT N**3/2 MULTIPLICATIONS ARE DONE.
C  F. L. BAUER AND C. REINSCH, P. 45 IN -LINEAR ALGEBRA-
C  BY J. H. WILKINSON AND C. REINSCH (SPRINGER-VERLAG, 1971)
C  THE INVERSE IS NOT GUARANTEED TO BE POSITIVE DEFINITE, DUE TO
C  ROUNDOFF ERROR.  NEVERTHELESS, THE CHOICE OF THE GAUSS-JORDAN METHOD
C  RATHER THAN CHOLESKY DECOMPOSITION IS INTENTIONAL.
C  H(*) IS USED AS A SCRATCH VECTOR.
C
 4040 NSMAL=0
      DO 4200 LINV=1,NACTV
        L=(NACTV+1)-LINV
        PIVOT=ERR(1,1)
        IF(PIVOT)4050,4050,4060
 4050   NSMAL=NSMAL+1
 4060   IF(NACTV-2)4140,4070,4070
 4070   DO 4130 K=2,NACTV
          Q=ERR(K,1)
          IF(PIVOT)4090,4080,4090
 4080     H(K)=RZERO
          GO TO 4120
 4090     IF(K-L)4100,4100,4110
 4100     H(K)=-Q/PIVOT
          GO TO 4120
 4110     H(K)=Q/PIVOT
 4120     DO 4130 M=2,K
 4130       ERR(K-1,M-1)=ERR(K,M)+Q*H(M)
 4140   IF(PIVOT)4160,4150,4160
 4150   ERR(NACTV,NACTV)=RZERO
        GO TO 4170
 4160   ERR(NACTV,NACTV)=RUNIT/PIVOT
 4170   IF(NACTV-2)4200,4180,4180
 4180   DO 4190 K=2,NACTV
 4190     ERR(NACTV,K-1)=H(K)
 4200   CONTINUE
C
      NRANK=NACTV-NSMAL
      IF(NRANK-NACTV)4210,4230,4230
 4210 CONTINUE
      WRITE(KW,4220)NRANK,NACTV
 4220 FORMAT(//44H THE SECOND DERIVATIVE MATRIX IS SINGULAR IN,
     X       7H MOERR.,9X,7H RANK =,I3,7X,8H ORDER =,I3//
     *       45H THEREFORE ALL PARAMETER ERRORS ARE INFINITE. )
C
C                              UNPACK THE ERROR MATRIX INTO THE UPPER
C                                   TRIANGLE OF ERR(*,*), DE-SCALING IT.
 4230 JV=0
      VIFMX=RZERO
      DO 4380 JX=1,NV
        IF(MASK(JX))4250,4240,4250
 4240   JV=JV+1
 4250   KV=0
        DO 4370 KX=1,JX
          ER=RZERO
          IF(MASK(JX))4370,4260,4370
 4260     IF(MASK(KX))4370,4270,4370
 4270     KV=KV+1
          TEMP=RZERO
          DENOM=SCALE(JV)*SCALE(KV)
          IF(DENOM)4280,4290,4280
 4280     TEMP=ERR(JV,KV)
          ER=TEMP/DENOM
 4290     IF(JX-KX)4370,4300,4370
 4300     IF(TEMP)4310,4310,4350
 4310     CONTINUE
          IF(NTRAC-(-2))4340,4320,4320
 4320     WRITE(KW,4330)JX,KX,TEMP
 4330     FORMAT(/6H THE (,I3,1H,,I3,23H) ELEMENT OF OSAV**-1 =,E12.5,
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     *     1X,45H THEREFORE ALL PARAMETER ERRORS ARE INFINITE. )      MOERR112
 4340      TEMP=-TEMP                                                 MOERR113
 4350      IF(TEMP-VIFMX)4370,4370,4360                               MOERR114
 4360      VIFMX=TEMP                                                 MOERR115
 4370      ERR(KX,JX+1)=ER                                            MOERR116
 4380    CONTINUE                                                     MOERR117
C                             SYMMETRIZE ERR.                         MOERR118
      DO 4390 JX=1,NV                                                 MOERR119
        DO 4390 KX=1,JX                                               MOERR120
          ERR(JX,KX)=ERR(KX,JX+1)                                     MOERR121
 4390     ERR(KX,JX)=ERR(JX,KX)                                       MOERR122
C                                                                     MOERR123
C                             COMPUTE AND PRINT THE STANDARD ERRORS.  MOERR124
      NDF=NPTS-NACTV                                                  MOERR125
      SCFAC=HUGE                                                      MOERR126
      IF(NDF)4410,4410,4400                                           MOERR127
 4400 SCFAC=NDF                                                       MOERR128
      SCFAC=QSQRT(FOBJ/SCFAC)                                         MOERR129
 4410 RESCL=NDF+NDF                                                   MOERR130
      IF(RESCL)4430,4430,4420                                         MOERR131
 4420 RESCL=QSQRT(RESCL)                                              MOERR132
 4430 CONTINUE                                                        MOERR133
      IF(NTRAC-(-1))4620,4440,4440                                    MOERR134
 4440 WRITE(KW,4450)NDF,NDF,RESCL,FOBJ,SCFAC                          MOERR135
 4450 FORMAT(///41H NUMBER OF DEGREES OF FREEDOM (N.D.F.) = ,         MOERR136
     *     15H(NPTS-NACTV) = ,I5//24H EXPECTED VALUE OF PHI = ,       MOERR137
     *     39H N.D.F. PLUS OR MINUS SQRT(2*N.D.F.) = ,I5,             MOERR138
     X     16H  PLUS OR MINUS ,E12.5//23H ACTUAL VALUE OF PHI = ,E12.5 MOERR139
     *     //39H RESCALING FACTOR = SQRT(PHI/N.D.F.) = ,E12.5 )       MOERR140
      WRITE(KW,4460)VIFMX                                             MOERR141
 4460 FORMAT(///36H MAXIMUM VARIANCE INFLATION FACTOR =,E12.5///      MOERR142
     *      32H APPROXIMATE STANDARD ERRORS..../60X,9H RESCALED/      MOERR143
     *     12X,1HJ,6X,7HMASK(J),9X,4HX(J),14X,5HERROR,12X,5HERROR )   MOERR144
      RESCL=HUGE                                                      MOERR145
      DO 4540 JX=1,NV                                                 MOERR146
        SCALJ=RUNIT                                                   MOERR147
        ER=ERR(JX,JX)                                                 MOERR148
        IF(ER)4470,4490,4480                                          MOERR149
 4470   ER=-QSQRT(-ER)                                                MOERR150
        SCALJ=-ER                                                     MOERR151
        GO TO 4490                                                    MOERR152
 4480   ER=QSQRT(ER)                                                  MOERR153
        SCALJ=ER                                                      MOERR154
 4490   IF(NDF)4520,4520,4500                                         MOERR155
 4500   IF(NRANK-NACTV)4520,4510,4510                                 MOERR156
 4510   RESCL=SCFAC*ER                                                MOERR157
 4520   SCALE(JX)=SCALJ                                               MOERR158
        WRITE(KW,4530)JX,MASK(JX),X(JX),ER,RESCL                      MOERR159
 4530   FORMAT(/10X,I3,I10,6X,E16.8,4X,E13.5,4X,E13.5 )               MOERR160
 4540   CONTINUE                                                      MOERR161
C                             COMPUTE AND PRINT THE CORRELATIONS.     MOERR162
      IF(NV-2)4620,4550,4550                                          MOERR163
 4550 CONTINUE                                                        MOERR164
      WRITE(KW,4560)(K,K=1,NV)                                        MOERR165
 4560 FORMAT(///45H LOWER TRIANGLE OF THE CORRELATION MATRIX....//    MOERR166
     *   12X,7H K .....I5,7I13/(11X,8I13))                            MOERR167
      WRITE(KW,4570)(MASK(K),K=1,NV)                                  MOERR168
 4570 FORMAT(/7X,12H MASK(K).....I5,7I13/(11X,8I13))                  MOERR169
      WRITE(KW,4580)                                                  MOERR170
 4580 FORMAT(/3X,1HJ,4X,7HMASK(J) )                                   MOERR171
      DO 4610 JX=1,NV                                                 MOERR172
        DO 4590 KX=1,JX                                               MOERR173
 4590     W(KX)=ERR(JX,KX)/(SCALE(JX)*SCALE(KX))                      MOERR174
        WRITE(KW,4600)JX,MASK(JX),(W(KX),KX=1,JX)                     MOERR175
 4600   FORMAT(/1X,I3,I8,5X,8E13.5/(17X,8E13.5))                      MOERR176
 4610   CONTINUE                                                      MOERR177
C                                                                     MOERR178
C  END MOERR.                                                         MOERR180
 4620 RETURN                                                          MOERR179
      END                                                             MOERR181
C                                                                     MOERR182
```

VITA

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Doctor of Philosophy

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